6G AND BEYOND: THE FUTURE OF WIRELESS COMMUNICATIONS SYSTEMS

I.F. AKYILDIZ

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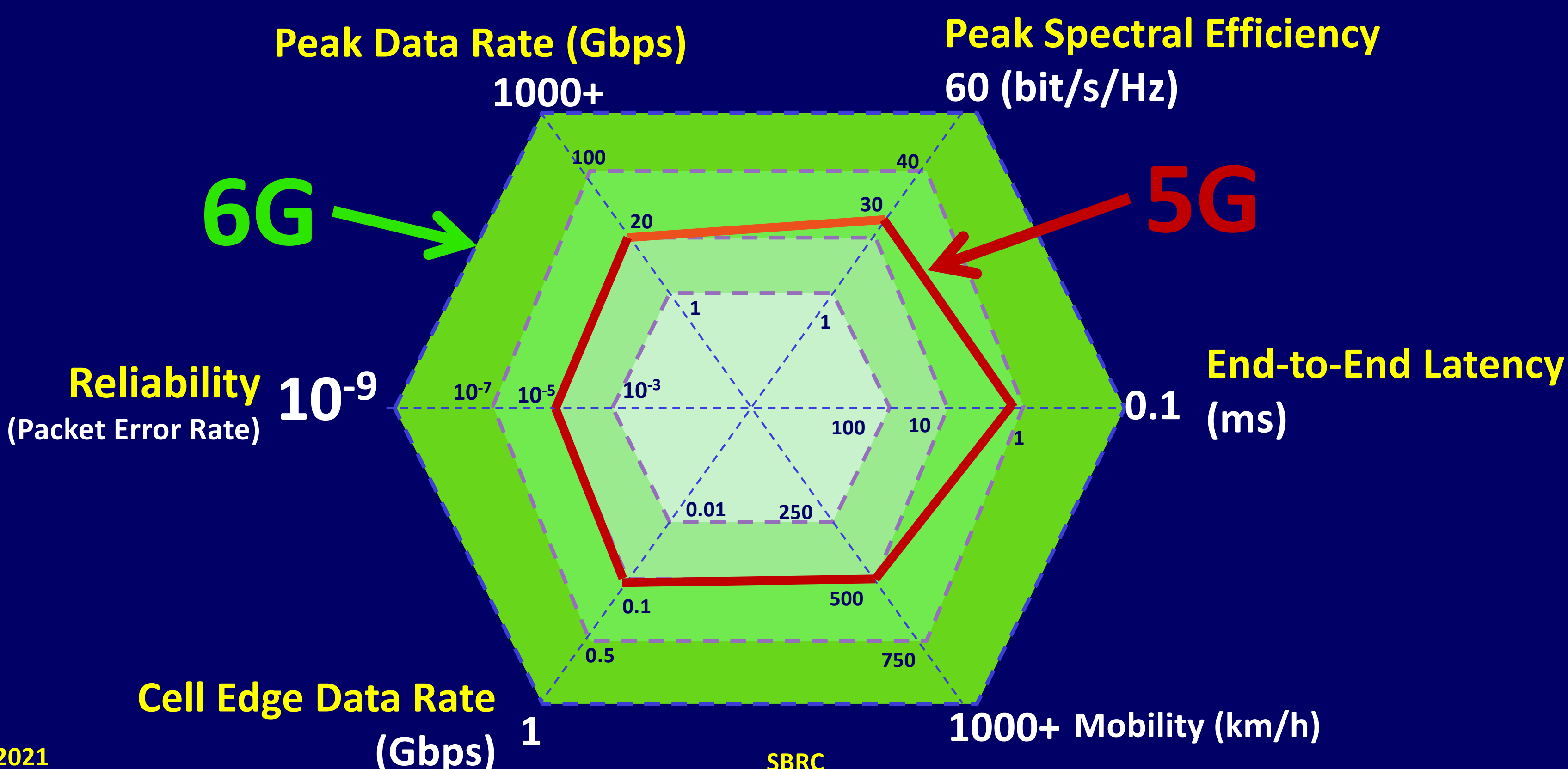
TRUVA, INC.

