Everywhere Reconfigurable Intelligent Surfaces: The New Bandwagon Problem in Wireless Communications

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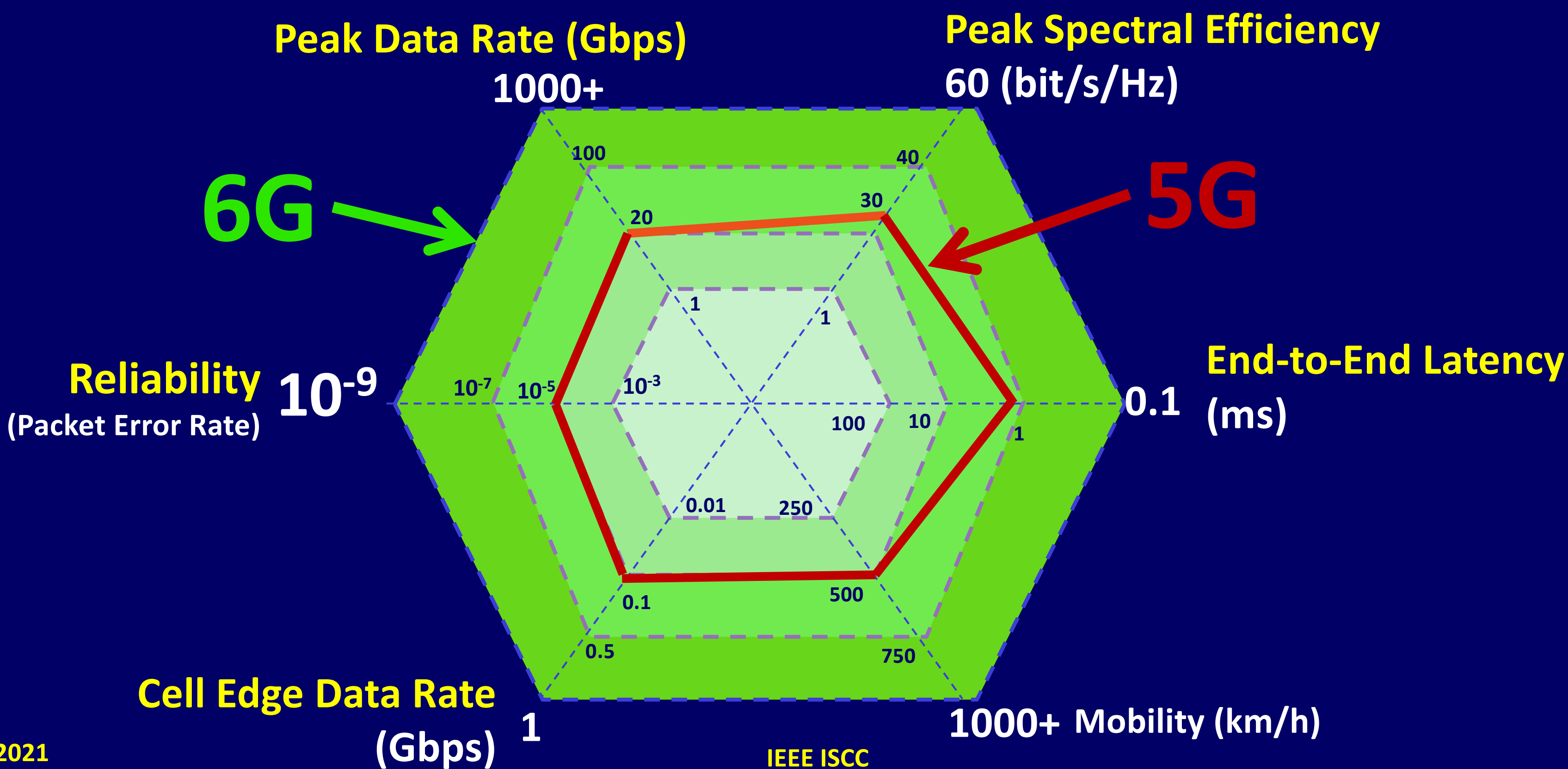
EVOLUTION FROM 5G TO 6G

I. F. AKYILDIZ, A. KAK, S. NIE

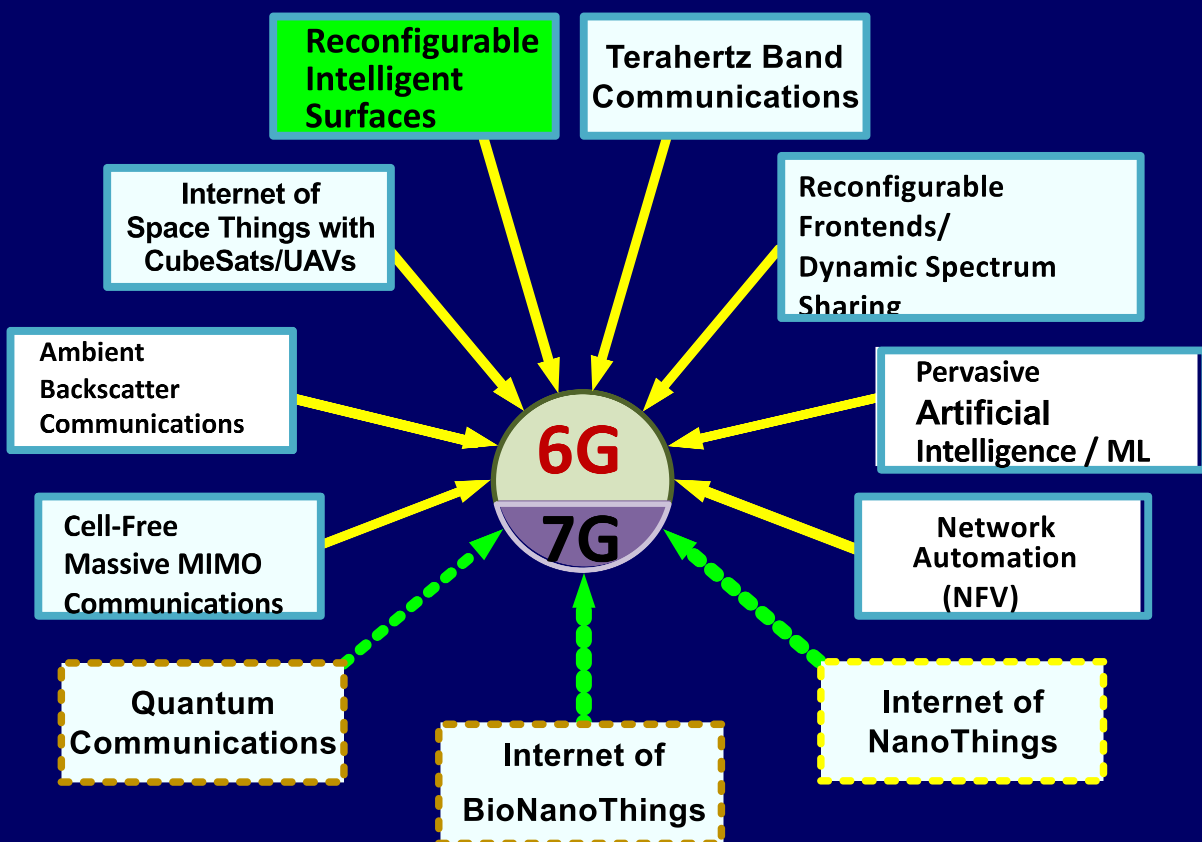
"6G AND BEYOND: THE FUTURE OF WIRELESS COMMUNICATIONS SYSTEMS",

IEEE ACCESS JOURNAL, VOL. 8, PP. 133995-134030, JULY 2020.

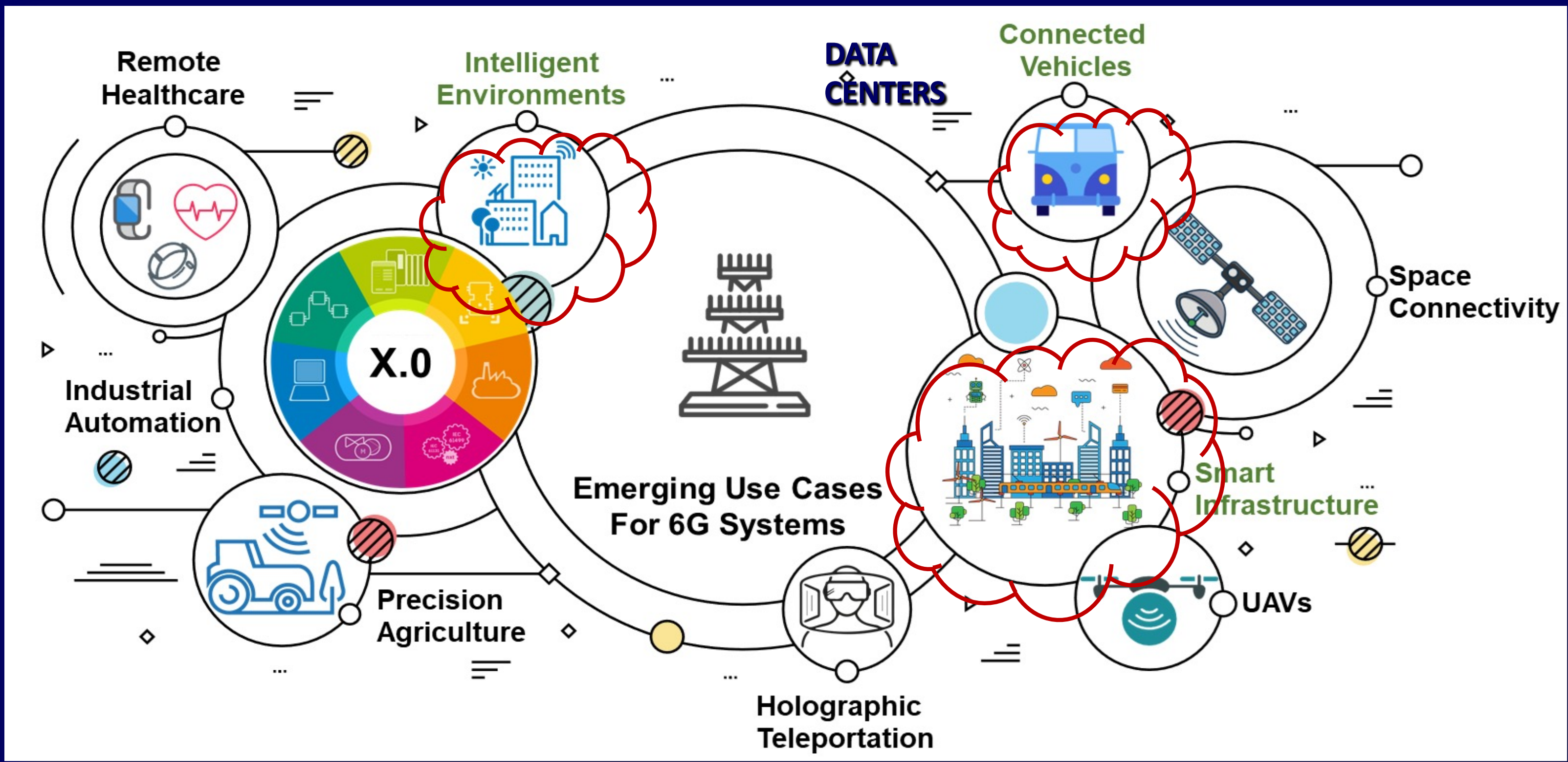


KEY ENABLING TECHNOLOGIES FOR 6G

I. F. AKYILDIZ, A. KAK, S. NIE
"6G AND BEYOND: THE FUTURE OF WIRELESS COMMUNICATIONS SYSTEMS",
IEEE ACCESS JOURNAL, VOL. 8, PP. 133995-134030, JULY 2020.



MAJOR USE CASES FOR 6G SYSTEMS



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HOW DID I END UP IN SURFACES ??

COMBATING DISTANCE PROBLEM IN THZ BAND COMMUNICATIONS

I.F. AKYILDIZ, C. HAN, S. NIE,

IEEE COMMUNICATIONS MAGAZINE, VOL. 56, PP. 102-108, JUNE 2018.

