TeraHertz Band Communication:
An Old Problem Revisited for 6G Wireless Systems

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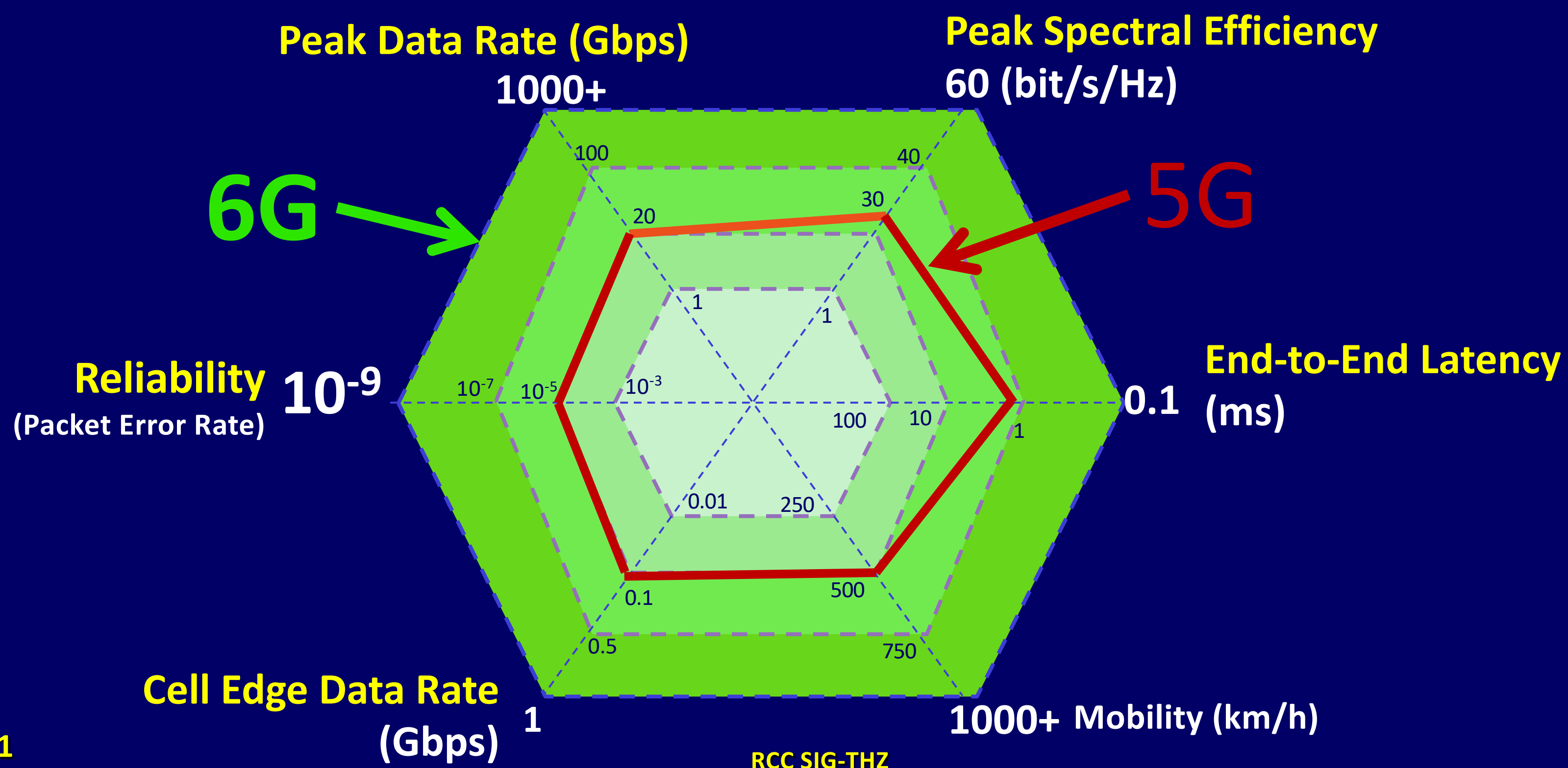
EVOLUTION FROM 5G TO 6G

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

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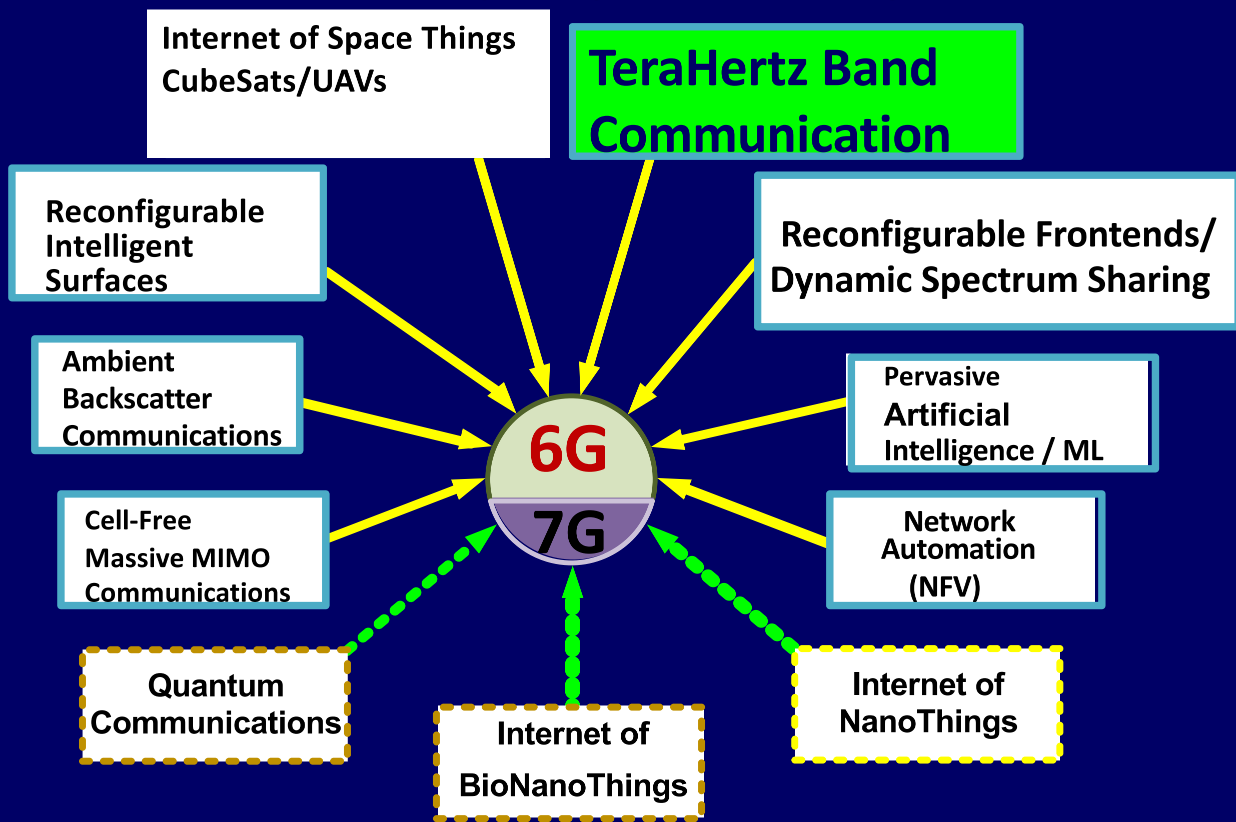
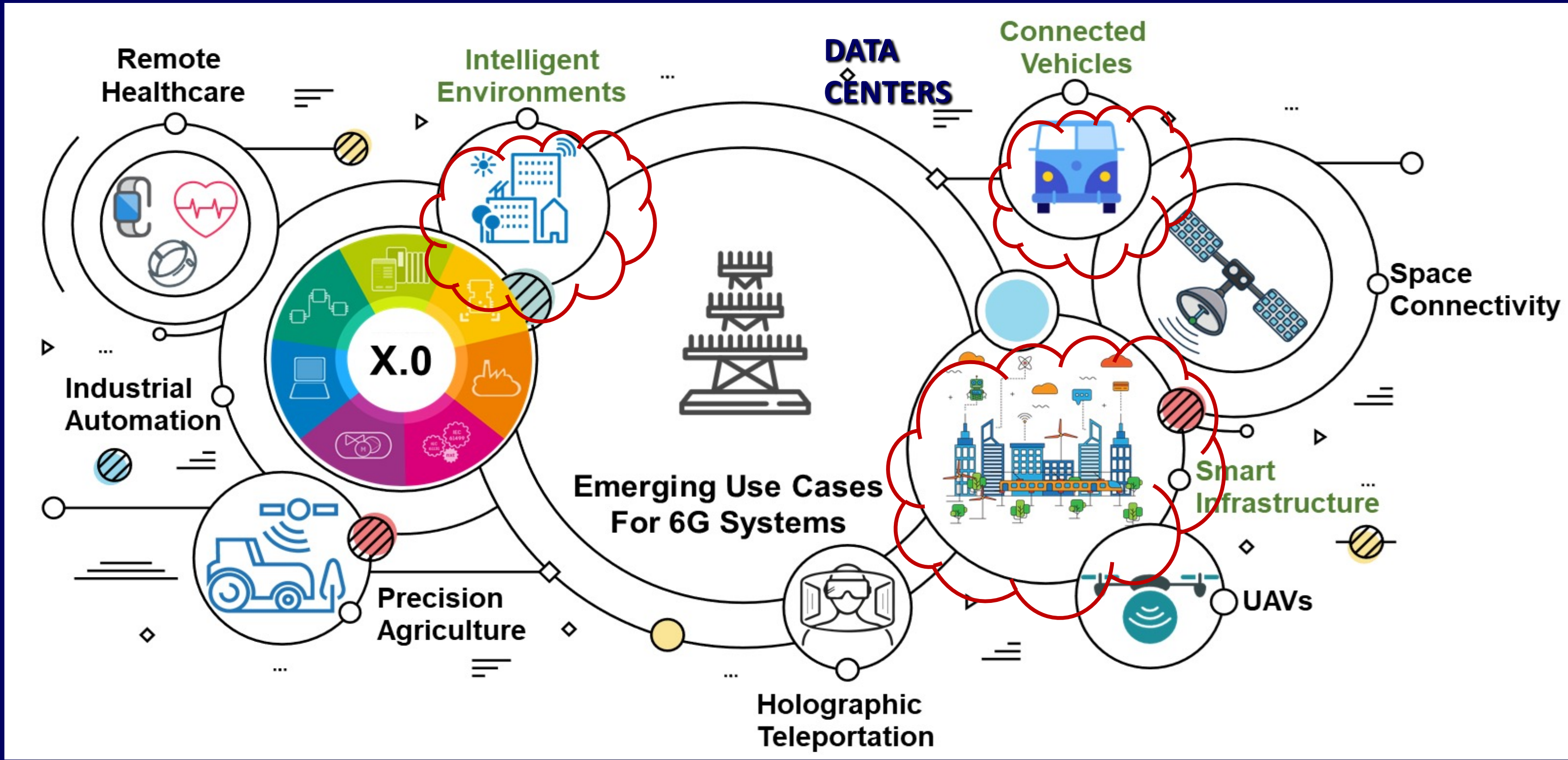