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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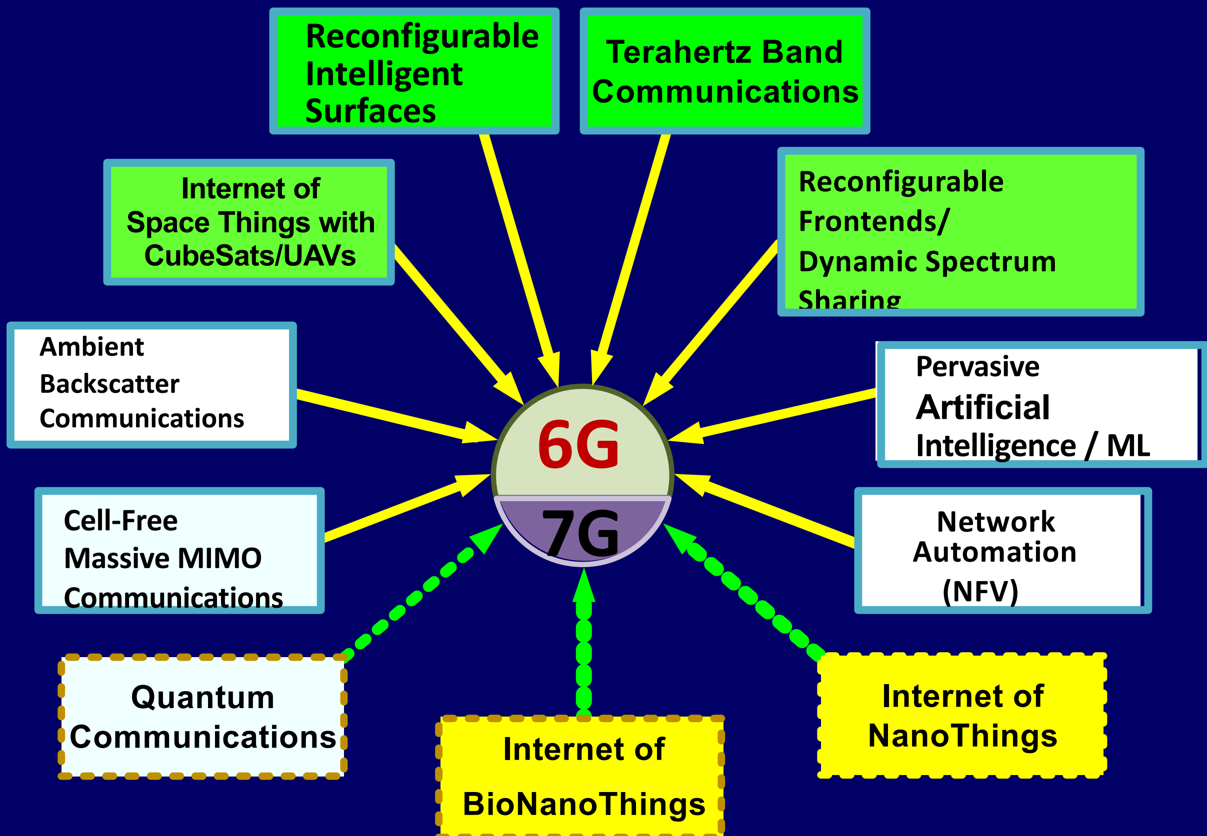
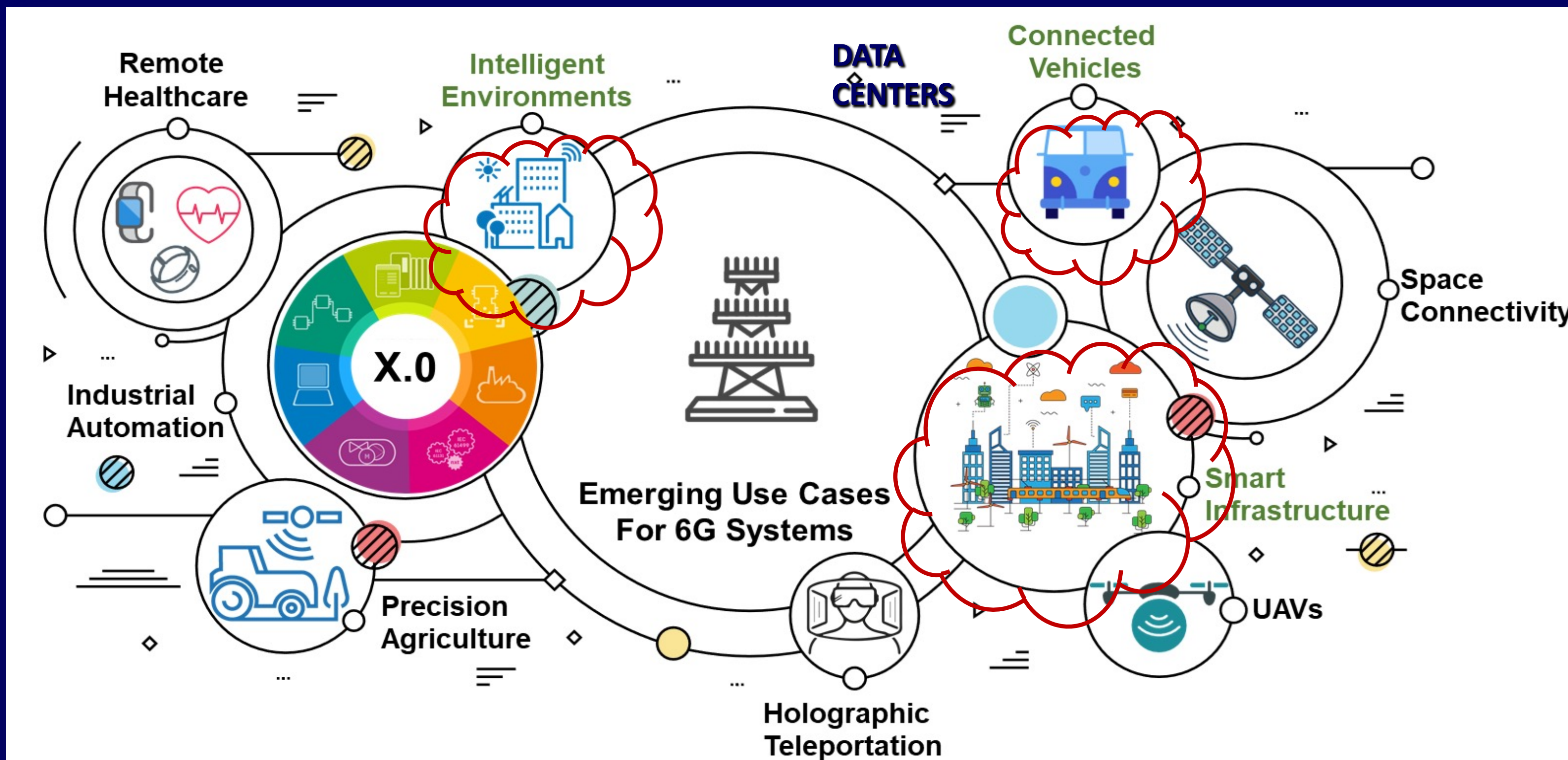