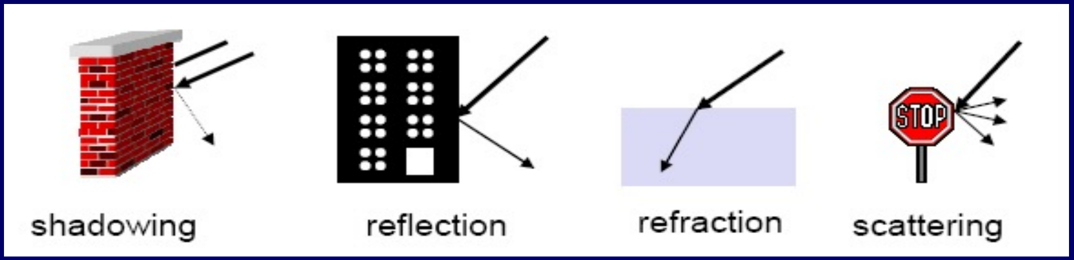
Objective: To increase the communication distance at mm-wave and THz band (0.06 – 10 THz)

- Multipath Effects
- Distance Adaptive Modulation
- Ultra Massive MIMO Communications
- Intelligent Environments (Reconfigurable Intelligent Surfaces)

WHY INTELLIGENT COMMUNICATION ENVIRONMENTS?

EM waves undergo multiple uncontrollable alterations as they propagate through a wireless environment.

- Path Loss
- Attenuation



Absorption

Diffraction

- Interference
- NLOS
- Fading
- Doppler Effects

- Distance esp. for 60GHz and TeraHertz bands
- Coverage
- Energy Consumption
- Security (e.g., Eavesdropping, Jamming, etc.)

CONVENTIONAL APPROACHES

- PHY Layer solutions, e.g., adaptive antenna, MIMO, beamforming, adaptive modulation, dynamic spectrum allocation, encoding and plethora of MAC and ROUTING protocols
- Although successful, they all have separate degrees of efficiency
- Also the random channel behavior still greatly affects the performance !!

CAN WIRELESS ENVIRONMENT HELP FOR COMMUNICATION?

- Seek a new solution how to tame the chaotic EM propagation
- Control and mitigate negative wireless communication effects, e.g., path loss and multi-path fading
- COATED SURFACES

  Objects, such as walls, receive a special coating that can sense impinging waves and actively "modify" them by applying an EM function, *e.g.,* include altering wave's direction, power, polarization and phase

→ **Wireless environment not PASSIVE → will provide direct control for wireless propagation**

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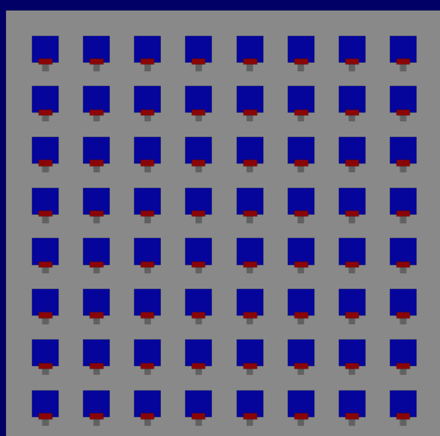
POSSIBLE SIMPLE SOLUTIONS

Passive Reflectarrays (1963)



Supports only:

Normal Reflection

Related to phased antenna arrays and reflectors.
Only phase can be controlled!!

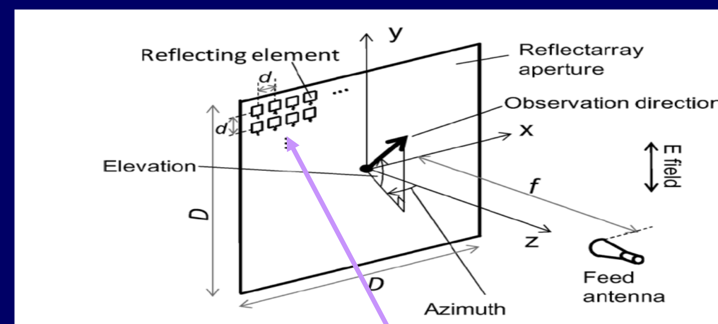


Fig. 1. Geometry of reflectarray antenna.

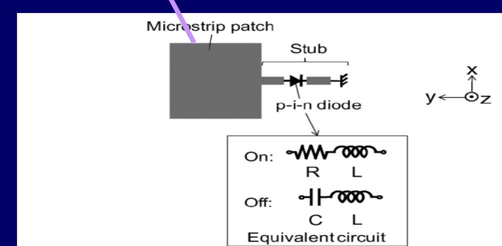


Fig. 2. Basic model of reflecting elements [10].

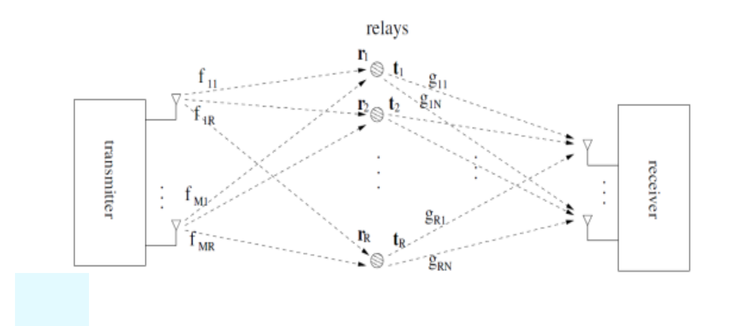
Switches or varactors can also be integrated to electronically control the phase of reflected field

POSSIBLE SIMPLE SOLUTIONS

Relays

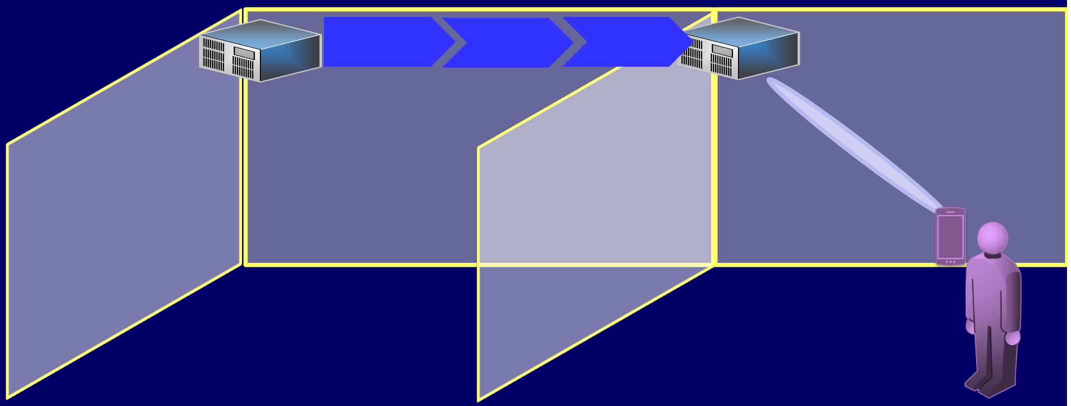
- Antenna pairs that can be placed over walls at regular intervals

- One or more out of the N outputs can be selected, thereby redirecting the input wave



: Wireless relay network with M antennas at the transmitter and N antennas at the receiver

Relays only partially customizable, reflect at predefined angles



Disadvantages:

- Longer delays
- More backhaul infrastructure cost;
- Inflexible for existing network layout

RECONFIGURABLE INTELLIGENT SURFACES (RIS)

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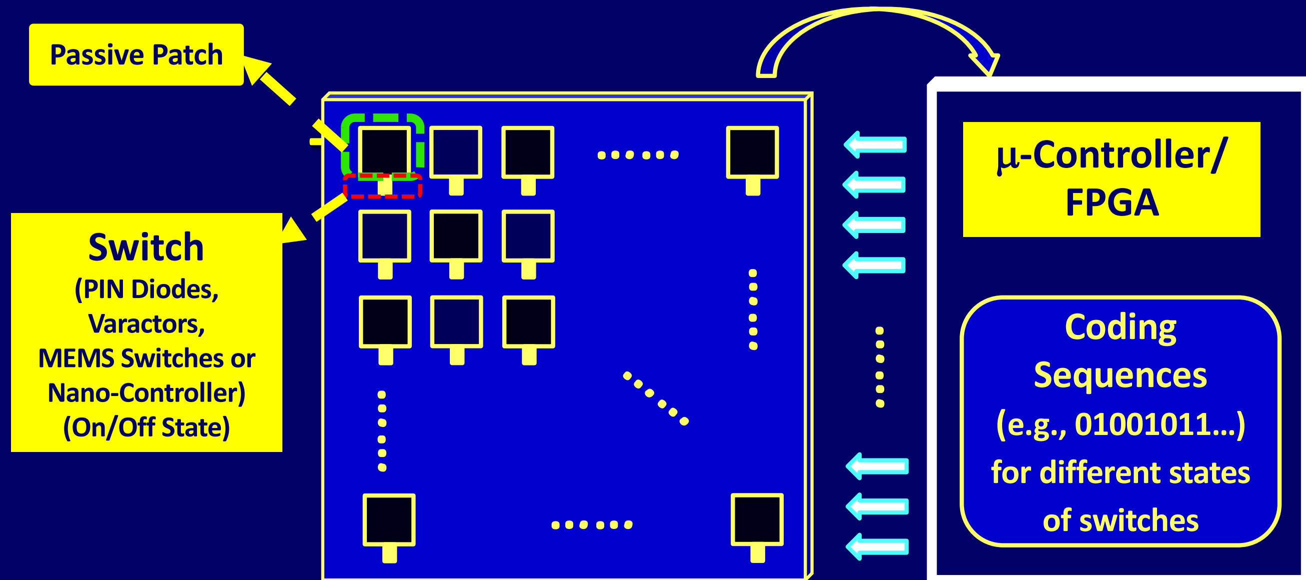
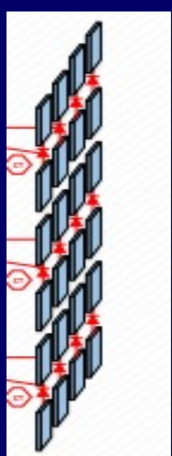
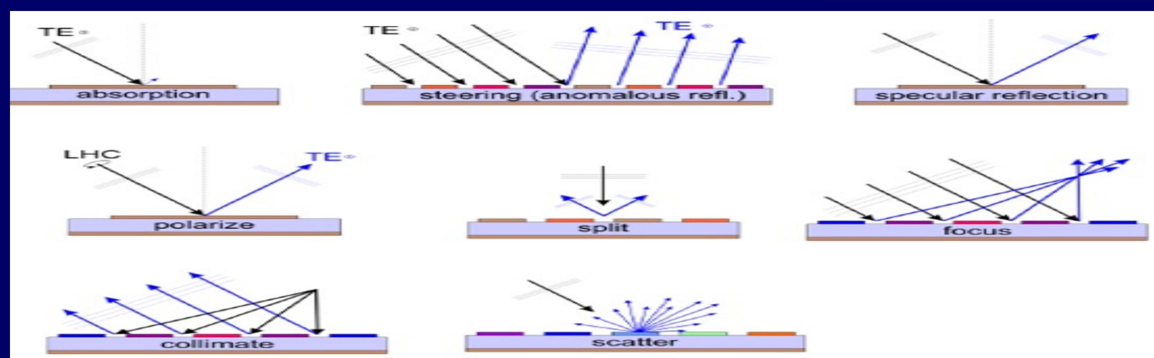
Intelligent Com Environments turn passive (inactive) wireless propagation environments into active participants in wireless signal transmission





Supports

Controlled Waves



COMPARISON

- **Surfaces** offer most **appealing** solution
- **Distinct advantages** in realizing communication applications over competing technologies (e.g., backscatter communication, MIMO, beamforming and relaying):
  - Passive nature
  - Resilient to noise (Surfaces do not need DA/AD converters, and power amplifiers)
  - Full-band operating frequency
  - Easy deployment e.g., on ceilings, indoor spaces, facades of buildings, human clothing, etc.

Table 1: Comparison of EM wave control techniques.