MAJOR USE CASES FOR 6G SYSTEMS



WHY TERAHERTZ?

I.F. AKYILDIZ, ET.AL.,
"TERANETS: ULTRA-BROADBAND COMMUNICATION NETWORKS IN THE TERAHERTZ BAND,"
IEEE WIRELESS COMMUNICATIONS MAGAZINE, VOL. 21, NO. 4, PP. 130-135, AUGUST 2014.

- **6G REQUIREMENTS** (Min End to End Latency; Very High Reliability; Very High Data Rates)
- **Exponential growth of wireless data traffic:**
  - More Devices → Multi-billion fixed-mobile-connected devices by 2025
  - Faster Connections → Wireless data rates have doubled every 18 months over the last three decades
  - Wireless Terabit-per-second (Tbps) links will become a reality within the next 5 years → HOW??? → Explore high frequencies !!

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BASIC REFERENCES TERAHERTZ BAND

I. F. Akyildiz, J. M. Jornet and C. Han,
"TeraNets: Ultra-broadband Communication Networks in the THz Band,”
IEEE Wireless Communications Magazine, August 2014.

I. F. Akyildiz, J. M. Jornet and C. Han,
”THz Band: Next Frontier for Wireless Communications,"
Longer version in
Physical Communication (Elsevier) Journal, September 2014.

TERANETS (FORMERLY GRANET; 2008-2013):

"GRAPHENE BASED NANO SCALE COMMUNICATION NETWORKS IN THZ BAND"

NSF; US ARMY; FIDIPRO; CATALUNA; HUMBOLDT; KACST, ETC..

2008-2013; 2013-2016 & 2016-2020 ; 2018-2022

- **Objectives:**
  - To demonstrate the feasibility of graphene-enabled EM communication
  - To establish the theoretical foundations for EM nanonetwork
  - To establish the theoretical and experimental foundations of ultra-broadband com nets in the (0.1-10) THz band

NANO Materials & Devices
- Nano-Transceivers✓
- Nano-Antennas and Arrays ✓
- Fabrication
- Experimental Measurement

THz Channel
- Line-of-Sight ✓
- Multi-path ✓
- 3D End-to-End ✓
- Ultra-massive MIMO
- Noise Modeling ✓
- Capacity Analysis ✓
- Experimental Measurement

THz Communications
- Pulse-based Modulation ✓
- Multi-band Modulation ✓
- Equalization
- Synchronization ✓
- Ultra-Massive MIMO ✓

Nano Networks
- Error Control ✓
- Medium Access Control ✓
- Addressing
- Neighbor Discovery
- Relaying
- Routing
- Transport Layer
- Cross-layer

Experimental and Simulation Testbeds

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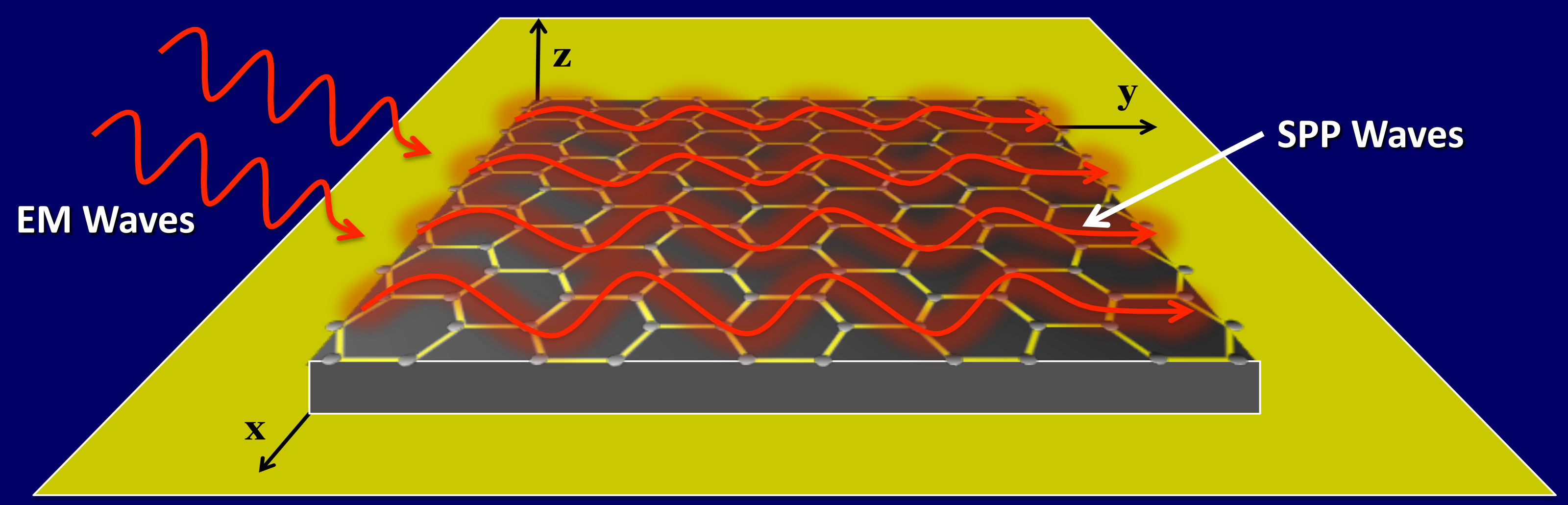
Experimental and Simulation Testbeds

GRAPHENE-BASED PLASMONIC NANO-ANTENNAS

I. F. Akyildiz and J. M. Jornet,
"Graphene-based Plasmonic Nano-antennas for Terahertz Band Communication in Nanonetworks,"
IEEE Journal of Selected Areas in Communications, Vol. 12, pp. 685-694, Dec. 2013.
Prelim. version in Proc. of 4th European Conference on Antennas and Propagation, 2010

U.S. Patent No. 9,643,841, issued on May 9, 2017.