MAJOR USE CASES FOR 6G SYSTEMS



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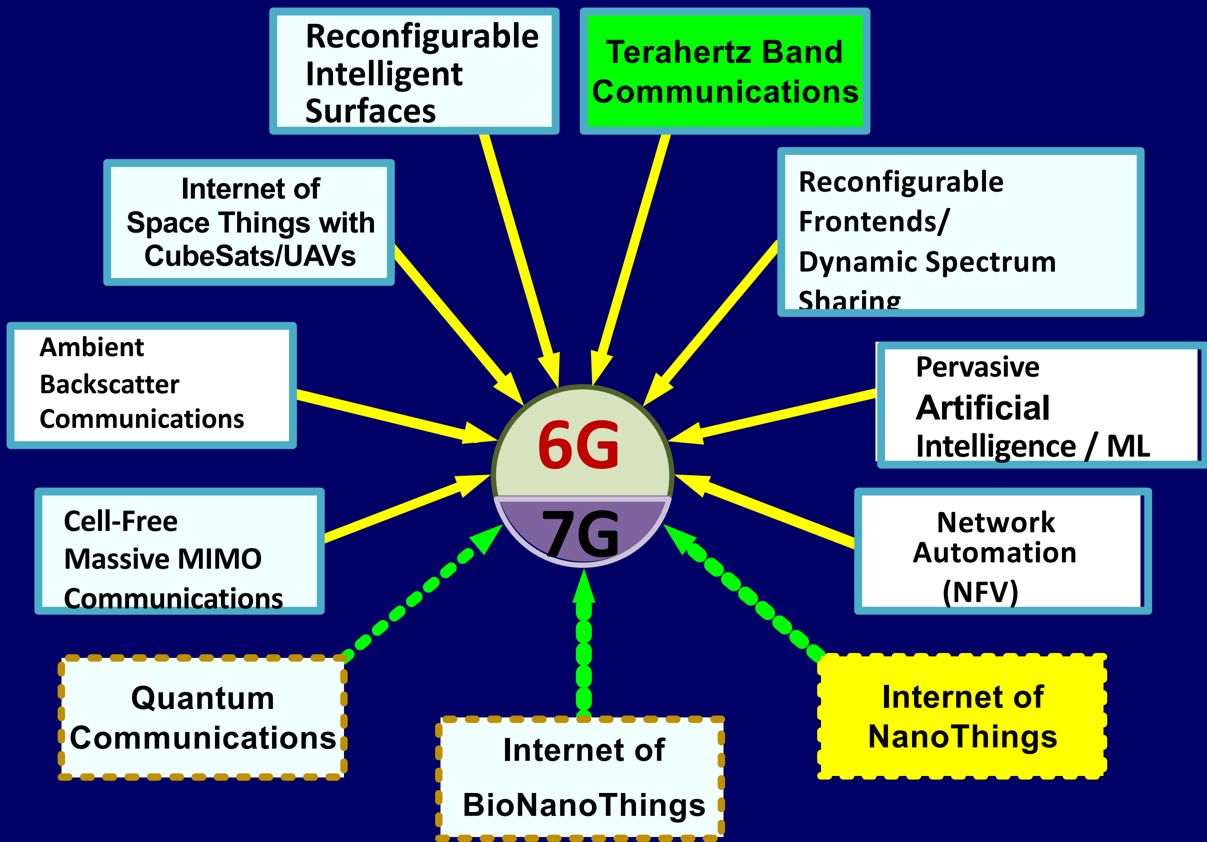


WHY TERAHERTZ?

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 !!

HOW DID I END UP IN TERAHERTZ BAND ??