	Far EM Field Control Type	Near EM Field Control Type	Spatial EM Control Granularity	Hardware Complexity	Deployment Scalability
Phased Array Antennas	Deterministic	Probabilistic	Medium	Highest	Lowest
Un-phased Antennas	Probabilistic	Probabilistic	Low	Low	High
Passive Reflectors	Probabilistic	Probabilistic	None	Lowest	Highest
HyperSurfaces	Deterministic	Deterministic	Highest	Low	High

DIFFERENT NOMENCLATURE

- Intelligent Communication Environments (ICE)
- Intelligent Communication Surfaces (ICF)
- Reconfigurable Intelligent Surfaces (RIS)
- Programmable Wireless Environments (PWE)
- Programmable Metasurfaces
- Hypersurfaces
- Large Intelligent Surfaces (LIS)
- Intelligent Reflecting Surfaces (IRS)
- Smart Radio Environments

....

USE CASES OF RISs
PROPAGATION CHANNEL ENHANCEMENT

Support multiple users and devices for high-throughput links

Indoor meeting rooms & offices

RISs

Highway billboards

Promising for high-speed V2I links in vehicular networks

Support large audiences with multimedia services

Stadiums

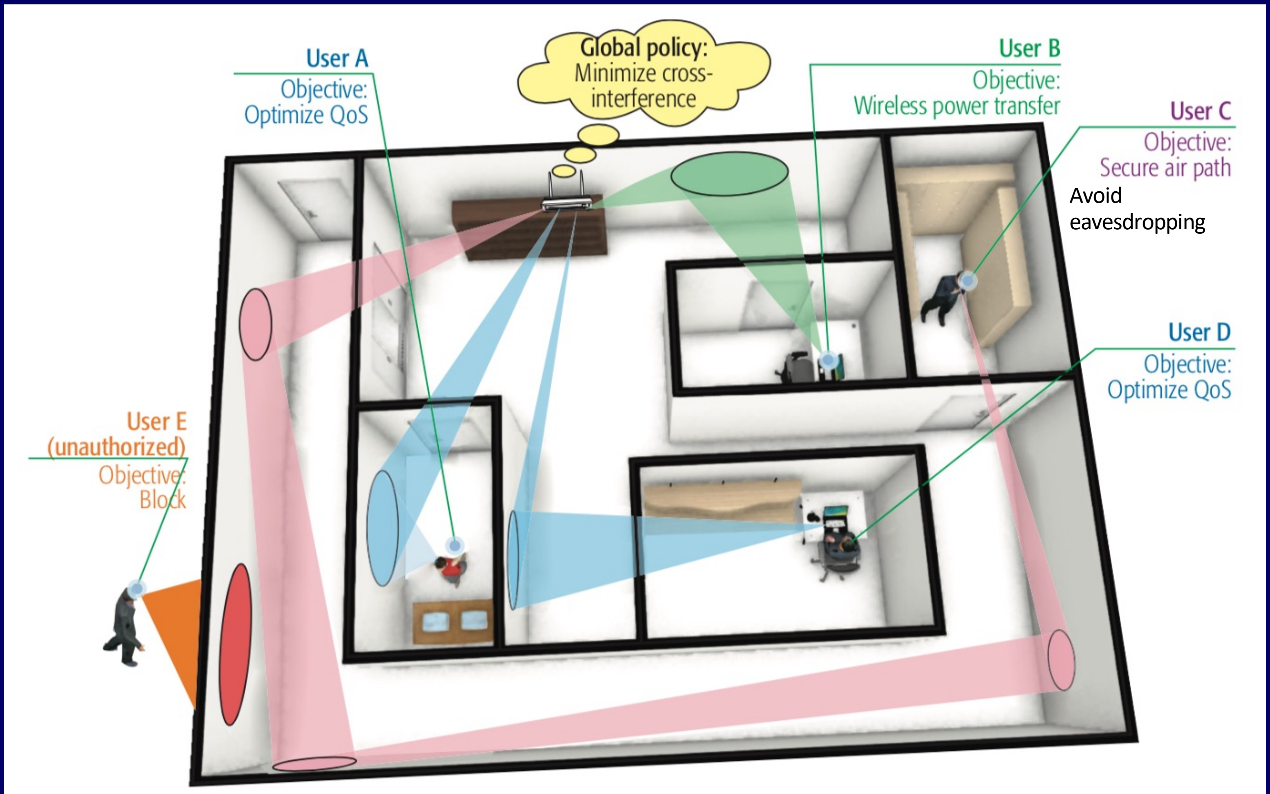
Shopping malls

Support large numbers of mobile users with high-speed connectivity

- Combating distance problem esp. for mm-wave and THz bands
- Solving NLOS issue

USE CASES: PHYSICAL LAYER SECURITY & WIRELESS POWER TRANFER

C. Liaskos, S. Nie, A. Tsioliaridou, A. Pitsillides, S. Ioannidis, & I.F. Akyildiz,
"A Novel Communication Paradigm for High Capacity and Security via Programmable indoor Wireless Environments in Next Generation Wireless Systems", Ad Hoc Networks (Elsevier) Journal, pp. 1-16, 2019.



ADDITIONAL BENEFITS

Optimization of Beamforming and Spatial Diversity

Spatial, spectral, and temporal allocations of resources for multi-user communications

Maximize data rates under energy constraints

Track mobile users and maintain their connectivity through phase shift optimizations

Optimum and adaptive decisions for QoS

Wireless Power Transfer

Security (Blocking Intruders, Avoiding Eaves Droppers, Jammers)

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CURRENT WORLDWIDE EFFORTS

HyperSurfaces
VisorSurf, EU-FET

SURFACES

Large Intelligent Surfaces
Huawei Paris and SUTD, Singapore

Reconfigurable Intelligent Surfaces Prototype and Experiments
Tsinghua, UESTC, China, Yonsei Univ. South Korea, Université Paris-Saclay, France, and Univ. of Southampton, U.K.

Space-Time-Coding Digital Metasurface
Southeast University, China

Programmable Metasurface
Sungkyunkwan University, South Korea

Intelligent Reflecting Surface
NUS, Singapore

Transparent Dynamic Metasurface
Docomo, Japan

Programmable Metasurface
Tsinghua University, China

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CURRENT GLOBAL PROTOTYPING EFFORTS

1. C. Liaskos, et al, "A New Wireless Communication Paradigm through Software-controlled Metasurfaces," IEEE Comm. Mag., 2018.
2. L. Zhang, et al., "Space-time-coding digital metasurfaces," Nature comm., 2018.
3. H. Yang, et al, "A programmable metasurface with dynamic polarization, scattering and focusing control," Scientific reports, 2016.
4. "DOCOMO Conducts World's First Successful Trial of Transparent Dynamic Metasurface", 2020.
5. N. M. Tran, et al, "A Novel Coding Metasurface for Wireless Power Transfer Applications", 2019.
6. L. Dai, et al. "Reconfig. intelligent surface-based wireless com: Antenna design, prototyping, and experimental results." IEEE Access, 2020.

Name of Surface	Frequencies	Surface Materials	Functionality	Surface Dimension	Configuration and Control
VisorSurf HyperSurfaces (EU Project) [1]	2.5 and 60 GHz Sub THz	Hypersurfaces: Software Defined Metasurfaces/Graphenes	Beamsteering, polarization, tuning, collimation, etc.	$\lambda/10$-$\lambda/5$ per element, 30X30 element/array	Layered architecture with controllers
Digital Coding Metasurfaces (Southeast Univ., China) [2]	10 GHz	Space-time-coding metasurfaces	Various beam steering patterns	8 × 8 elements	FPGA control board
Programmable Metasurface (Tsinghua Univ., China) [3]	9 – 12 GHz	Rectangular-shaped patch antennas	Polarization, scattering and focusing	320 active units per surface	FPGA control board & PIN diodes for ON/OFF
Transparent Dynamic Metasurface (Docomo, Japan) [4]	28 GHz	Transparent dynamic metasurfaces	Full penetration, partial and full reflections	20 cm × 20 cm	N/A
Programmable Metasurface (Sungkyunkwan Univ., SK) [5]	5.8 GHz	1-bit coding metasurfaces	Wireless power transfer	16 × 16 elements	States controlled by PIN diodes
Reconfigurable Intelligent Surfaces (Tsinghua Univ., UESTC, China and Université Paris-Saclay, France) [6]	2.3 GHz and 28.5 GHz	2-bit coding metasurfaces	Energy-efficient wireless communications	16 × 16 elements	States controlled by PIN diodes

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EU-FET PROJECT VISORSURF

http://www.visorsurf.eu

- **Design, build, and demonstrate software-defined metasurfaces (HyperSurfaces) with end-to-end functionality**

- **"A HyperVisor for MetaSurface Functionalities"**
  - **Controlling & customizing EM propagation with software!**

- **Start date: 1/1/2017**
- **Duration: 42 months**
- **Coordinator: FORTH Crete, Greece**
- **8M Euro (2017-2021)**

VISORSURF TEAM (FORTH CRETE; AUG. 2019)

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RECONFIGURABLE INTELLIGENT SURFACES

INTELLIGENT ENVIRONMENTS

BASIC REFERENCES

- A. Pitsillides, C. Liaskos, A. Tsioliaridou, S. Ioannidis, I. F. Akyildiz, "Wireless Communication Paradigm Realizing Programmable Wireless Environments through SW-controlled Metasurfaces" US PATENT, 10.547.116 B2; January 28, 2020.

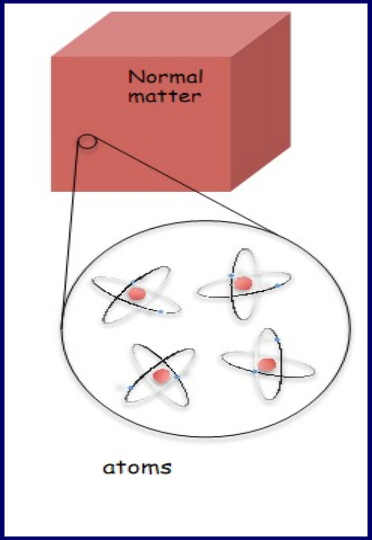
- C. Liaskos, S. Nie, A. Tsioliaridou, A. Pitsillides, S. Ioannidis, I. F. Akyildiz, "A New Wireless Communication Paradigm through SW-controlled Metasurfaces" IEEE Communications Magazine, Sept. 2018.

- C. Liaskos, A. Tsioliaridou, A. Pitsillides, I.F. Akyildiz, N. Kantartzis, A. Lalas, X. Dimitropoulos, S. Ioannidis, M. Kafesaki, and C. Soukoulis, "Design and Development of Software Defined Metamaterials for Nanonetworks," IEEE Circuits and Systems Magazine, vol. 15, no. 4, pp. 12-25, 4^{th} Quarter 2015.