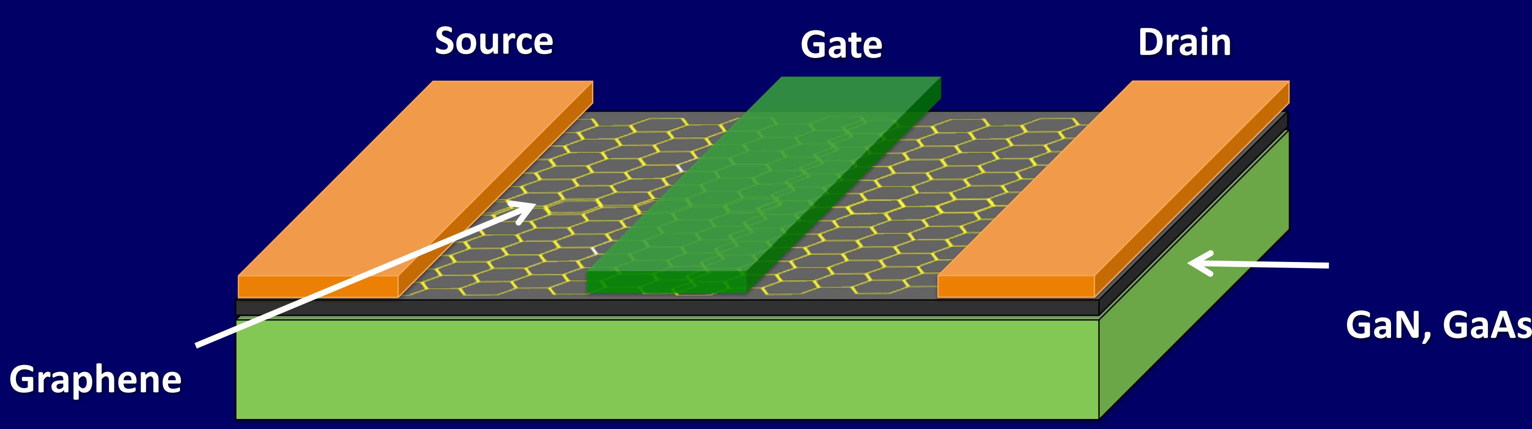
- Graphene supports the propagation (efficient radiation) of Surface Plasmon Polariton (SPP) waves at frequencies in THz (0.1-10 THz):
  - Global oscillations of electric charge at the interface between graphene and a dielectric material



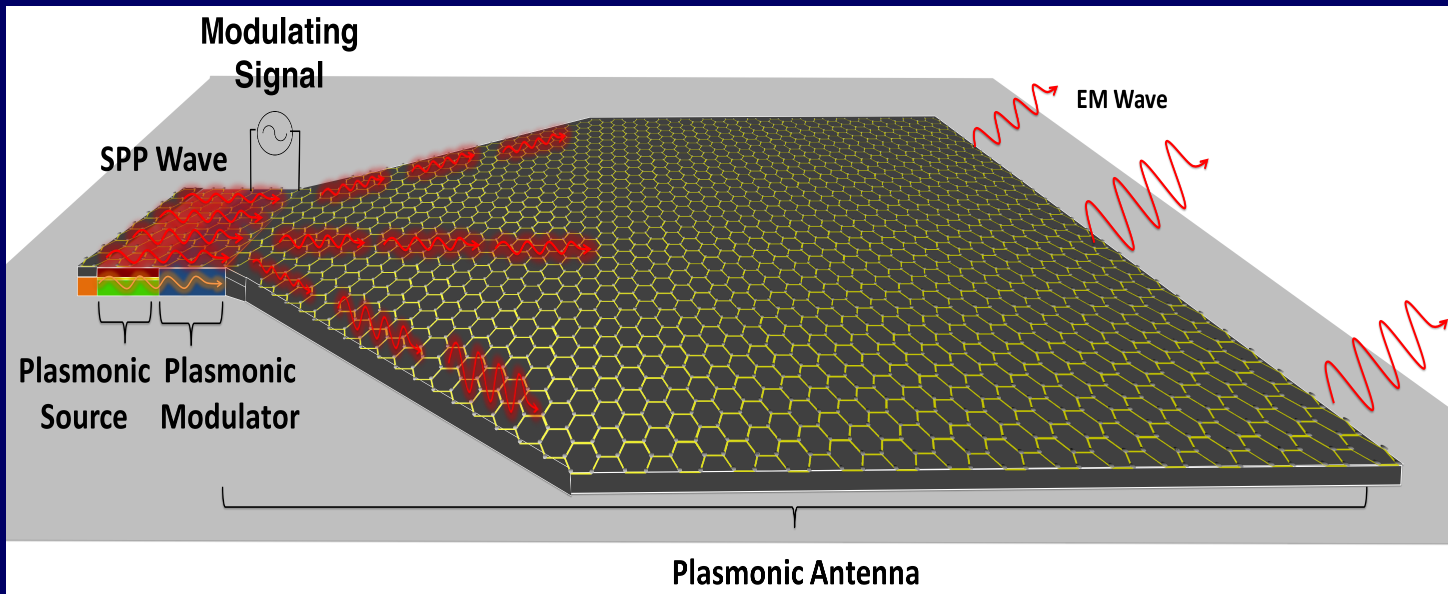
TERAHERTZ BAND PLASMONIC NANO-TRANSCEIVER

I. F. Akyildiz and J. M. Jornet,
"Graphene-based Plasmonic Nano-transceiver for Wireless Communication in the THz Band,"
PROC. EUR. CONF. ANTENNA PROP. (EUCAP), APRIL 2014.
U.S. PATENT NO. 9,397,758 ISSUED ON JULY 19, 2016.

- Generates/detects the signals radiated/received by the nano-antenna
- Built with Graphene (NOVELTY), GaN & GaAs
- Based on a High Electron Mobility Transistor (HEMT)



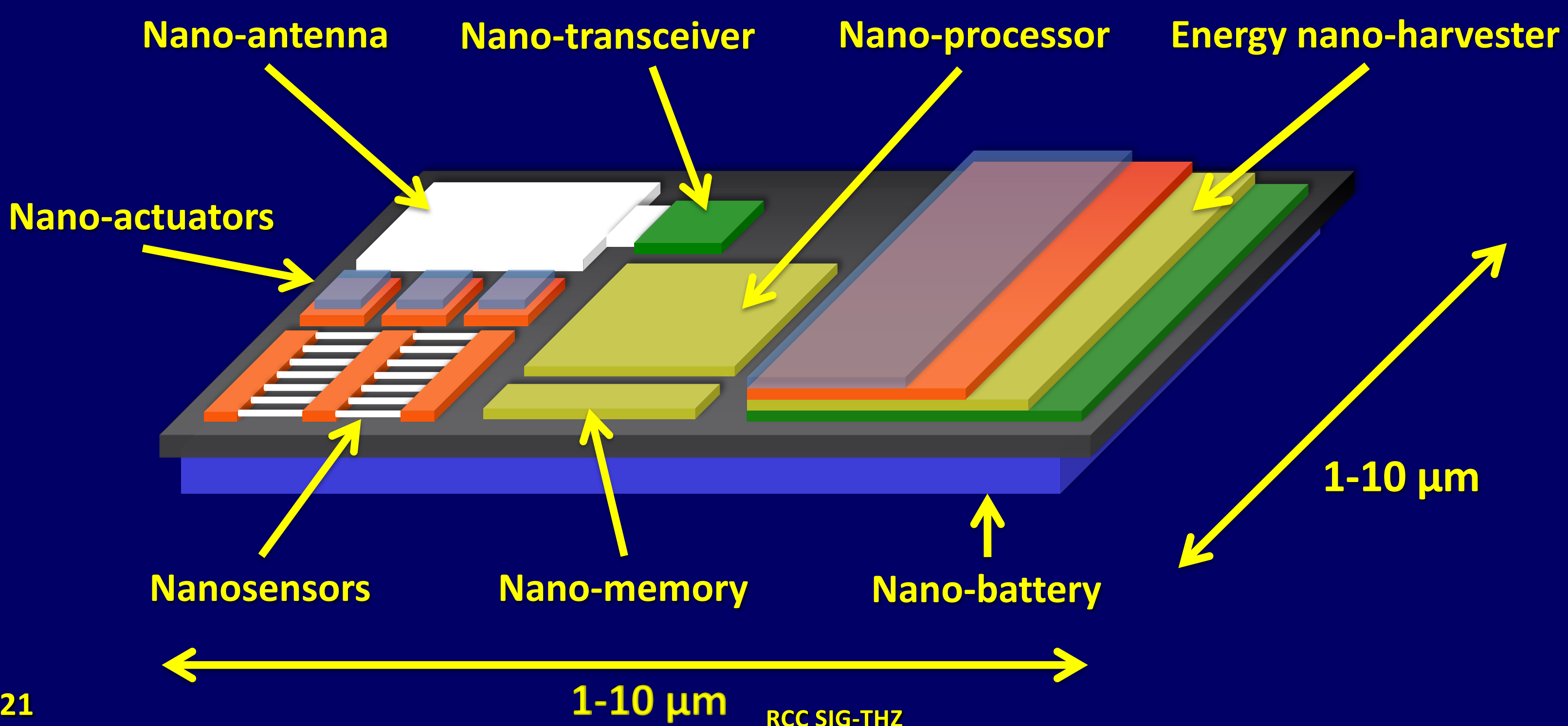
TERAHERTZ BAND PLASMONIC FRONT-END (TRANSCEIVER+ANTENNA)



DESIGN OF NANO-THINGS

I. F. Akyildiz and J. M. Jornet, "Electromagnetic Wireless Nanosensor Networks," Nano Communication Networks (Elsevier) Journal, March 2010.

I.F. Akyildiz and J.M. Jornet, "Internet of Nano-Things", IEEE Wireless Communications Magazine, Dec. 2010.