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

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/

IoNT MARKET (MAY 26, 2020)

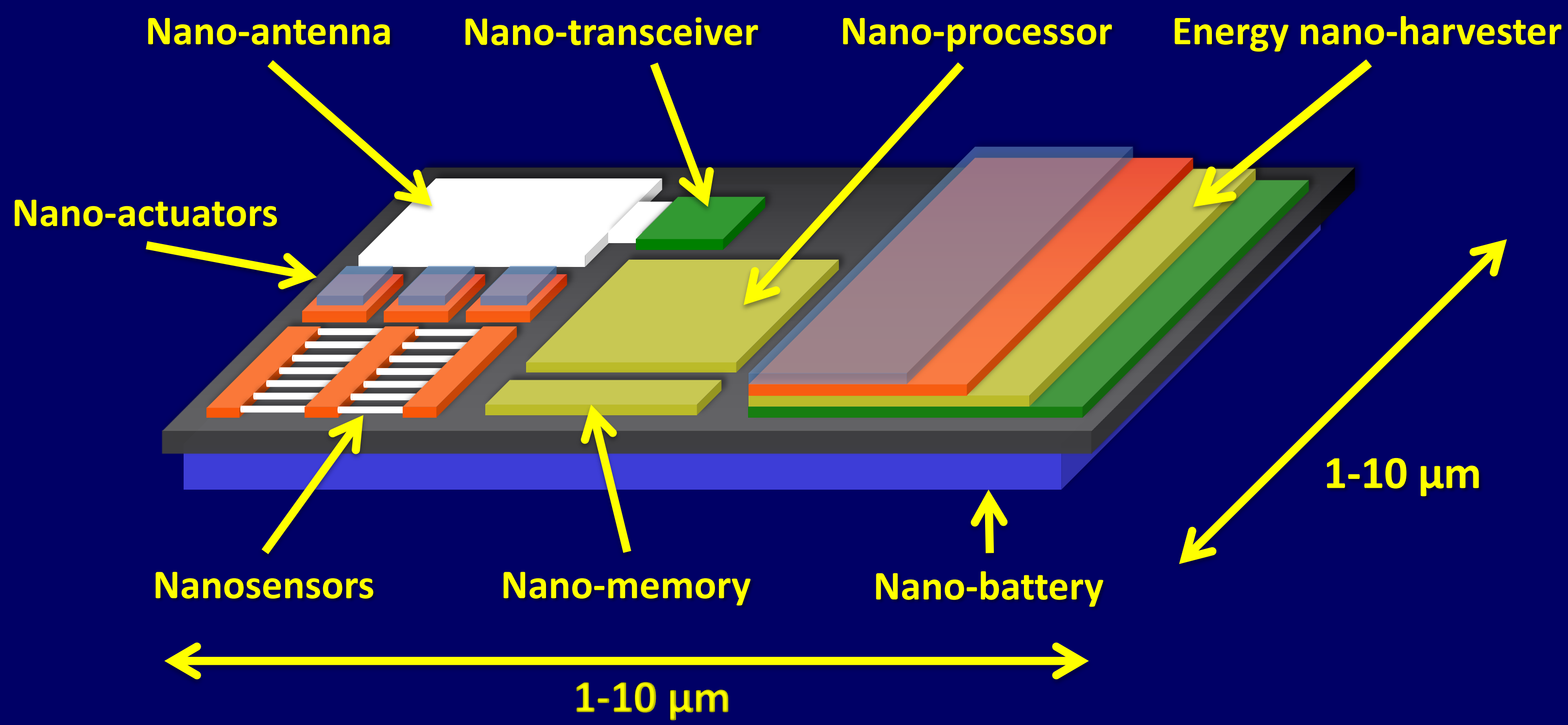
Latest Innovative Report on Internet of Nanothings (IoNT) Market Breaking the Ground Worldwide:

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/

DESIGN OF NANO-THINGS

I. F. AKYILDIZ AND J. M. JORNET,
"ELECTROMAGNETIC WIRELESS NANOSENSOR NETWORKS,"
NANO COMMUNICATION NETWORKS (ELSEVIER) JOURNAL, MARCH 2010.



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

GRAPHENE

- First 2D crystal ever known (Only 1 atom thick !!!)
- World's thinnest and lightest material
- World's strongest material
  - e.g., harder than diamond, 300 times stronger than steel
- Bendable
- Conducts electricity much better than fiber and copper
- Transparent material
- Very good sensing capabilities

→Enable a plethora of new applications for device technology at the nanoscale and also at larger scales:
  - e.g., processors, memories, batteries, antennas,tx, sensors, etc

GRAPHENE-BASED PLASMONIC NANO-ANTENNAS

I. F. Akyildiz and J. M. Jornet,

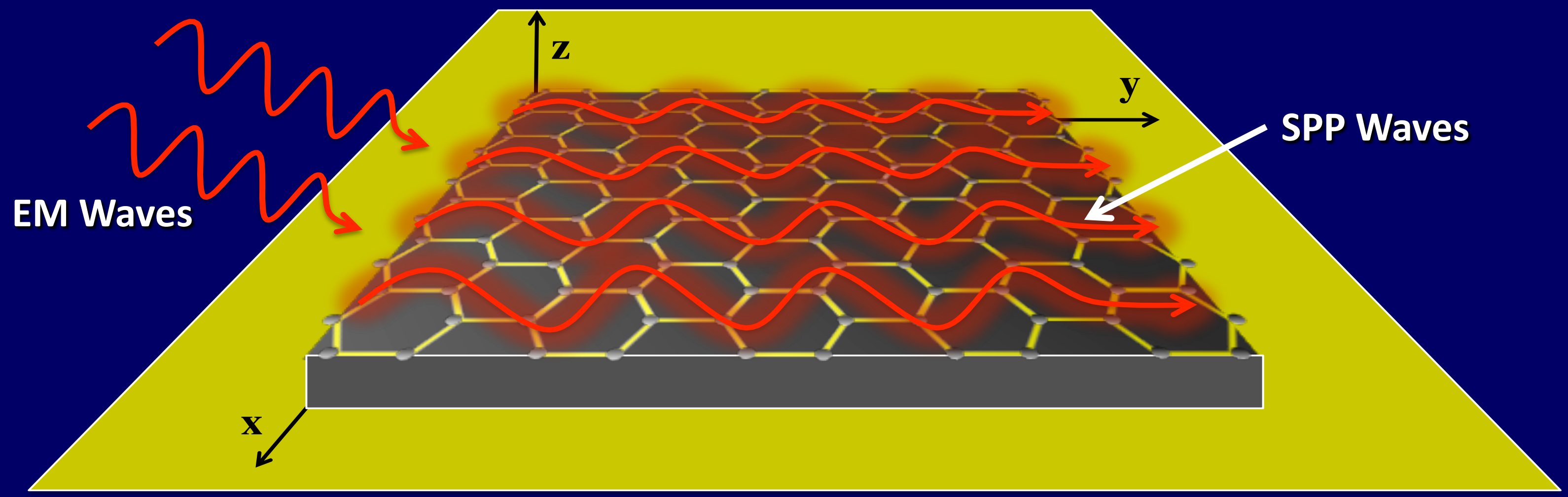
"Graphene-based Plasmonic Nano-antennas for Terahertz Band Communication in Nanonetworks,"