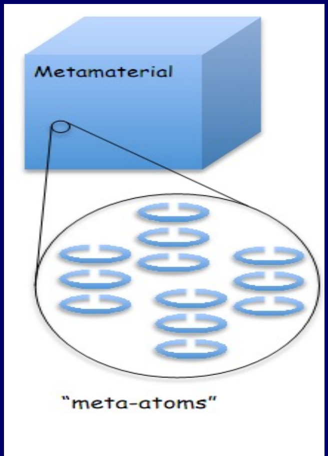
More → http://www.visorsurf.eu

NATURAL MATERIALS VS METAMATERIALS

Natural materials properties depend on the atomic synthesis



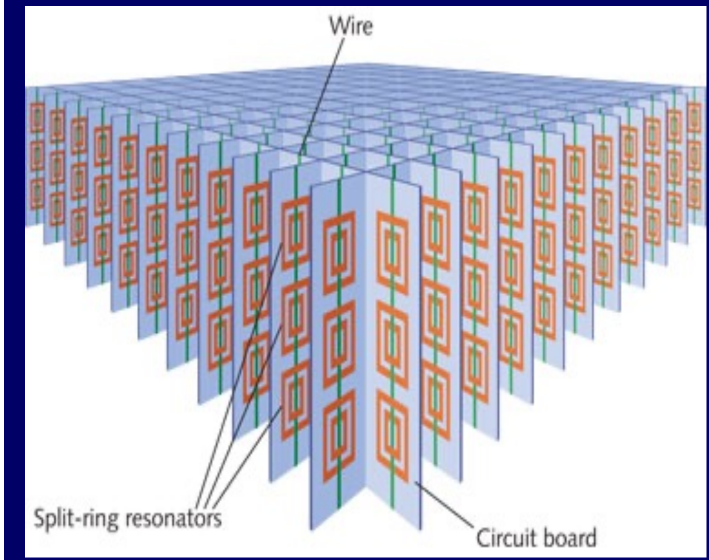
Metamaterials are artificial periodic structures which behave collectively as media with effective new properties



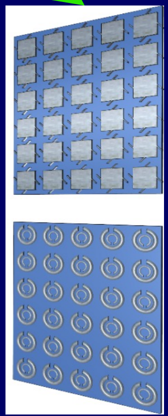
Key elements are the sub-wavelength features that exhibit local controllable electric and magnetic response, hence controllable permittivity and permeability, also anisotropy, chirality, dispersion …

METAMATERIALS

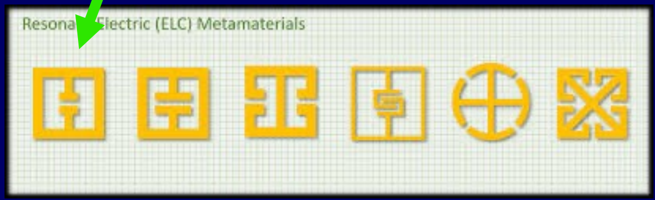
- A metamaterial ("beyond") is a material engineered to have a property that is not found in nature
- Manipulation of EM waves: block, absorb, enhance, or bend waves, to achieve benefits that go beyond what is possible with conventional materials
- Their precise shape, geometry, size, orientation and arrangement gives them their smart properties

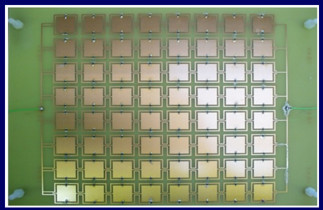


Metasurfaces are their 2D versions

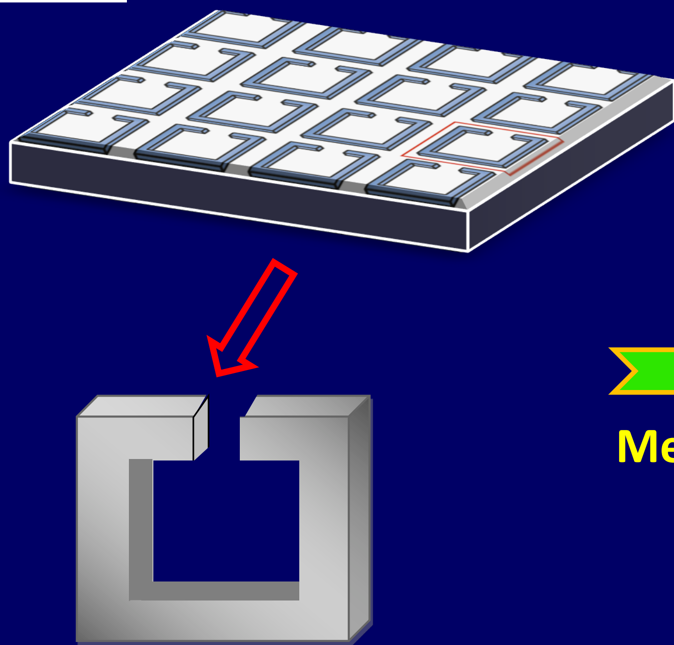


uses repeating patterns of meta atoms (copper strips, patches) deposited on an insulator material





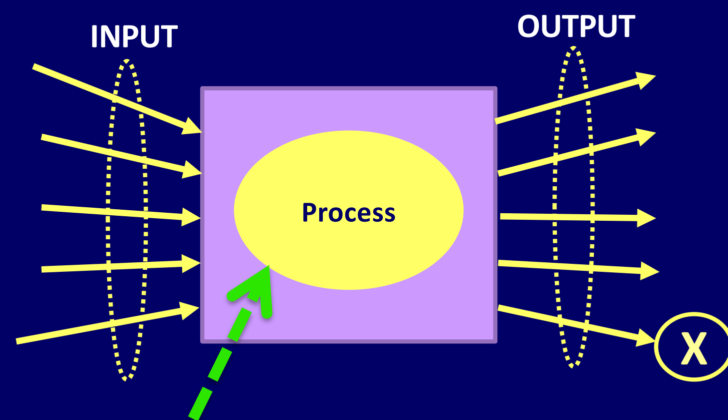
METAMATERIAL BASICS



Schematics of the Elementary Cell

Metasurfaces

Completely re-engineer incoming (impinging) EM waves



STEER (changing directions), ABSORB (reducing power), POLARIZE, SPLIT, FREQ_FILTER, ALTER_PHASE, FOCUS, CUSTOM EM/MAG FIELD at output(s)

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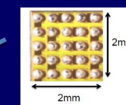
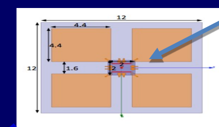
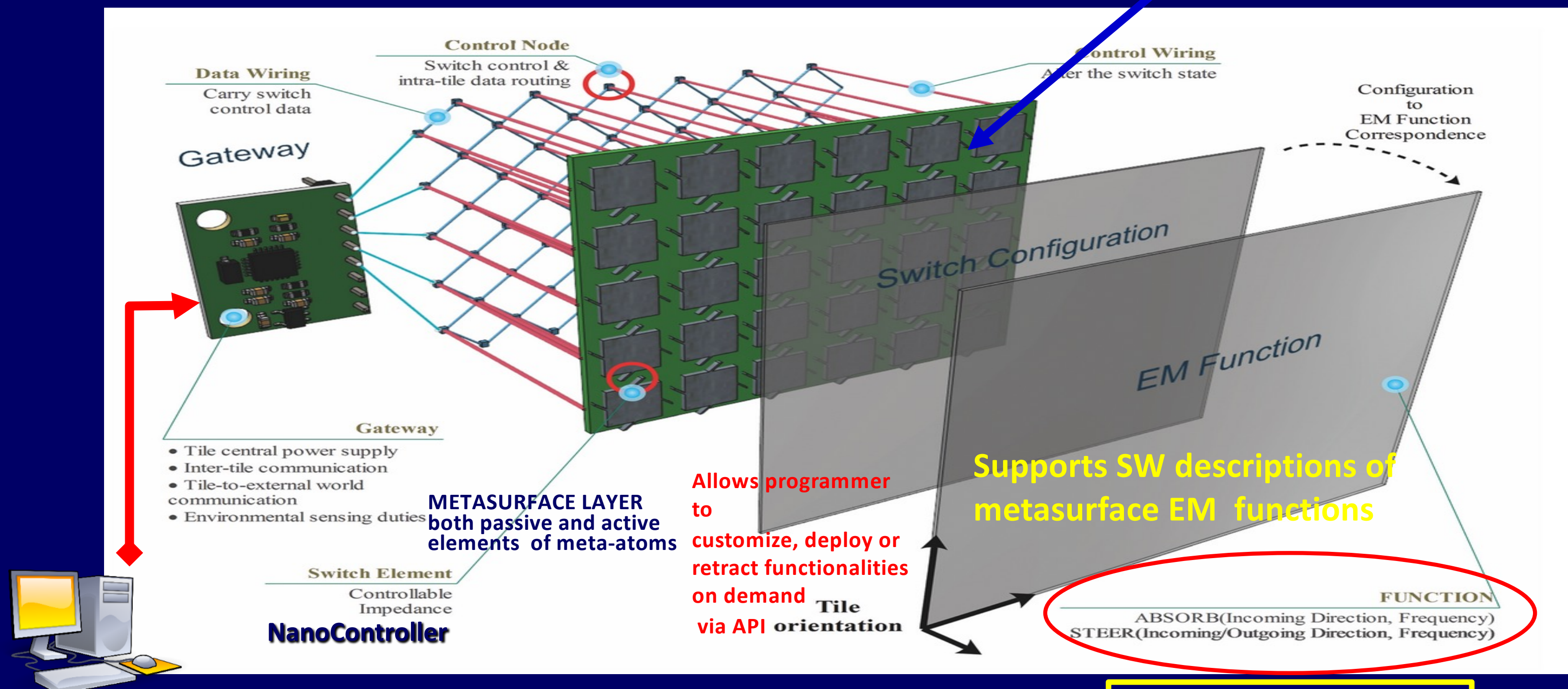
HYPERSURFACES: PROGRAMMABLE (SOFTWARE DEFINED) METASURFACES

A. PITSILLIDES, C. LIASKOS, A. TSIOLIARIDOU, S. IOANNIDIS, I. F. AKYILDIZ,
"WIRELESS COMMUNICATION PARADIGM REALIZING PROGRAMMABLE WIRELESS ENVIRONMENTS THROUGH SOFTWARE-CONTROLLED METASURFACES"
US PATENT, 10.547.116 B2; JANUARY 28, 2020.





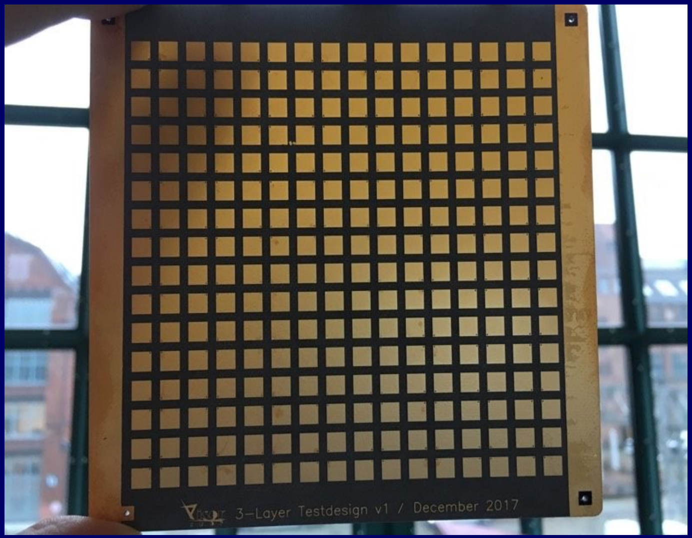
meta atoms/
metallic patches/
unit cells



Deployed Functions

PROTOTYPING

COURTESY OF FRAUNHOFER INSTITUTE BERLIN



- **First prototype is ready for evaluation**
  - **Software & Hardware**

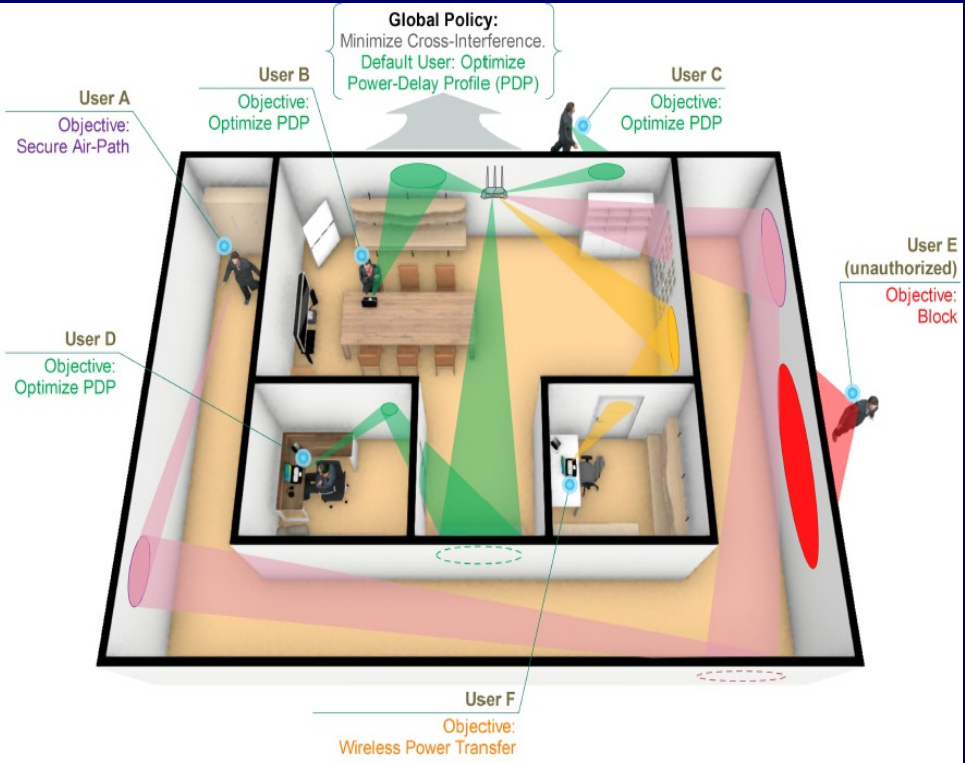
- **More prototypes to follow:**
  - **Exotic ASIC solutions**
  - **Graphene-based, THz control**