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SCIENTIFIC AMERICA:
TOP 10 EMERGING TECHNOLOGIES OF 2016

- Internet of Things goes NANO

https://www.scientificamerican.com/report/the-top-10-emerging-technologies-of-2016/

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IoNT MARKET (MAY 26, 2020)

Latest Innovative Report on Internet of Nanothings (IoNT) Market Breaking The Ground Worldwide:

Cisco Systems, IBM, Intel, Qualcomm, Accenture, Apple, ARM, Atmel, Atos, Bosch, Broadcom, CTS, Dell, Echelon, GE, Gemalto , Google, Hitachi, HP

https://coleofduty.com/military-news/2020/05/26/latest-innovative-report-on-internet-of-nanothings-iont-market-breaking-the-ground-worldwide-cisco-systems-ibm-intel-qualcomm-accenture-apple-arm-atmel-atos-bosch-broadcom-cts-dell-ech/

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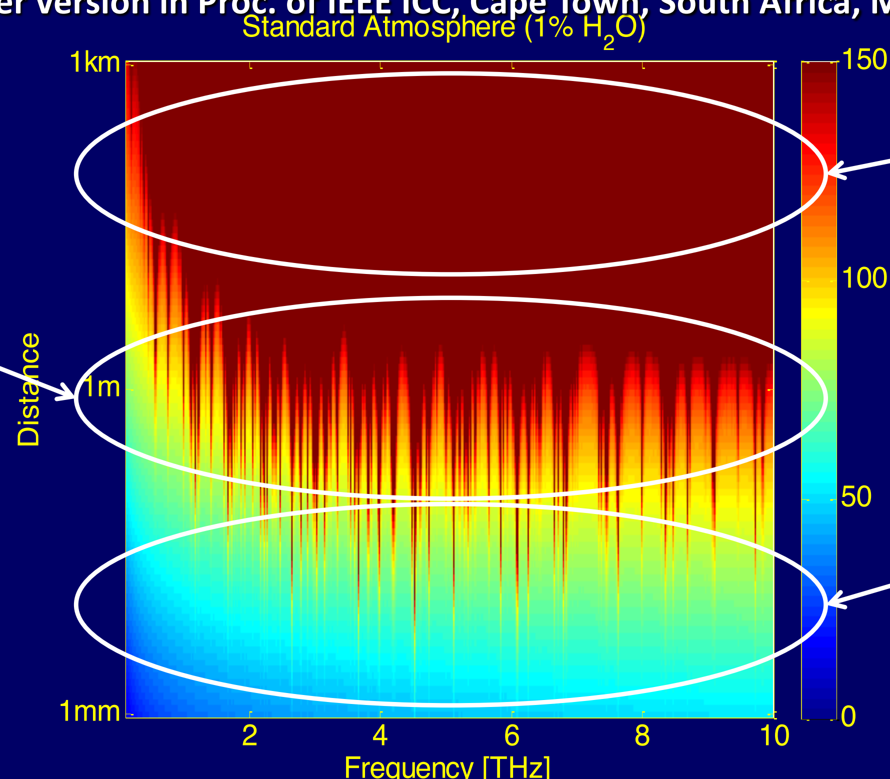
Experimental and Simulation Testbeds

TERAHERTZ CHANNEL

J.M. Jornet and I.F. Akyildiz,
"Channel Modeling and Capacity Analysis of EM Wireless Nanonetworks in the THz Band",
IEEE Transactions on Wireless Communications, Oct. 2011.
Shorter version in Proc. of IEEE ICC, Cape Town, South Africa, May 2010.

For the middle range, there are several windows TENS OF GIGAHERTZS WIDE.
Can we exploit this?



We can certainly not go further

Almost absence of molecules in short distances does simplify everything in the short range

RCC SIG-THZ

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Experimental and Simulation Testbeds

NEW MODULATION TECHNIQUE

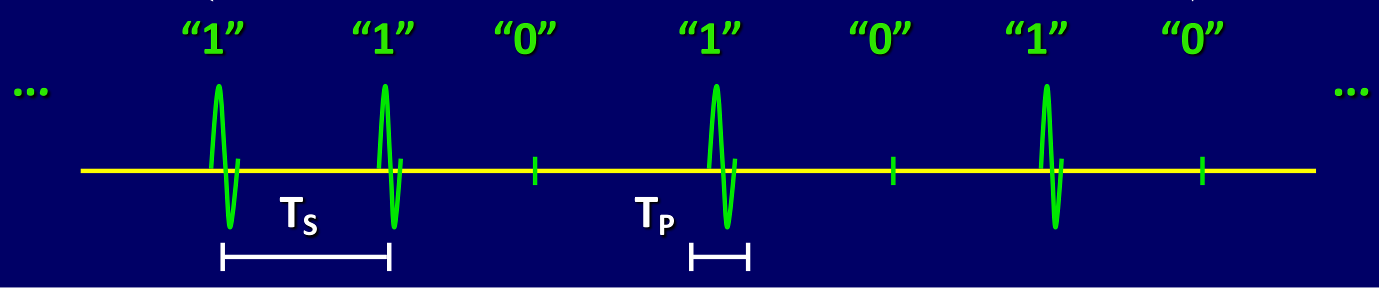
J.M. Jornet and I.F. Akyildiz,
"Information Capacity of Pulse-based Wireless Nanosensor Networks",
Proc. of the 8th Annual IEEE SECON, Salt Lake City, Utah, June 2011.

- A new modulation scheme based on femtosecond-long pulses spread in time:

  TS-OOK (Time Spread On/Off Keying Mechanism)

A logical "1" is encoded with a pulse:
* Pulse length: T_p= 100 fs
* Pulse energy: < 1 pJ !!!

A logical "0" is encoded with silence:
* Ideally no energy is consumed!!!
* After an initialization preamble, silence is interpreted as 0s



Pulses are spread in time to simplify the transceiver architecture...

GRAND CHALLENGE

- DISTANCE PROBLEM !!!
- MORE SEVERE IN "OUTDOOR & MOBILE THZ SYSTEMS"

CHALLENGES IN THZ BAND COMMUNICATIONS IN OUTDOOR SCENARIOS & MOBILE SYSTEMS

Longer Transmission Distances

(High Attenuation)

Shadowing effects caused by dense obstructions such as buildings

Higher signal energy dispersion caused by frequency-selective fading

Higher mobility of tx and scatterers in environments which lead to larger Doppler shift

Scintillation effect (atmospheric turbulence) due temperature & humidity of environment

COMBATING DISTANCE PROBLEM IN THZ BAND COMMUNICATIONS

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

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

TRUVA, INC.

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

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

COMBATING DISTANCE PROBLEM: MULTIPATH EFFECTS

C. Han, A.O. Bicen and I.F. Akyildiz,
"Multi-Ray Channel Modeling and Wideband Characterization for Wireless Comms in the THz Band,"
IEEE Transactions on Wireless Communications, vol. 14, no. 5, pp. 2402-2412, May 2015.

- Analytical multipath channel model based on ray tracing techniques
  - As a superposition of LOS (a), reflected (b), scattered (c) and diffracted (d) paths
- **Multipath propagation → achieving less path loss**
- Distances (<10m)
  - Multipath helps
  - THz Band channel behaves as a single transmission window almost 10THz wide
- Distances (>10m)
  - Reflected and scattered paths are important
  - Impact of scattering increases with higher roughness level
  - Molecular absorption limits the THz Band channel to a set of multi-GHz-wide subwindows

COMBATING DISTANCE PROBLEM: DISTANCE ADAPTIVE MODULATION

C. Han, O. Bicen, and I.F. Akyildiz,
"Multi-Wideband Waveform Design for Distance-adaptive Wireless Comms in the THz Band,"
IEEE Transactions on Signal Processing, vol. 64, no.4, pp. 910-922, February 2016.

- Develop a distance-aware bandwidth-adaptive resource allocation scheme
  - Dynamically control the BW utilization, the spectrum allocation, the modulation technique, and the transmit power on each sub-window
- Propose a strategic spectrum allocation for multi-users
  - Center spectrum of the spectral windows to the long-distance users first
  - Side spectrum of the spectral windows to the short-distance users
- Developed resource allocation scheme and strategic spectrum allocation principle are numerically evaluated with the aims to
  - Improve the communication distance
  - Enable multiple ultra-high-speed links in the THz band networks

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COMBATING DISTANCE PROBLEM: ULTRA-MASSIVE MIMO

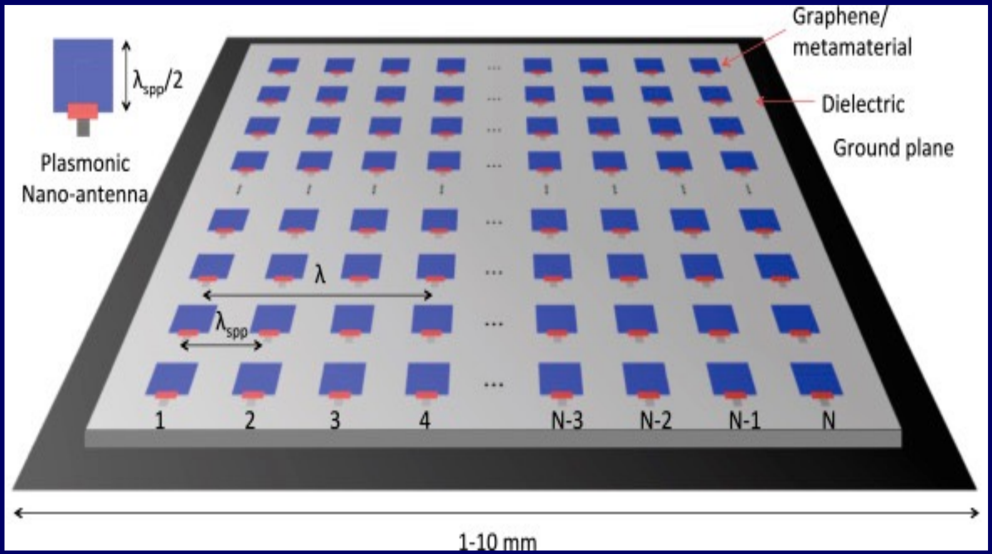
I. F. Akyildiz and J. M. Jornet

"Realizing Ultra-Massive MIMO Communication in the (0.06–10) TeraHertz Band"

Nano Communication Networks, (Elsevier) Journal, Vol. 8, pp. 46-54, March 2016;

U.S. Patent 15/211,503 awarded on Sept. 7, 2017.