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



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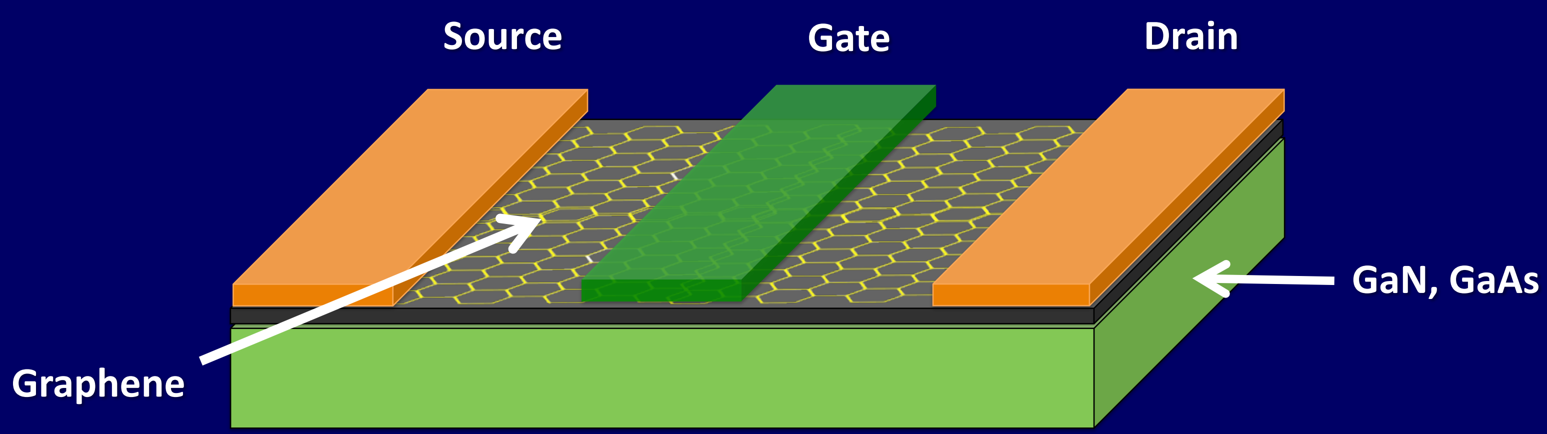
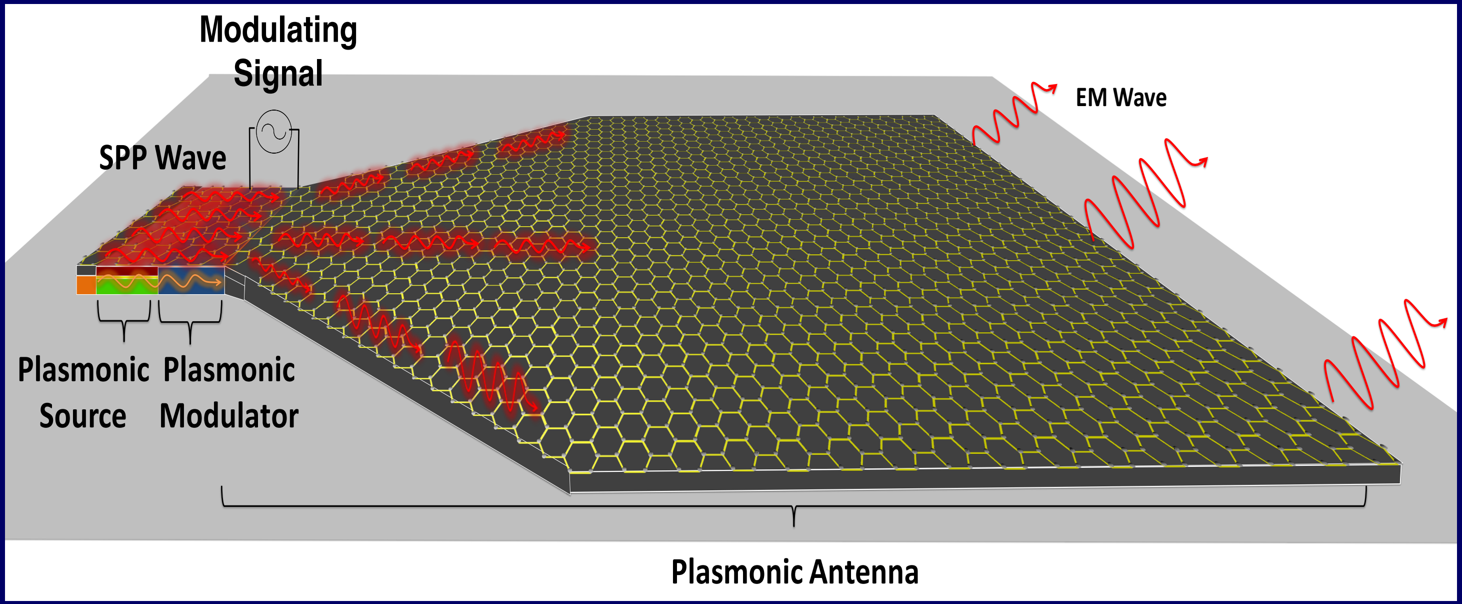
TERAHERTZ BAND PLASMONIC NANO-TRANSCEIVER