- **Paving the way for smart, connected materials with programmable physical properties**

CONFIGURING PROGRAMMABLE WIRELESS ENVIRONMENTS

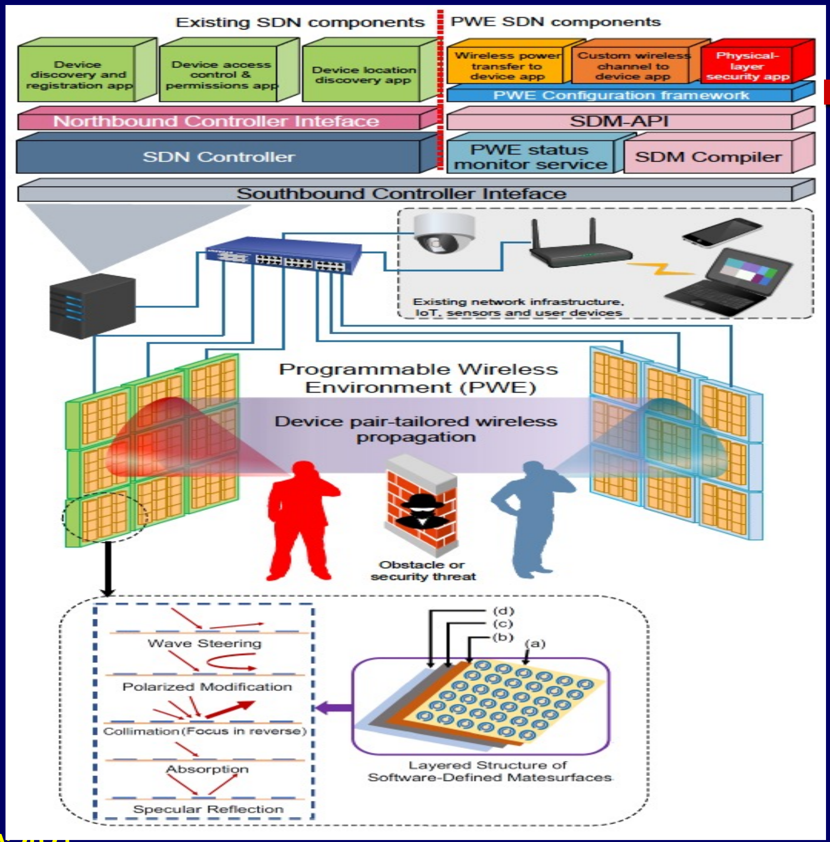
C. Liaskos, A. Tsioliaridou, S. Nie, A. Pitsillides, S. Ioannidis and I. F. Akyildiz,
"An Interpretable Neural Network for Configuring Programmable Wireless Environments,"
IEEE 20th Int. Workshop on Signal Processing Advances in Wireless Communications (SPAWC), Cannes, France, pp. 1-5, 2019.

- **Objective:** Configure all or some of the SURFACES in the environment with appropriate EM manipulation functions
- Configuring such environments in order to maximize the received power delay profile for Users B,C, D
- Methodology
  - Modeling wireless propagation as a custom, interpretable, back-propagating NN
  - SDM elements are treated as nodes and their cross-interactions as links
  - With a training period of NN, the network learns the propagation basics of SDMs and configures them to facilitate the communication of users within their vicinity



SDN BASED ARCHITECTURE

C. Liaskos, S. Nie, A. Tsioliaridou, A. Pitsillides, S. Ioannidis and I. F. Akyildiz,
"End-to-end Wireless Path Deployment with Intelligent Surfaces Using Interpretable Neural Networks,"
IEEE Transactions on Communications, vol. 68, no. 11, pp. 6792–6806, 2020.



- **A system/network-level simulator includ. EM wave property characterization**
  - 3D channel performance modeling & analysis
    - Various communication scenarios for use cases: indoor, outdoor, D2D, V2X, multi-user case, etc.
  - MAC and routing protocols
  - Software-defined networking functionalities
  - Reliability/robustness tests
  - Automatic Network Slicing for NFV

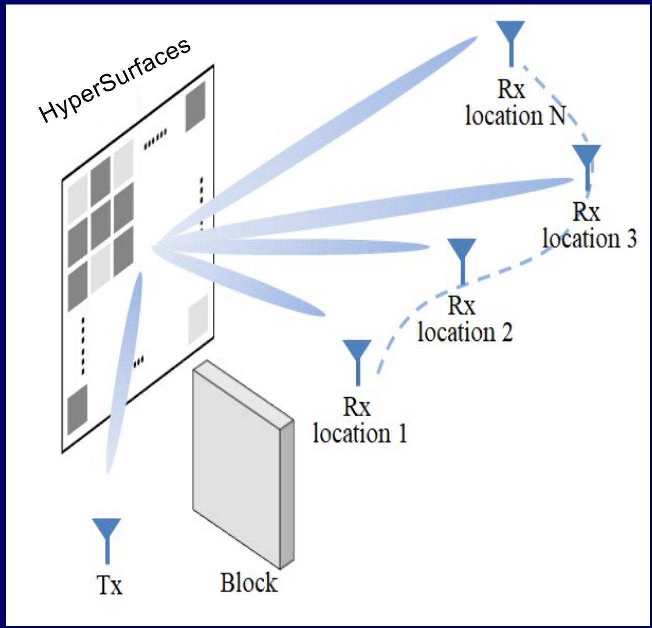
MOBILITY-AWARE BEAM STEERING

C. Liaskos, S. Nie, A. Tsioliaridou, A. Pitsillides, S. Ioannidis, and I.F. Akyildiz,
"Mobility-Aware Beam Steering in Metasurface-Based Programmable Wireless Environments,"
IEEE Int. l Conference on Acoustics, Speech and Signal Processing (ICASSP), Barcelona, Spain, pp. 9150-9154, May 2020.

- HyperSurfaces can be effectively configured for static Tx – Rx locations, but the KEY questions are
  - What if there is mobility?
  - Can the surface adapt in time?

- Objective: Develop a beamforming approach that is mobility aware and can account for location imprecision

- Our solution: An analytical model describing
  - Misalignment between user-emitted waves and PWE configuration
  - Each HSF unit measures received signal strengths and deduce UE location based on cumulative values measured by all HSF units
- Beam steering approach based on wave manipulation precision can effectively mitigate the misalignment effects



GRAPHENE BASED SURFACE FOR TERAHERTZ BAND

S.S. Dash, C.S. Liaskos, I. F Akyildiz and A. Pitsilides,
"Graphene Hypersurface for Manipulation of THz Waves",
4th Int. Conf. on Material Engineering and Manufacturing, Tokyo, Japan, April 10-13, 2020.

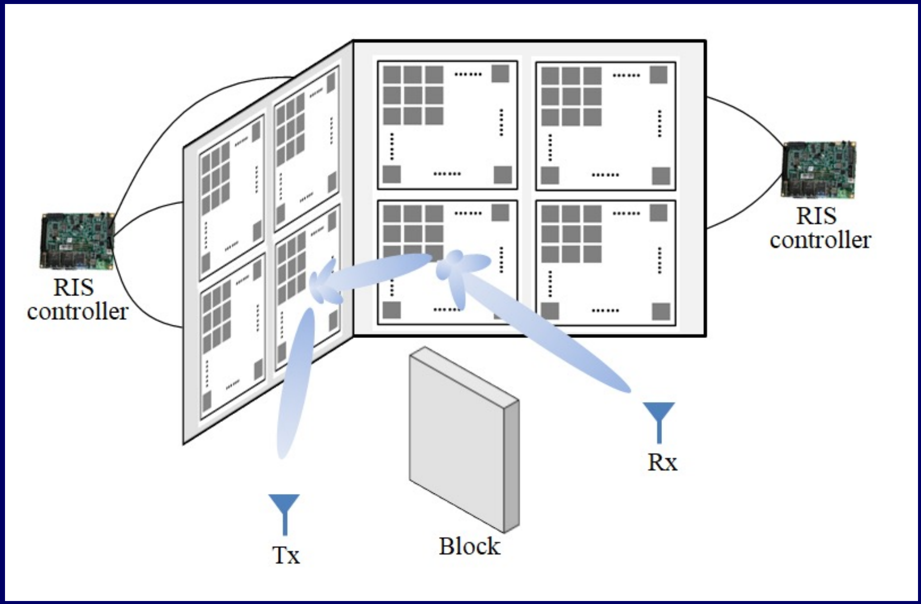
S.S. Dash, C.S. Liaskos, I. F Akyildiz and A. Pitsilides,
"Wideband Perfect Absorption Polarization Insensitive Reconfigurable Graphene Metasurface for THz Wireless Environment",
IEEE Workshop on Microwave Theory and Techniques in Wireless Com, Oct 2019, Riga, Latvia.

- **THz band susceptible to acute signal attenuation owed to molecular absorption.**
  - RIS with graphene meta-atom designs could act as a smart environment for THz (2.5THz) communications mitigating the attenuation effects and extending the communication range
  - Graphene metasurface that will perfectly absorb impinging THz wave radiation
    - Wide band and wide angle; for both TE (transverse electric) and TM (transverse magnetic) polarizations; Under normal and oblique incidence; and at reconfigurable frequencies.

OPEN RESEARCH TOPICS

- Practical deployments and how multiple surfaces can coordinate with each other considering QoS such as latency, losses, etc.

  – Optimal placement of surfaces under QoS constraints
  – Distributed Control
  – Low-latency coordination scheme
  – HW architecture of controlling system for distributed RIS system



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OPEN RESEARCH TOPICS

– Any frequency spectrum and wireless architecture (indoors and outdoors communication environments): mm-waves, D2D and 5G, THz

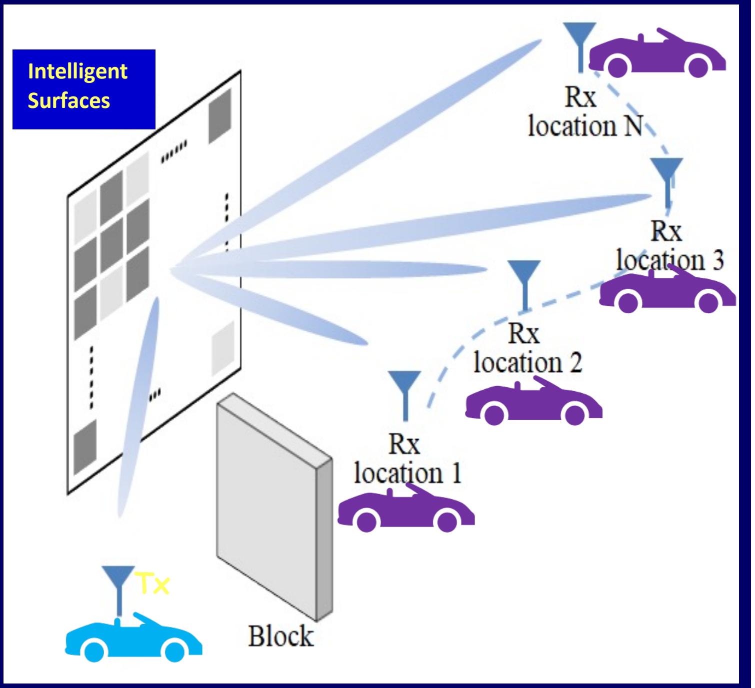
- Solve path loss, fading, interference and NLOS problems
- Joint optimization of antenna beamforming and RIS configurations

OPEN RESEARCH TOPICS

- How to acquire CSI in rapid time-varying channel? Spectrum Sensing

- How to detect, track, and localize multiple mobile users/objects in channels?
  - User mobility leads to rapid variation beam space channels
  - Conventional real-time channel estimation schemes involve unaffordable pilot overhead
  - Real-time beam tracking scheme for high-speed users/vehicles and random trajectories