Planar Array with 32x32 antenna elements in total of 1024 elements

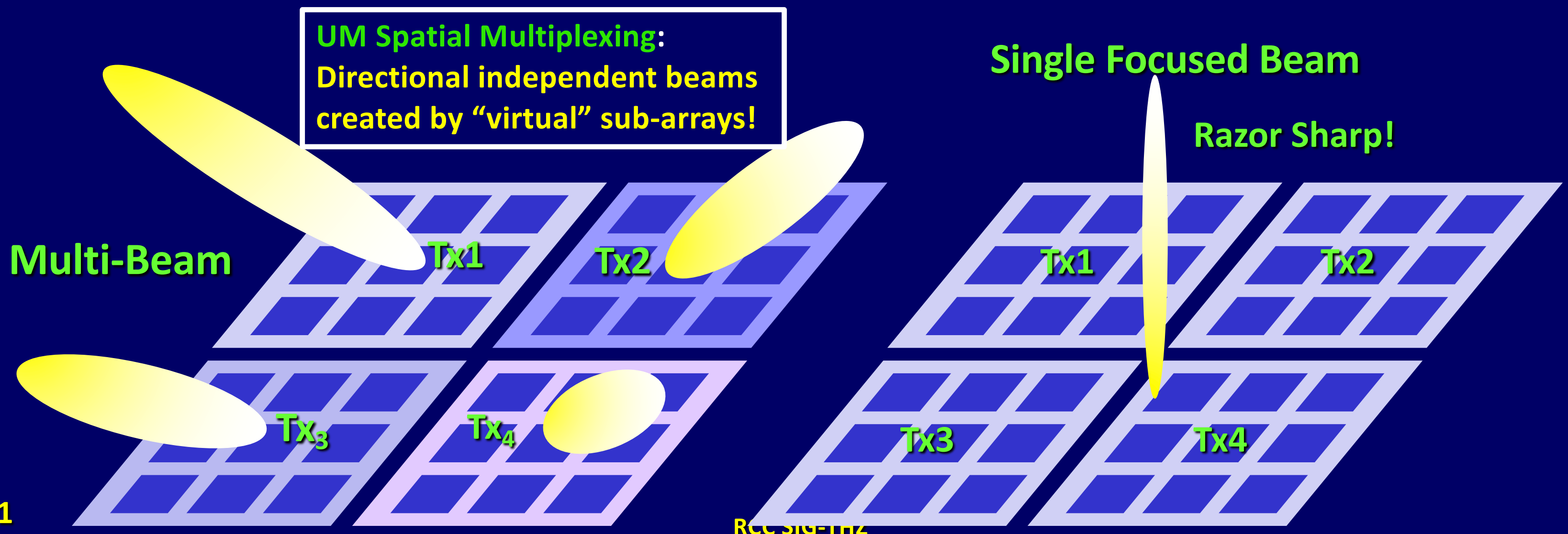


UM-MIMO can achieve at least 10-fold increase in transmission distance at 300 GHz and 1 THz compared to M-MIMO

DYNAMIC ULTRA MASSIVE MIMO FOR INTELLIGENT BEAMFORMING

S. NIE AND I. F. AKYILDIZ,
"BEAMFORMING IN INTELLIGENT ENVIRONMENTS BASED ON UM MIMO PLATFORMS IN MM WAVE & THZ BANDS,"
IEEE ICASSP, BARCELONA, SPAIN, PP. 8683-8687, 2020

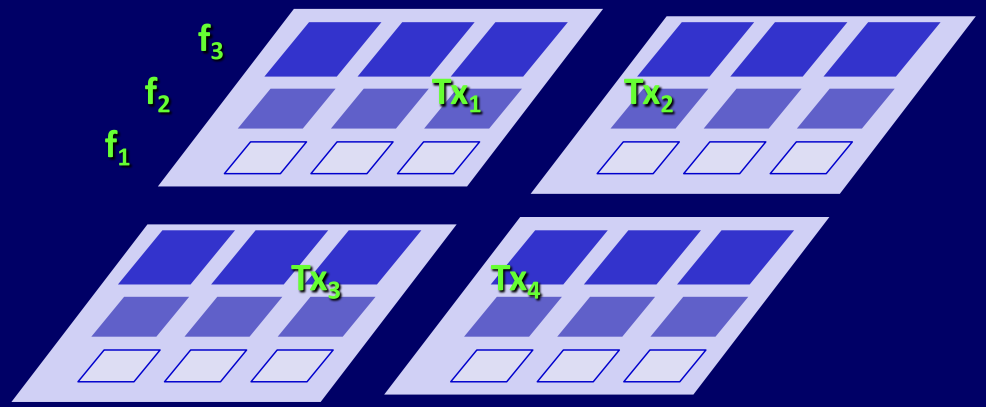
- By properly feeding antenna elements, antenna array can be dynamically switched among different modes
- Increased throughput and multi-user capacity
- Maximum communication range
- Also apply ML algorithms for intelligent beamforming



MULTI-BAND ULTRA MASSIVE MIMO

S. NIE AND I. F. AKYILDIZ,
"BEAMFORMING IN INTELLIGENT ENVIRONMENTS BASED ON UM MIMO PLATFORMS IN MM WAVE & THZ BANDS,"
IEEE ICASSP, BARCELONA, SPAIN, PP. 8683-8687, 2020

Allows simultaneous transmission over multiple transmission windows by electronically tuning the response of fixed-length plasmonic antennas



CHALLENGES FOR UM MIMO

S. NIE AND I. F. AKYILDIZ,
"CODEBOOK DESIGN FOR DUAL-POLARIZED UM MIMO COMMUNICATIONS AT MM WAVE AND THZ BANDS,"
IEEE ICASSP, 2021.

- How to accurately estimate channel coefficients for UM-MIMO channel?
  - Antenna spatial correlation & Estimation of thousands of parallel channels

- How to operate the UM antenna arrays to realize the different modes (Dynamic UM MIMO Mode; Multiband UM MIMO Mode)
  - Need to control voltage and delay at each array element
    - Exploit parallelization as well as array thinning techniques

- Optimal control of each antenna array element, codebook design, beamforming beam steering

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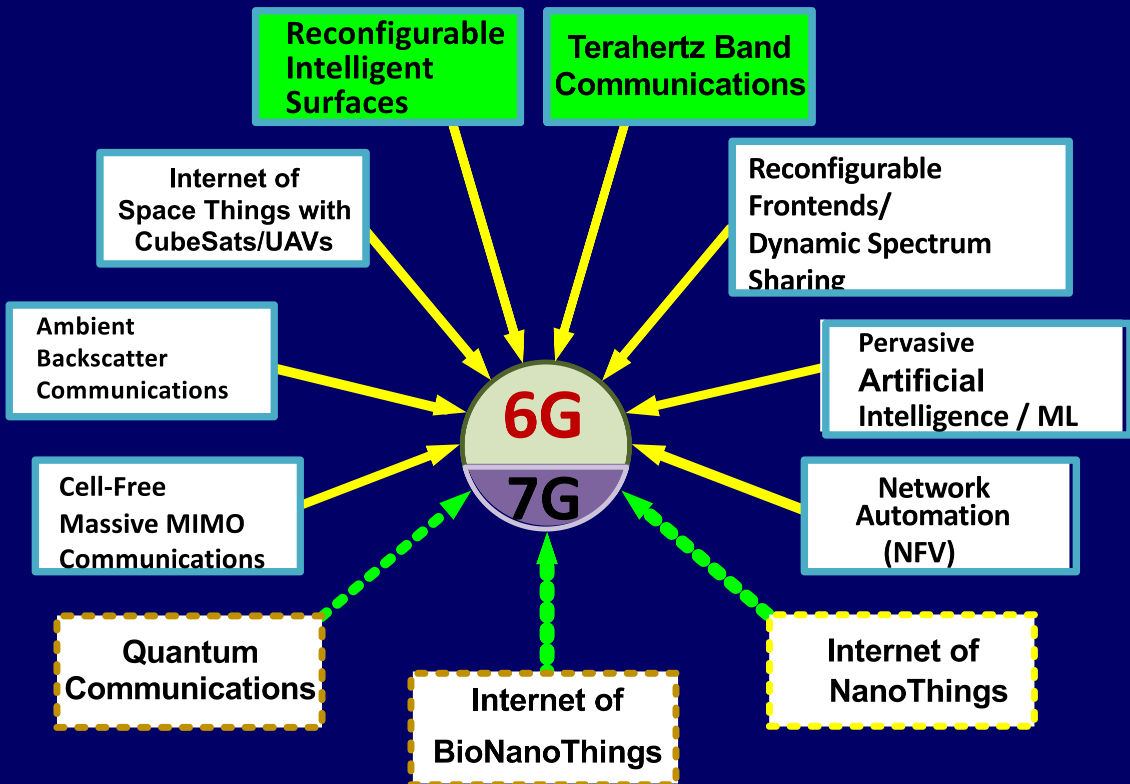


RECONFIGURABLE INTELLIGENT SURFACES
INTELLIGENT ENVIRONMENTS
BASIC REFERENCES

- 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, 4th Quarter 2015.