I. F. Akyildiz and J. M. Jornet,
"Graphene Plasmonic Nano-transceiver for Wireless Communication in the THz Band,"
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)



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- Ultra-Massive MIMO✓
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Nano Networks

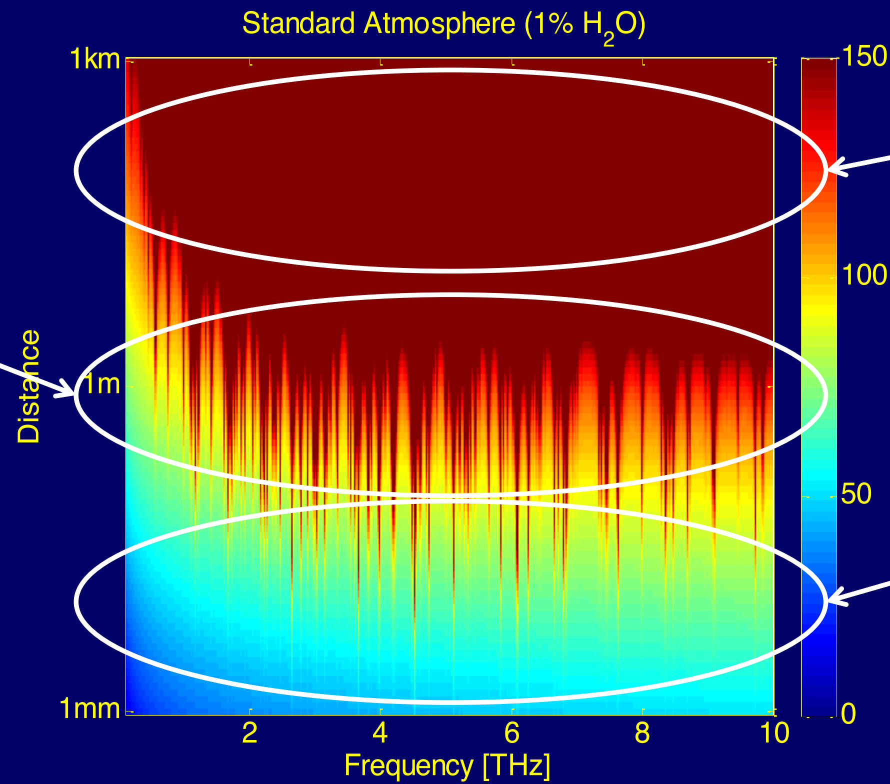
- Error Control ✓
- Medium Access Control ✓
- Addressing
- Neighbor Discovery
- Relaying
- Routing
- Transport Layer
- Cross-layer

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.