- Resources in the spatial, temporal, and spectral domains should be allocated in an optimal manner to satisfy per mobile users demand

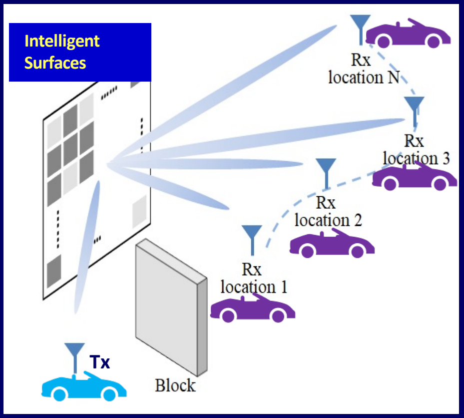


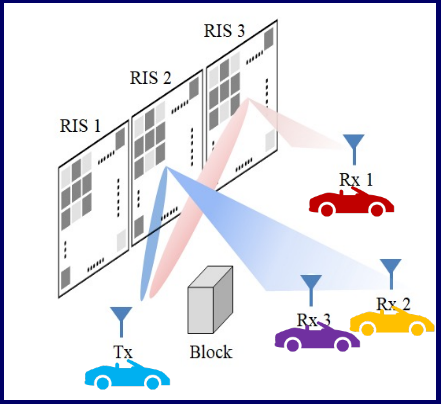
OPEN RESEARCH TOPICS

- Multiple Surfaces Deployments and Coordination (Optimization)
- Routing Algorithms
- Medium Access Control for Multiuser Communications

Challenges:

- Passive reflection in RISs limits the beamforming gains
- Performance loss due to limited phase shift resolution
- Channel Estimation



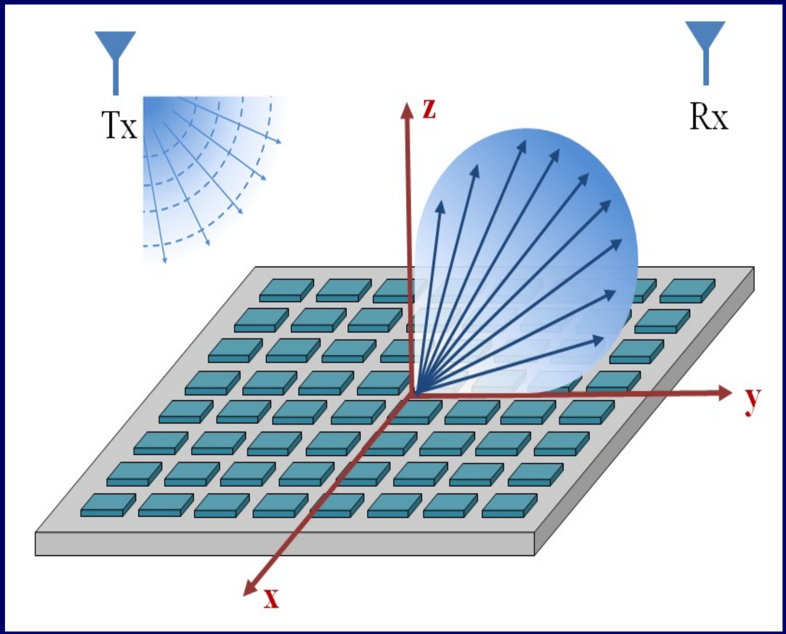


OPEN RESEARCH TOPICS

Actual Hardware Design and Implementation/Hardware Defects

- To what extent can we tolerate individual unit failure that will not affect the beam patterns generated by the surfaces?

- How versatile can different HW designs be such that they can comply with different requirements, including energy consumption, delay, throughput, and user mobility?

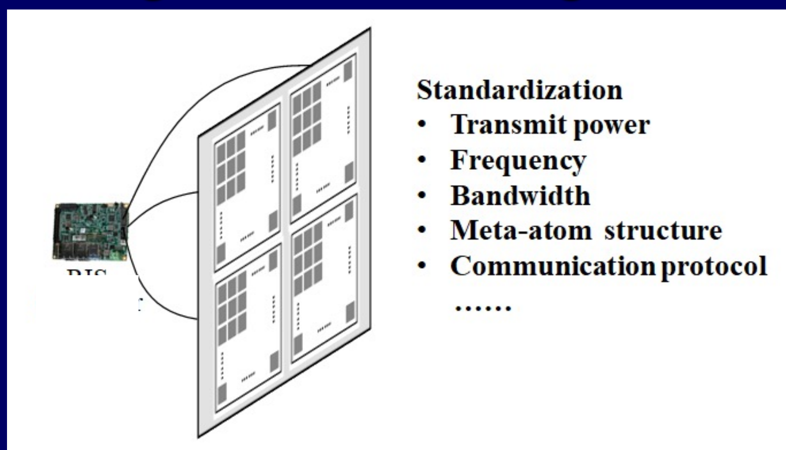


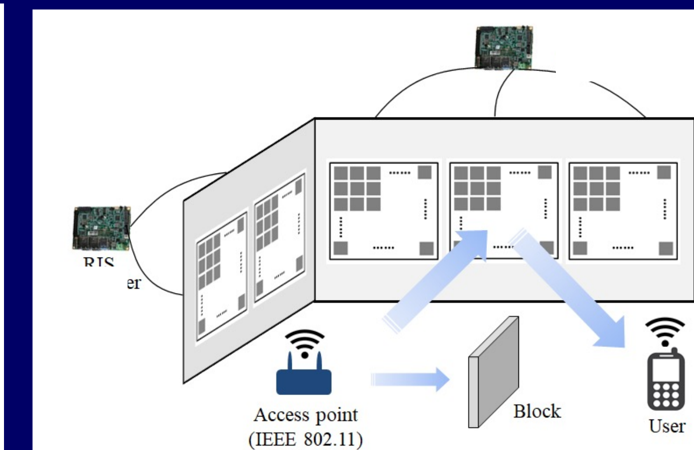
OPEN RESEARCH TOPICS

- **Bridge the gap between theoretical analysis and real-world deployments**
  - **Physical design of surface units and controllers with full functionality, reconfigurability, low cost and low power consumption**
  - **AI-driven tools for designing surfaces given specific application scenario**
  - **Enormous # of devices, large demands of real-time video streaming, higher mobility, etc.**

OPEN RESEARCH TOPICS

- **Standardization and Assessment**
  - HW structures and communication protocols
  - Integration into existing wireless communication networks (5G, 6G, IEEE





- A joint effort, from public and private sectors, is necessary to converge to a series of design standards to facilitate faster testing and production.

MORE OPEN RESEARCH PROBLEMS

Fundamental performance limits of the RIS

Algorithms & Protocols to achieve fundamental performance limits

Performance gains of RIS compared with current wireless networks

Smart design tools for metasurfaces (AI-driven), tailoring their overall design to an application scenario.

Novel SW tools for scalable metasurface physics simulation (non-periodic non-linear cases).

Ultra low-latency fault tolerant internetworking of metasurfaces.

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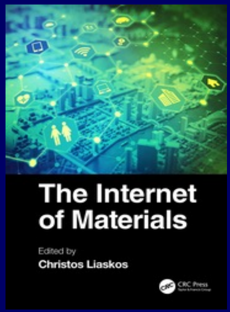
10 TECH TRENDS

IT FUTURE

- NEXT GENERATION MATERIALS*
- PROCESS AUTOMATION & VIRTUALIZATION & AUTOMATIC SLICING
- BIOREVOLUTION (BIONANOTHINGS)
- NG COMPUTING
- GREEN ENERGY (CLEAN TECH)
- SUPER FAST CONNECTIVITY (almost zero End to End Latency)
- VIRUS SHIELD for IoT and Trusted Infrastructure
- AI /ML Based Future of Programming
- SDN/NFV
- PERVASIVE AI/ML



CRC Press, Dec. 2020

https://doi.org/10.1201/9781003043805

Partly from McKinsey&Company

LESSON: DARPA NEWS (2014):

4 DARPA PROJECTS BIGGER THAN THE INTERNET

1. ATOMIC GPS
   (C-SCAN → Chip-Scale Atomic Navigation
   QuASAR → Quantum Assisted Sensing)

2. Terahertz Frequency Electronics, Devices,
   Meta-materials and Communication

3. A Virus Shield for the Internet of Things
   (The High Assurance Cyber Military Systems program, or HACMS)

4. Rapid Threat Assessment

Internet of MetaMaterial Things

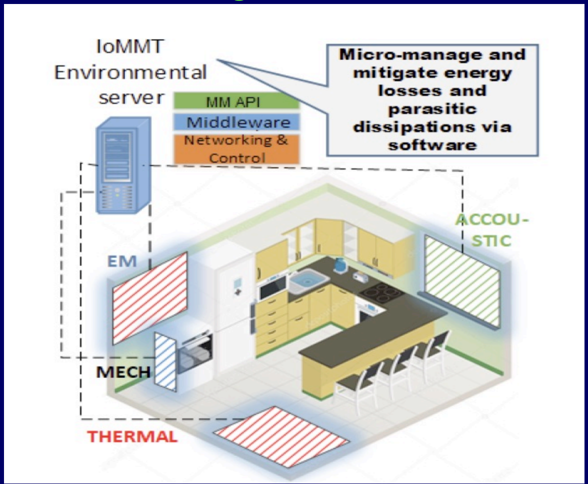
C. Liaskos, G. Pyrialakos, A. Pitilakis, A. Tsioliaridou, M. Christodoulou,
M. Kantartzis, S. Ioannidis, A. Pitsillides, and I.F. Akyildiz,
"The Internet of MetaMaterial Things and Their Software Enablers",
ITU Journal of Future and Evolving Technologies (J FET), Volume 1, Issue 1, Pages 55-77, Dec. 2020.

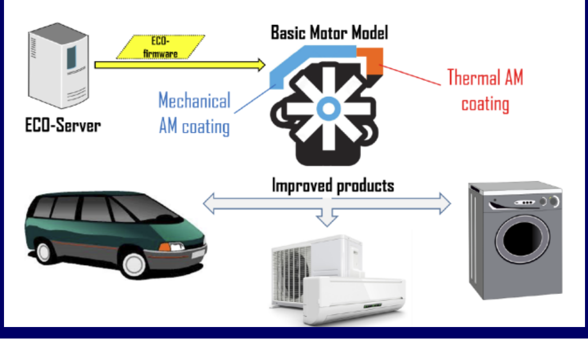
Artificial materials with real-time tunable physical properties can be interconnected to form a network to realize energy propagation through software-controlled EM, acoustic, and mechanical energy waves

Expansion of the IoT to the level of physical material properties, such as electrical and thermal conductivity, mechanical elasticity, and acoustic absorption.

Groundbreaking potential across many industrial sectors!

Will significantly enrich the IoT ecosystem by connecting anything at any place by optimizing the physical energy propagation between the metamaterial devices during their lifetime, via eco-firmware updates.





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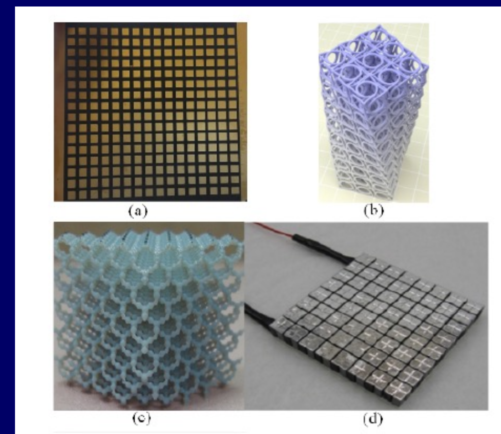
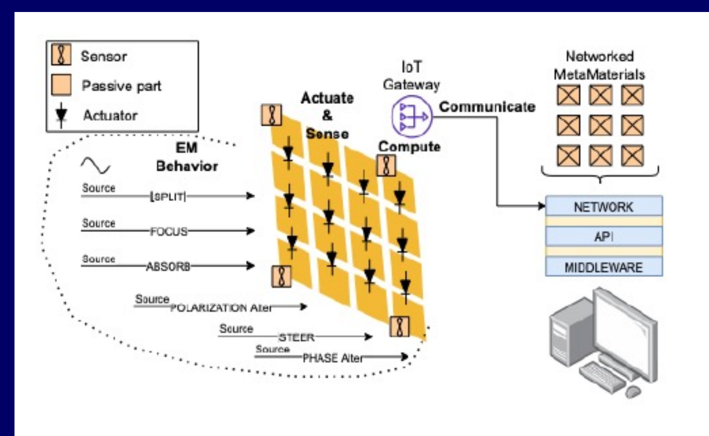
Two Key Enablers



1. **MetaMaterials**
   (electro-magnetic (a), mechanical (b), acoustic c) and thermo-dynamic (d), quantum-mechanic metamaterials)

   (Metamaterials can produce any custom departing EM wave as a response to any impinging wave, just by tuning the state of embedded switches/actuators).