DIFFERENT NOMENCLATURE

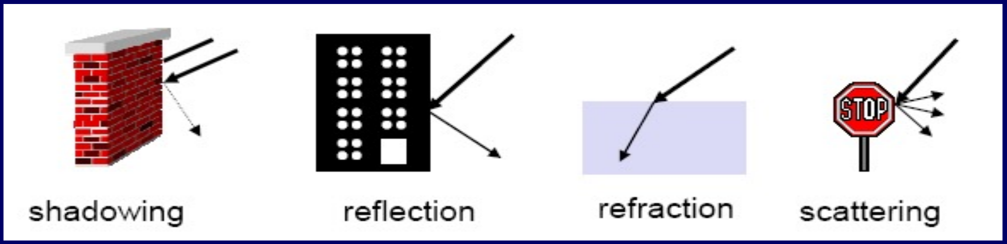
- Intelligent Communication Environments (ICE)
- Intelligent Communication Surfaces (ICF)
- Reconfigurable Intelligent Surfaces (RIS)
- Programmable Wireless Environments (PWE)
- Programmable Metasurfaces
- Hypersurfaces
- Large Intelligent Surfaces (LIS)
- Intelligent Reflecting Surfaces (IRS)
- Smart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

……..

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.)

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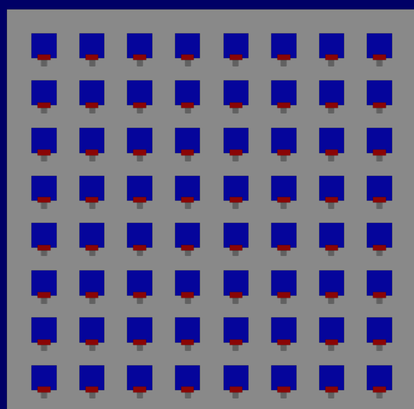
CONVENTIONAL APPROACHES

- 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 !!

POSSIBLE SIMPLE SOLUTIONS

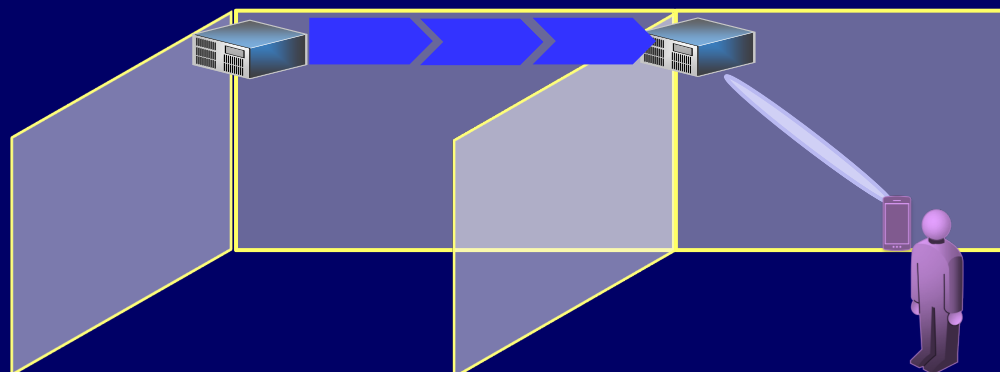
Passive Reflectarrays



Supports only:

Normal Reflection

Relays

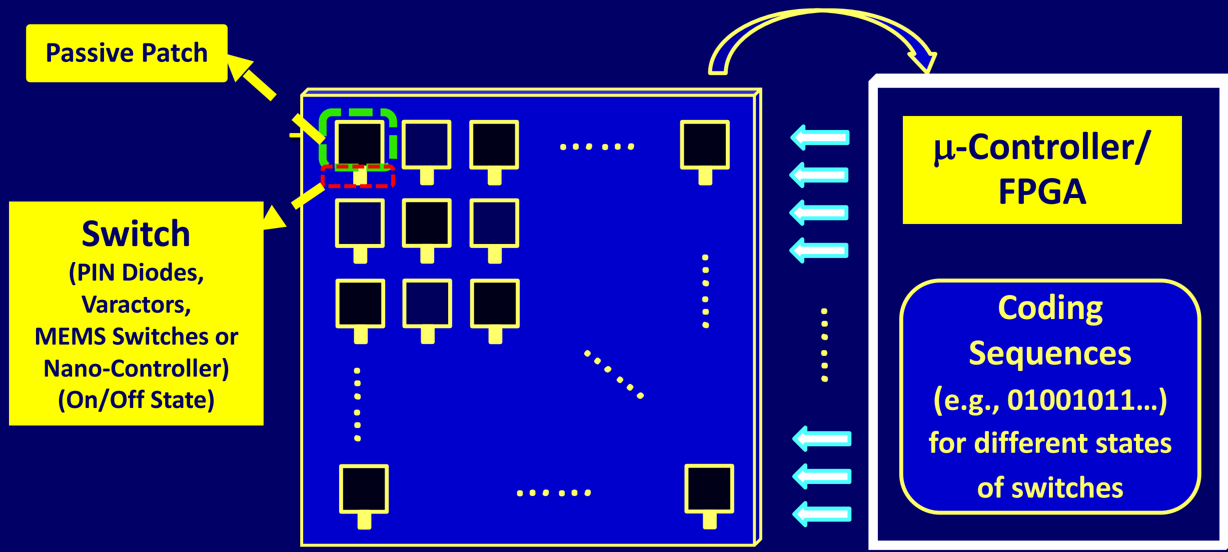


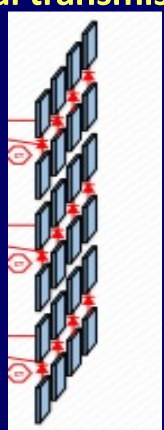
Disadvantages:

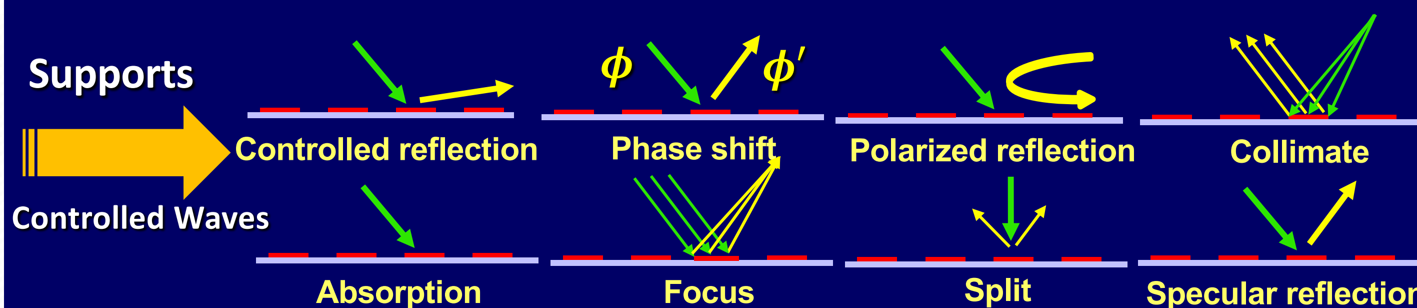
- Longer delays
- Inflexible for existing network layout

RECONFIGURABLE INTELLIGENT SURFACES (RIS)

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







USE CASES OF RISs
PROPAGATION CHANNEL ENHANCEMENT

Support multiple users and devices for high-throughput links

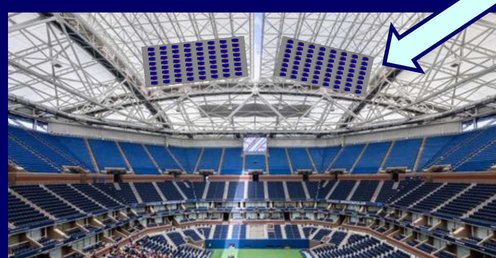
Indoor meeting rooms & offices

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

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)

TRUVA, INC.

EU-FET PROJECT VISORSURF

http://www.visorsurf.eu

Visor SURF

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

- "A Hyper<u>Visor</u> for Meta<u>Surf</u>ace Functionalities"
  - Controlling & customizing EM propagation with software!

- Start date: 1/1/2017
- Duration: 42 months
- Coordinator: FORTH Crete, Greece
- 7M Euro (2017-2021)

FORTH Foundation for Research & Technology - Hellas
Signal GeneriX Ltd Advanced Signal Solutions
University of Cyprus
UNIVERSITAT POLITÈCNICA DE CATALUNYA BARCELONATECH UPC
FhG Fraunhofer Gesellschaft
Aalto University

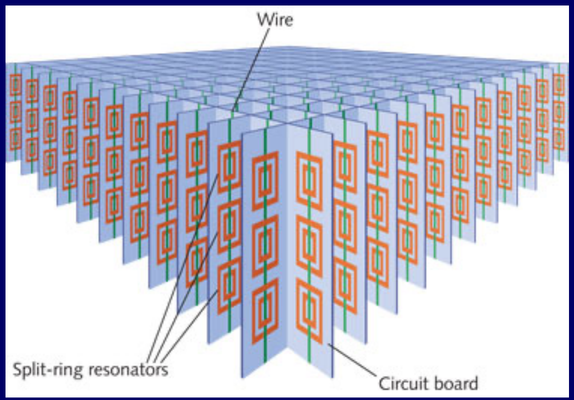
VISORSURF TEAM (FORTH CRETE; AUG. 2019)

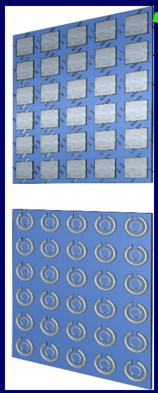
METAMATERIALS FOR LOWER FREQUENCIES
GRAPHENES FOR HIGH FREQUENCIES

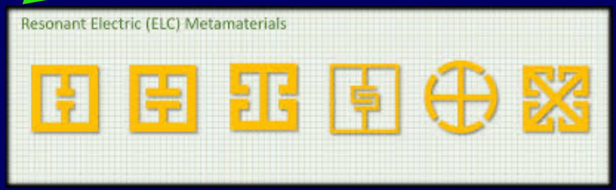
- A metamaterial ("beyond") is a material engineered to have a property that is not found in nature

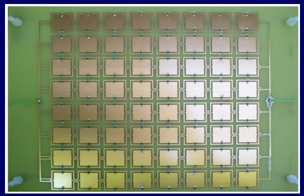
- Manipulation of EM waves: block, absorb, enhance, or bend waves, to achieve benefits that go beyond what is possible with conventional materials

- Their precise shape, geometry, size, orientation and arrangement gives them their smart properties

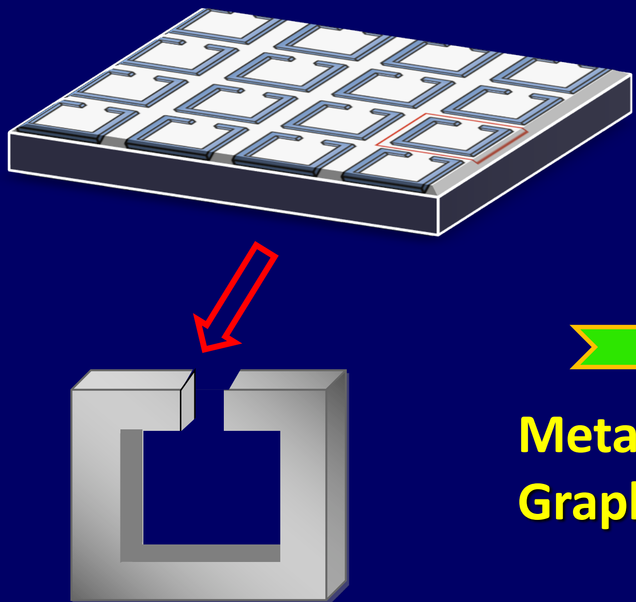




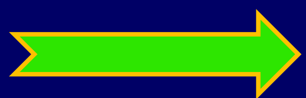




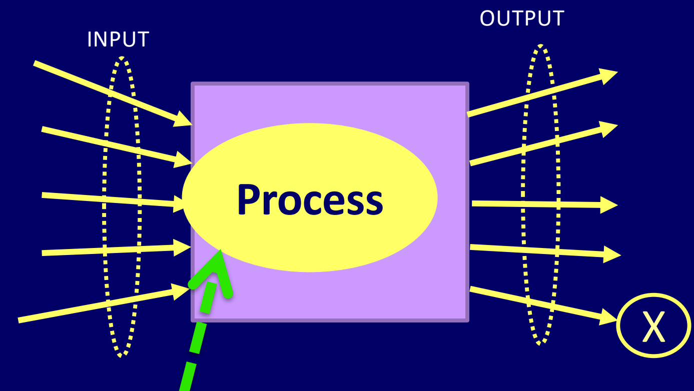
METAMATERIAL BASICS



Schematics of the Elementary Cell



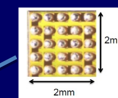
Completely re-engineer incoming EM waves

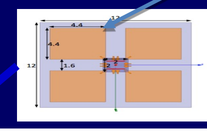


STEER, ABSORB, POLARIZE, SPLIT, FREQ_FILTER, ALTER_PHASE, FOCUS, CUSTOM EM/MAG FIELD At output(s)

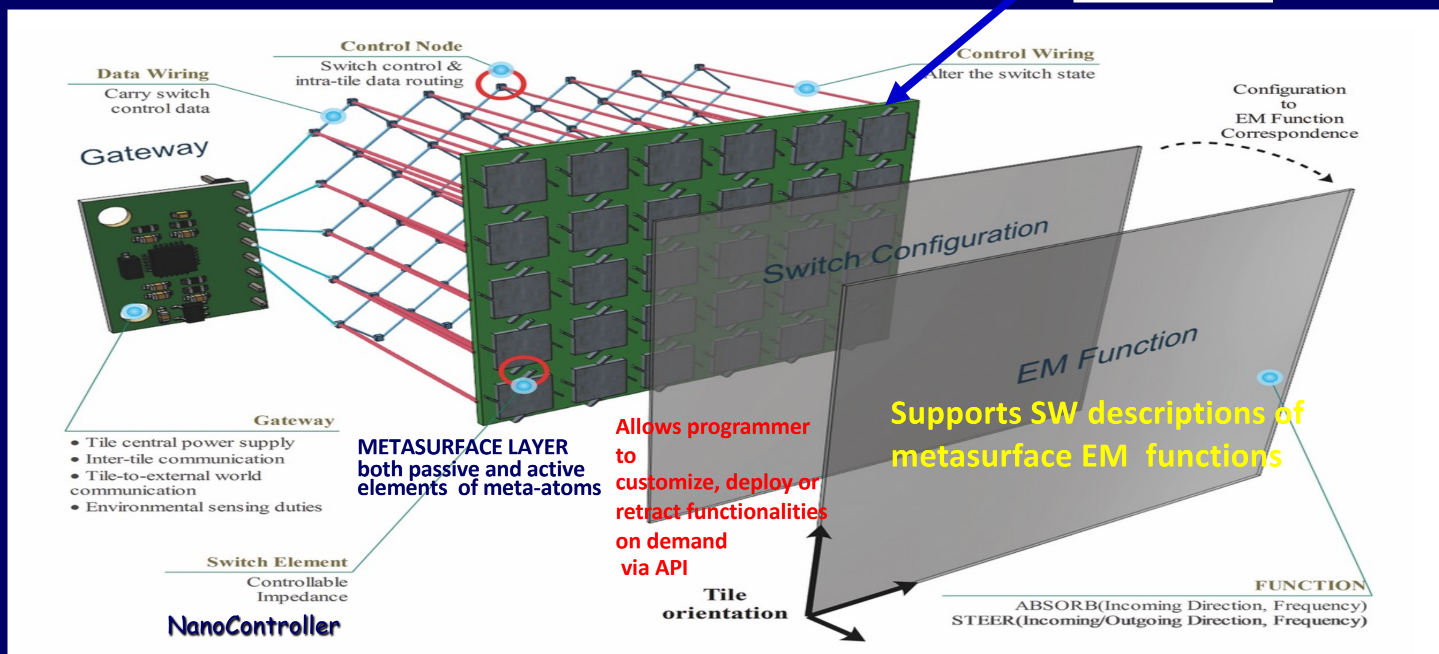
HYPERSURFACES: PROGRAMMABLE (SOFTWARE DEFINED) SURFACES

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



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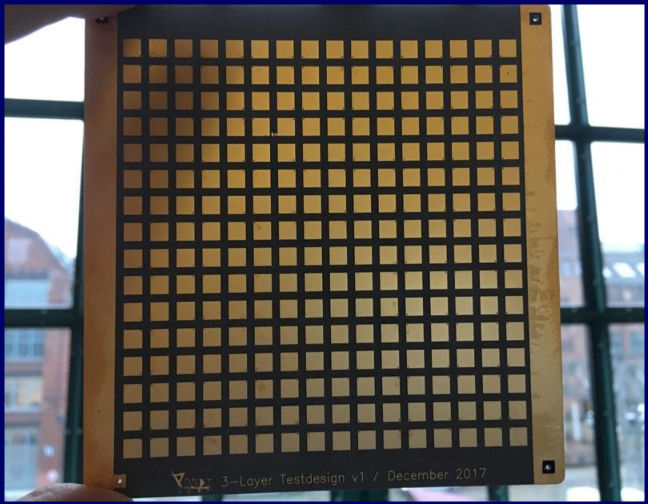
PROTOTYPING