2. **Networked of MetaMaterials**



Networked Metamaterial structure and Possible Energy Wave Interactions

FUTURE RESEARCH

- **How can the IoMMT prolong the life-cycle of products across deployment scales?**

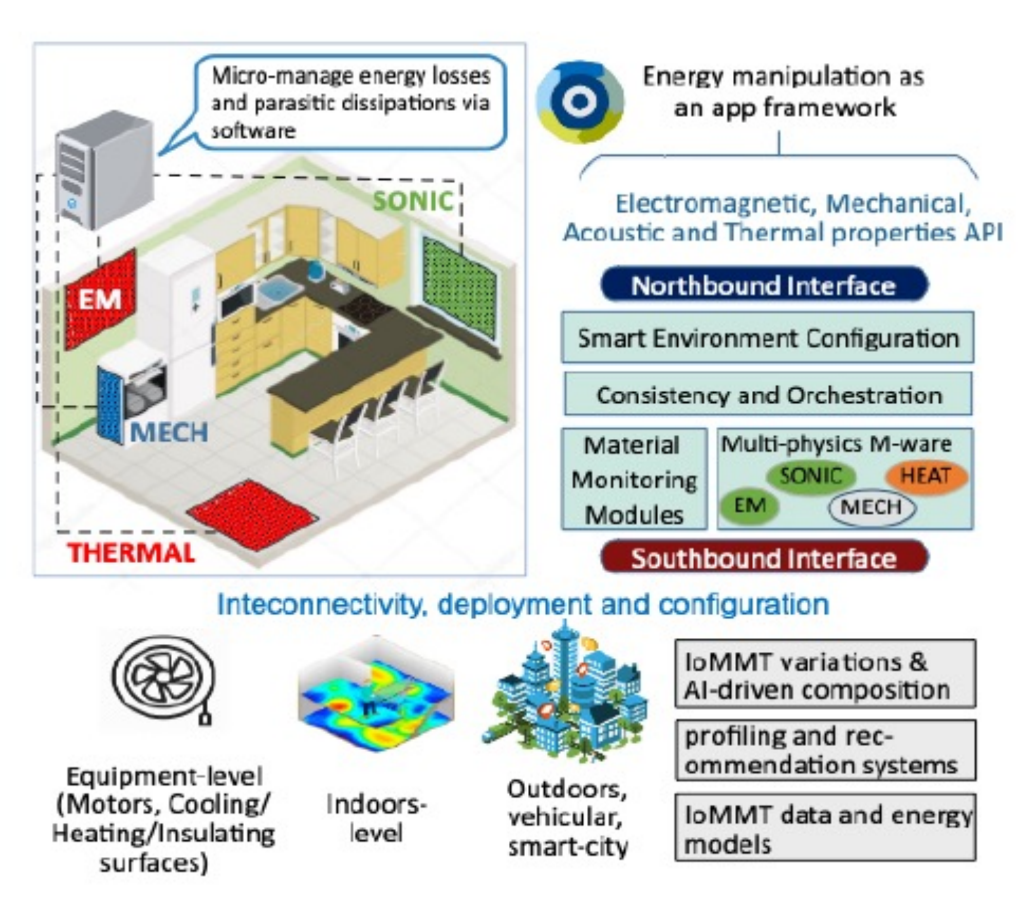
- **How can the IoMMT help maintain a high-speed product development pace, without sacrificing ecological concerns during the product design phase?**

- Concept of Circular Economy (CE) → to evaluate the IoMMT paradigm

- CE seeks to make technological products reusable, repairable and recyclable (multi uses) across their lifetime (i.e., development, purchase, usage and disposal) by introducing cross-product and cross-manufacturer interactions.

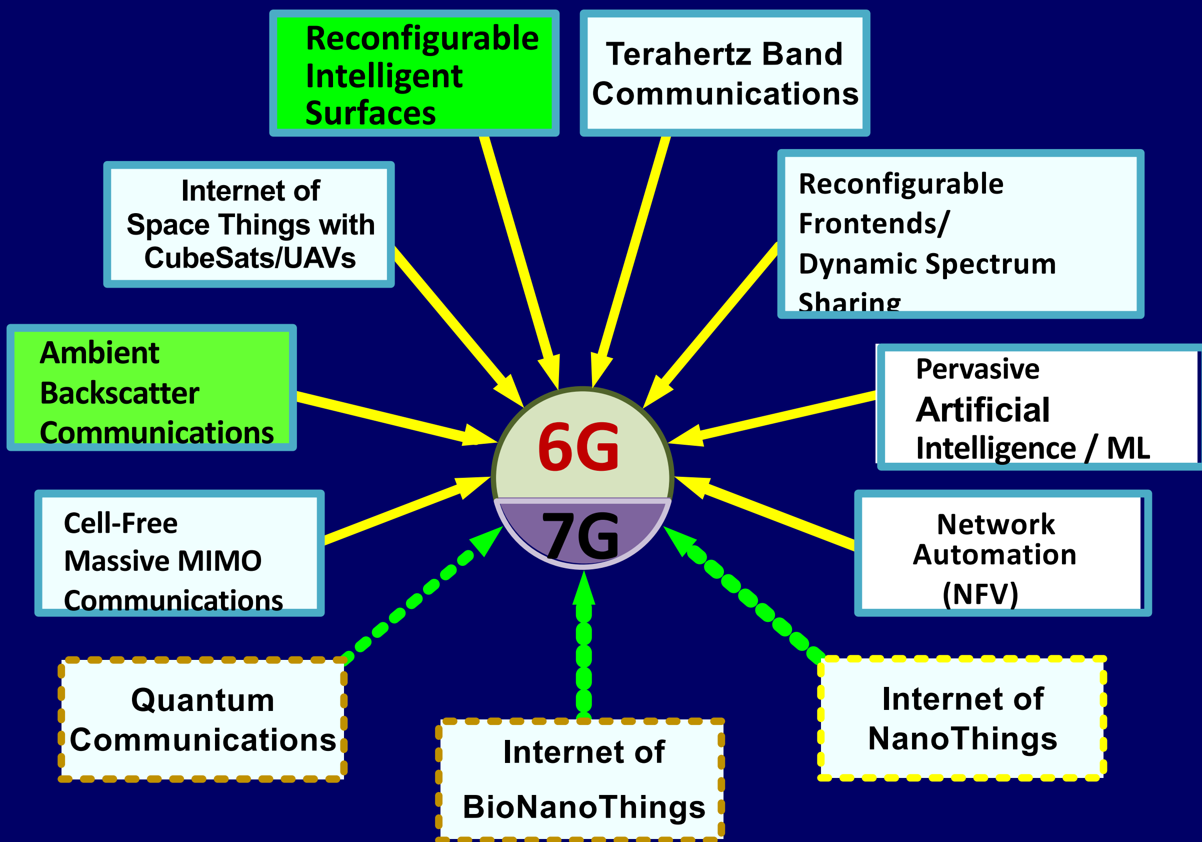
- IoMMT is by its nature impactful for the energy and ecological footprint of multiple products, across disciplines and scales.
- Need for theoretical and modeling foundations of the IoMMT.

OUR VISION FULL STACK FOR IoMMT



KEY ENABLING TECHNOLOGIES FOR 6G

I. F. AKYILDIZ, A. KAK, S. NIE
"6G AND BEYOND: THE FUTURE OF WIRELESS COMMUNICATIONS SYSTEMS",
IEEE ACCESS JOURNAL, VOL. 8, PP. 133995-134030, JULY 2020.



WHAT IS BACKSCATTER COMMUNICATION ?

- Separation of the carrier signal generation from the communication process.
- Carrier can be emitted by an external device, while the BC-enabled devices:
  i) absorb part of it to become active, and
  ii) modulate it on the fly, thus attaching information to it.
- Simple BC device HW (no battery and no carrier generation circuitry)
- External device generating the carrier can either be a
  BC system-dedicated source (common in RFID), or any wireless transmitter, e.g. WiFi, cellular and Bluetooth.
- Dedicated source case is common in RFID
- Non-dedicated case, known as **Ambient BC (ABC)**

AMBIENT BACKSCATTERING COMMUNICATIONS

- Traditional backscatter communications have many drawbacks
  - Requires proximity between backscatter Tx and RF sources
    - Limited coverage area and device usage
  - Backscatter Tx are passive
    - Only transmit when requested by backscatter Rx
  - Backscatter Rx and RF source are co-located
    - Strong self-interference
- A better solution for low-power communications?

Ambient Backscattering

  - Communication by utilizing surrounding signals broadcast from ambient RF sources, e.g., TV towers, FM towers, cellular BS, and Wi-Fi APs

ADVANTAGES OF AMBIENT BACKSCATTERING COMMUNICATIONS

- Does not require dedicated spectrum
- Effective in addressing communication and energy efficiency problems for low-power communications systems such as IoT
- Backscatter Tx does not generate RF signals, instead it modulates and reflects the signals received
- Backscatter devices can operate actively when harvest sufficient energy

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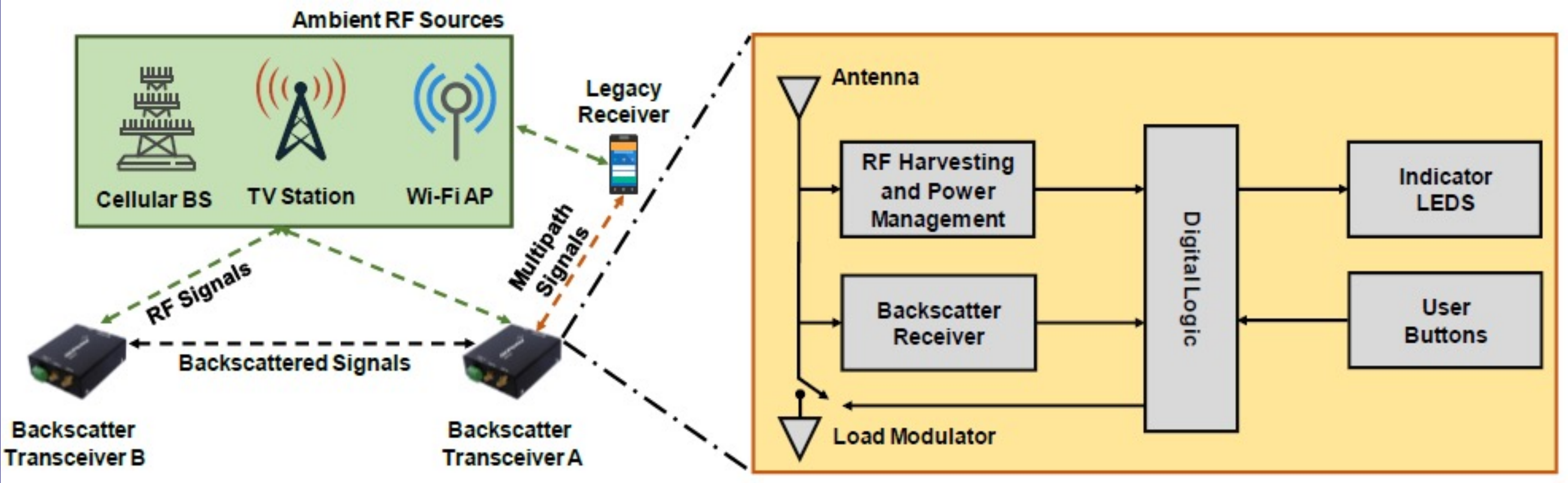
AMBIENT BACKSCATTER COMMUNICATIONS SYSTEMS ARCHITECTURE