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

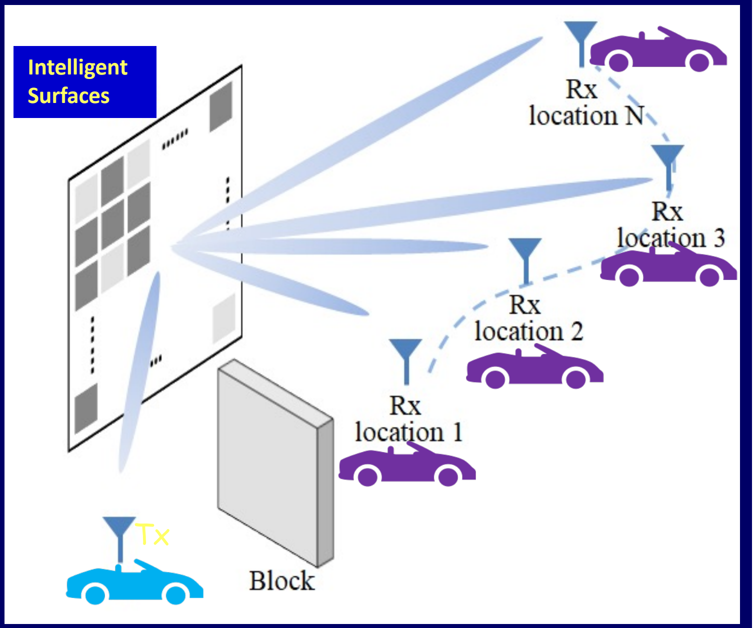
CHALLENGES: MULTI-HOP OUTDOOR THZ COMMUNICATION

US ARMY; 2018-2022.

MultiHop THz Band Network	THz MultiBand UM MIMO Communications
• 3D End to End Channel Characterization (Polarization diversity; Mobility; Realistic terrain Environments). • Transmission Distance Analysis in Various Terrains (Coverage Probability and Interference) • Cross Layer (PHY/MAC/Routing Protocol Design)	• 3D UM MIMO Channel Model for Tactical Environments • Mutual Coupling Effect Study • All-spectrum access scheme (from RF to mm-wave to THz • AI-empowered autonomous configuration of spectral, spatial, and power resources • Environment-adaptive solution for MCS (Modulation and Coding scheme) selection

OPEN RESEARCH TOPICS INDOOR/OUTDOOR THZ SYSTEMS

- How to acquire CSI in rapid time-varying THz channel?
  - Can we use spectrum sensing in time-varying channel estimation?
- How to detect, track, and localize multiple mobile users/objects in channels?
  - User mobility leads to rapid variation of THz beamspace channels
  - Conventional real-time channel estimation schemes involve unaffordable pilot overhead
- Real-time beam tracking scheme for high-speed vehicles and random trajectories



How to synchronize users transmitting at Tbps?

- THz clocks are unreliable → Phase noise, clock skew

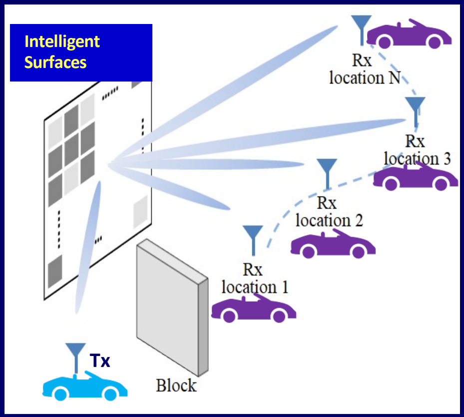
- Digital synchronization techniques cannot be utilized
  - Fastest Analog-to-Digital Converters < 100 Giga-samples-per-second
  - Need for sub-Nyquist sampling

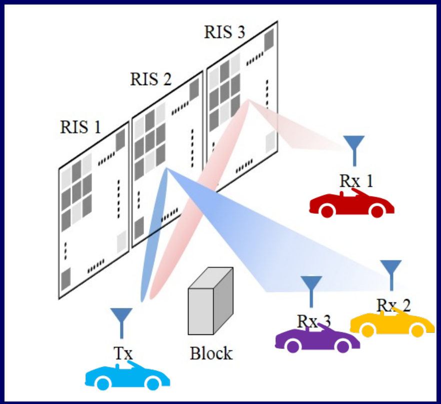
OPEN RESEARCH TOPICS IN INDOOR/OUTDOOR THZ SYSTEMS

- 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





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WHAT TYPE OF MAC PROTOCOLS SHALL BE USED?

- Deafness Problem
  - Pencil-thin beams make it difficult for users to find each other
  - Multi-beam antenna radiation patterns can be utilized
- Multi-user interference?
  - Expectedly very low

HOW TO PERFORM MULTI-HOP RELAYING AND ROUTING?

- New routing metrics:
  - Capture properties of the THz band (distance-dependent bandwidth) and PHY
  - Novel bufferless routing protocols:
    - What to do with a packet when you do not have a route for it (and no time to find it)?

- **How to ensure end-to-end reliability?**
  - Will traditional TCP congestion and flow control do with Tbps links?

ERROR CONTROL IN THZ FREQUENCY CHANNELS

- **How can we minimize transmission error in THz channel?**
  - High atmospheric attenuation → deteriorated SNR and degraded BER

- **New error control framework is needed**
  - Jointly consider ARQ, FEC, Error Prevention Codes (EPC), and hybrid EPC

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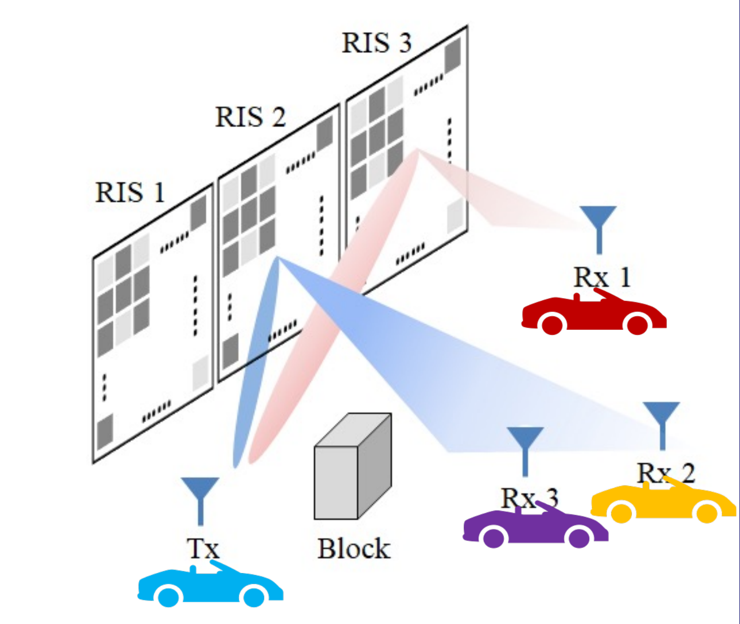
OPEN RESEARCH TOPICS FOR INDOOR/OUTDOOR THZ SYSTEMS

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

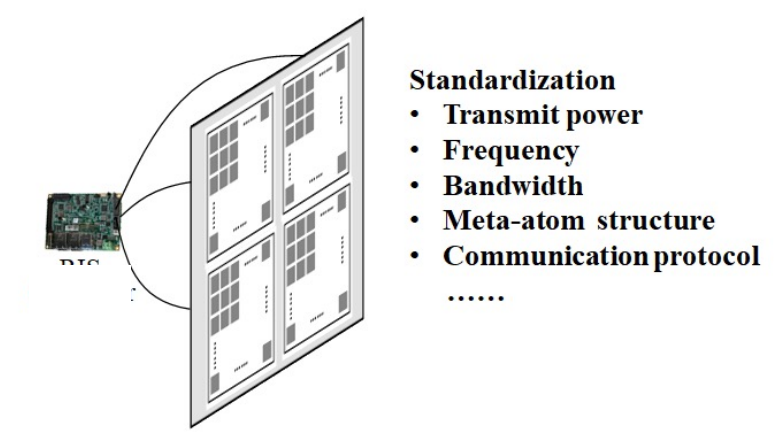
- Fair scheduling algorithms

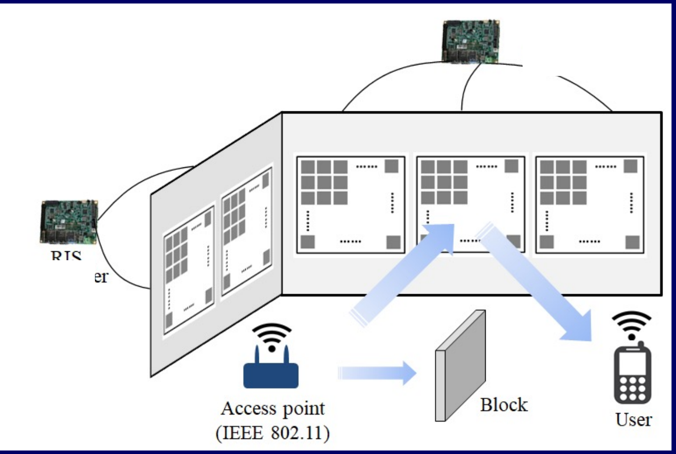


OPEN RESEARCH TOPICS FOR INDOOR/OUTDOOR THZ SYSTEMS

Standardization and Assessment

- HW structures and communication protocols
- Integration into existing wireless communication networks (5G, 6G, IEEE 802.11, IoTs)





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

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