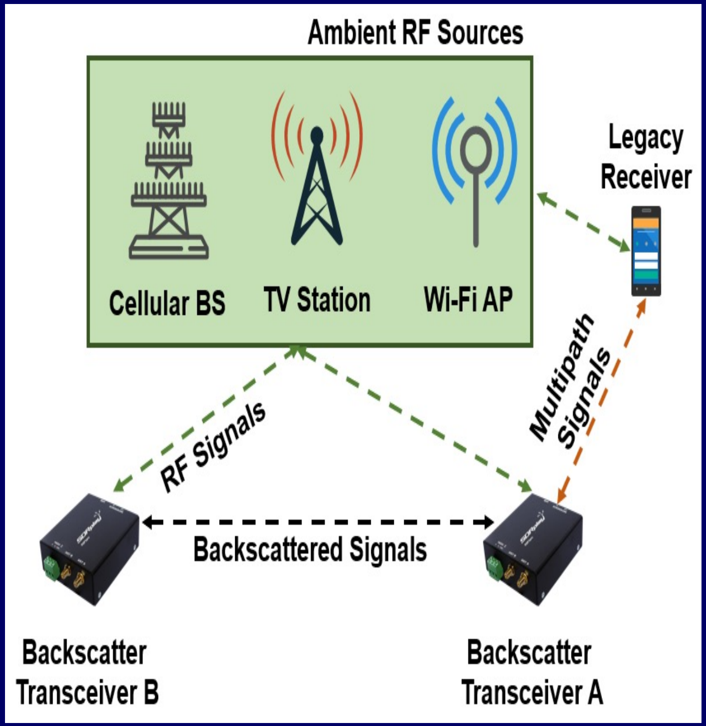
- Three major components in Ambient Backscatter Communications Systems (ABC)
  - RF sources (e.g., TV towers, Wi-Fi APs, etc.)
  - Ambient Backscatter Tx
  - Ambient Backscatter Rx

  co-located and become a transceiver

AMBIENT BACKSCATTER COMMUNICATIONS OPERATION PRINCIPLE

- **Before data transmission, backscatter transceiver *A* absorbs ambient RF signals using an energy harvester**

- **The input of the backscatter transceiver A is a stream of bits 1 and 0**
  - When the input bit is 0, the transistor is off → backscatter transceiver *A* is in non-reflecting/absorbing state
  - When the input bit is 1, the transistor is on → backscatter transceiver *A* is in reflecting state
    - Backscatter transceiver A is able to transfer bits to backscatter transceiver B



APPLICATIONS OF ABC IN 6G

- **Next Generation IoT**
  - Long-lasting sensors without additional power source
    - Toxic gas detection
    - Movement monitoring
    - RFID in logistics
- **Biomedical Applications**
  - Battery-free wearable devices
    - Heart rate monitors
    - Sleep monitors

AMBIENT BACKSCATTER COMMUNICATIONS
OPEN PROBLEMS

- **Scheduling algorithms for ABC transceivers**
  - Maximization of ambient signals' usability
  - Minimization of interference from heterogeneous ambient signals
- **Standards and network protocols**
  - On packet format, network stack, and MAC protocol, etc.
- **Security and jamming issues**
  - Simple coding and modulation schemes make ABCS vulnerable to attacks
  - Need to design simple but effective solutions to enable secure transmission

CAN WE USE RIS FOR ABC?

C. LIASKOS, A. TSIOLIARIDOU, S. IOANNIDIS, A. PITSILLIDES, I.F. AKYILDIZ,
"REALIZING AMBIENT BACKSCATTER COMMUNICATIONS WITH INTELLIGENT SURFACES IN 6G WIRELESS SYSTEMS"
IEEE WIRELESS COMMUNICATIONS MAGAZINE, 2021.

Key Idea

Use the deterministic control over EM wave propagation offered by RIS to stabilize the power levels and carrier quality for ABC devices.

Dual Role of SURFACES

i) Optimize the communication channel of regular devices, such as WiFi access points and mobile phones,

ii) Also partially redirecting and equalizing their EM emissions towards ABC devices in a stable manner.

Minimization of jamming and interference between ABC and common devices is taken into account.

USE OF RIS FOR AMBIENT BACKSCATTER COMMUNICATIONS

C. Liaskos, A. Tsioliaridou, S. Ioannidis, A. Pitsillides, I.F. Akyildiz,
"Realizing Ambient Backscatter Communications with Intelligent Surfaces in 6G Wireless Systems"
IEEE Wireless Communications Magazine, 2021.

ABC device does not create RF signals.

ABC communication is based on modulated reflection of RF waves arriving to the ABC device from external sources

ABC device power supply is the external RF signal itself, which the device simultaneously receives, harvests and modifies for re-transmission (top right)

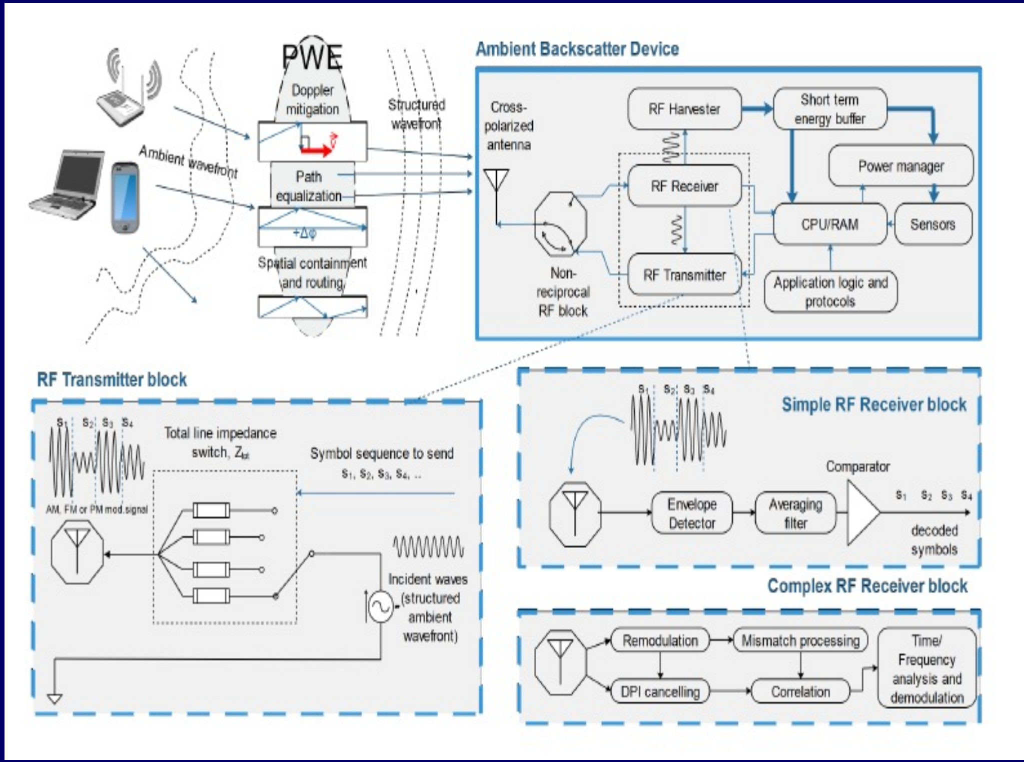
RF signal reception block approaches for ABC generally follow two trends (bottom right).

Simple RF receiver block constitutes of an envelope detector for signal demodulation.

ABC RF transmismitter block logic (bottom left)

ABC is equipped with a multistate impedance switch that causes changes to the RF signal passing through it, commonly in amplitude or phase.

These changes map to the series of data symbols that the ABC device needs to communicate.



CAN WE USE SURFACES IN UNDERWATER COMMUNICATION?

Z. SUN, H. GUO, P. WANG AND I.F. AKYILDIZ

"ACOUSTIC INTELLIGENT SURFACE SYSTEM FOR RELIABLE AND EFFICIENT UNDERWATER COMMUNICATIONS",

ACM WUWNET CONF., 2022

- **Key problems of existing acoustic underwater communications:**
  - Low bandwidth → low data rate
  - Multipath fading in shallow water → low reliability

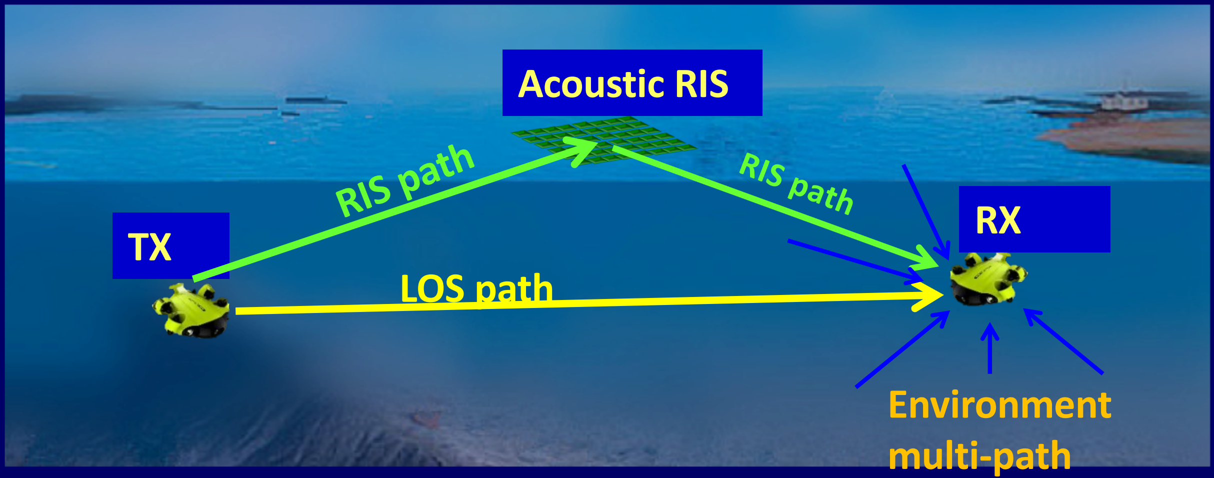
- **A Natural Idea:** **Use Ultra-Massive MIMO and Beamforming to explore spatial diversity!**
  - Achieve MIMO capacity → higher data rate
  - Mitigate multipath fading → more reliable link

PROBLEMS TO REALIZE UNDERWATER MIMO

- **Requirements of UW acoustic MIMO:**
  - **Number of MIMO elements: the larger, the better (ultra-massive MIMO).**
  - **Size of each elements: at least half-wavelength interval between each transducer.**
  - **Cost of each elements: non-trivial cost of an acoustic transducer**
  - **Power consumption of each elements: acoustic transducer needs more power.**

- **Not all UW devices can carry and operate such *large, costly,* and *power-hungry* acoustic MIMO (e.g., wireless sensors and small AUVs).**

OUR SOLUTION: UNDERWATER ACOUSTIC INTELLIGENT SURFACE



- **Advantages:**
  - TX and RX nodes do not need MIMO equipment.
  - Create large number of controlled reflection-paths:
    - To enhance the LOS path.
    - To mitigate the multipath fading.

OUR CONTRIBUTIONS

- EM wave-based intelligent surface has been widely investigated, but the acoustic RIS has not.
- How to realize the acoustic RIS? Hardware Design
  - Acoustic reflector has completely different mechanism from EM reflectors.
  - We designed and rigorously modeled the reconfigurable acoustic reflector array to realize the acoustic IS.
- Where to deploy the acoustic RIS? Deployment Strategy
  - We developed the deployment strategy to find the optimal position for the acoustic RIS in the 3D UW space
- How to operate the acoustic RIS? Control Algorithms and Protocols
  - We proposed the light-weight operation framework to utilize the spatial diversity enabled by acoustic RIS.

OPEN RESEARCH ISSUES

- **Acoustic RIS Hardware**
  - How to increase the number of reflectors in an acoustic RIS?
  - How to reduce the size, cost, and power consumption of the acoustic RIS?
- **Multiple Acoustic RISs**
  - How much additional gain if more acoustic RISs are introduced?
  - Deployment strategy? How to operate the multi-RIS system?
- **Mobile Acoustic RIS**
  - Deployed acoustic RIS may not be strictly stationary in ocean environments.
  - Acoustic RIS may also carried by mobile UW vehicles.
  - How to utilize and control the mobile acoustic RIS?