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



We can certainly not go further

The almost absence of molecules in short distances does simplify everything in the short range

NEW MODULATION TECHNIQUE

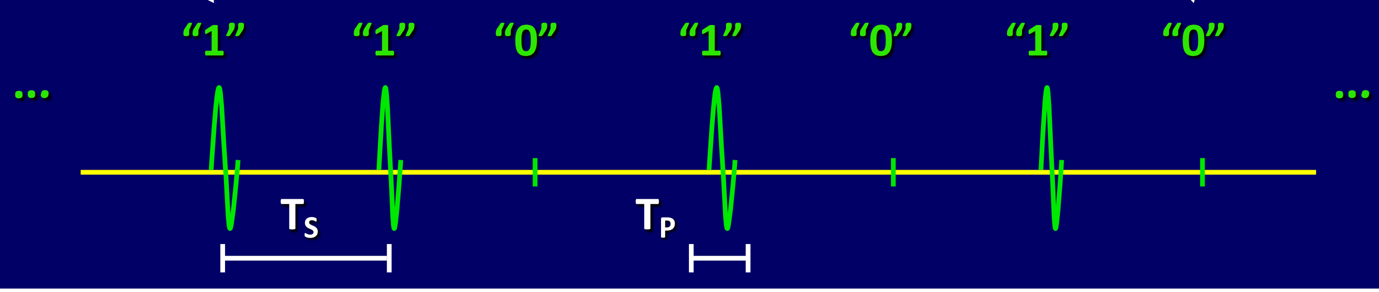
J.M. Jornet and I.F. Akyildiz,
"Information Capacity of Pulse-based Wireless Nanosensor Networks",
Proc. of the 8th Annual IEEE SECON, Salt Lake City, Utah, June 2011.

- 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

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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
- 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 → achieve less path loss
- For short transmission distances (<1m)
  - Multipath helps
  - THz Band channel behaves as a single transmission window almost 10 THz wide
- With increasing transmission distance (>1m)
  - 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

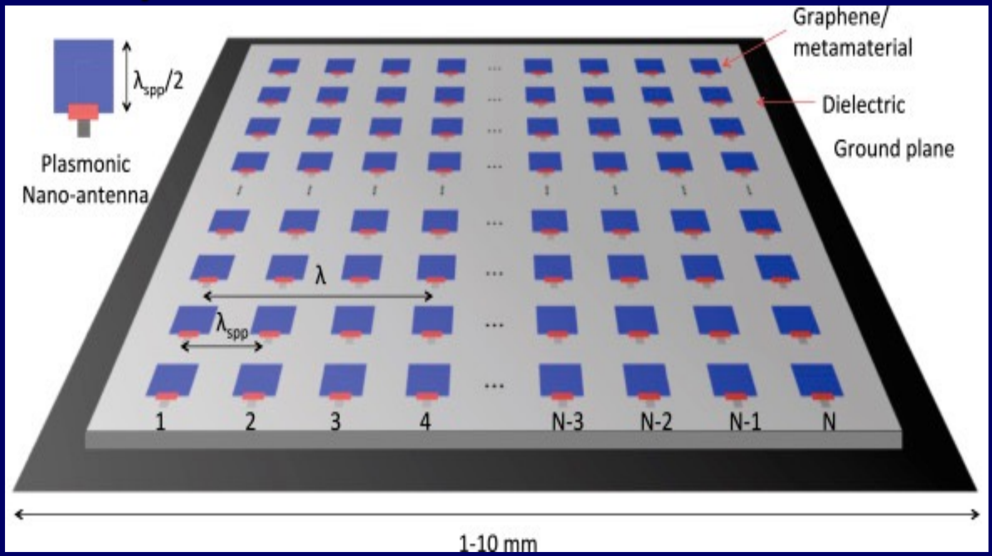
C. Han, O. Bicen, and I.F. Akyildiz,
"Multi-Wideband Waveform Design for Distance-adaptive Wireless Coms in the THz Band,"
IEEE Transactions on Signal Processing, vol. 64, no.4, pp. 910-922, February 2016.

- 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 principle for the multi-user network
  - 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

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

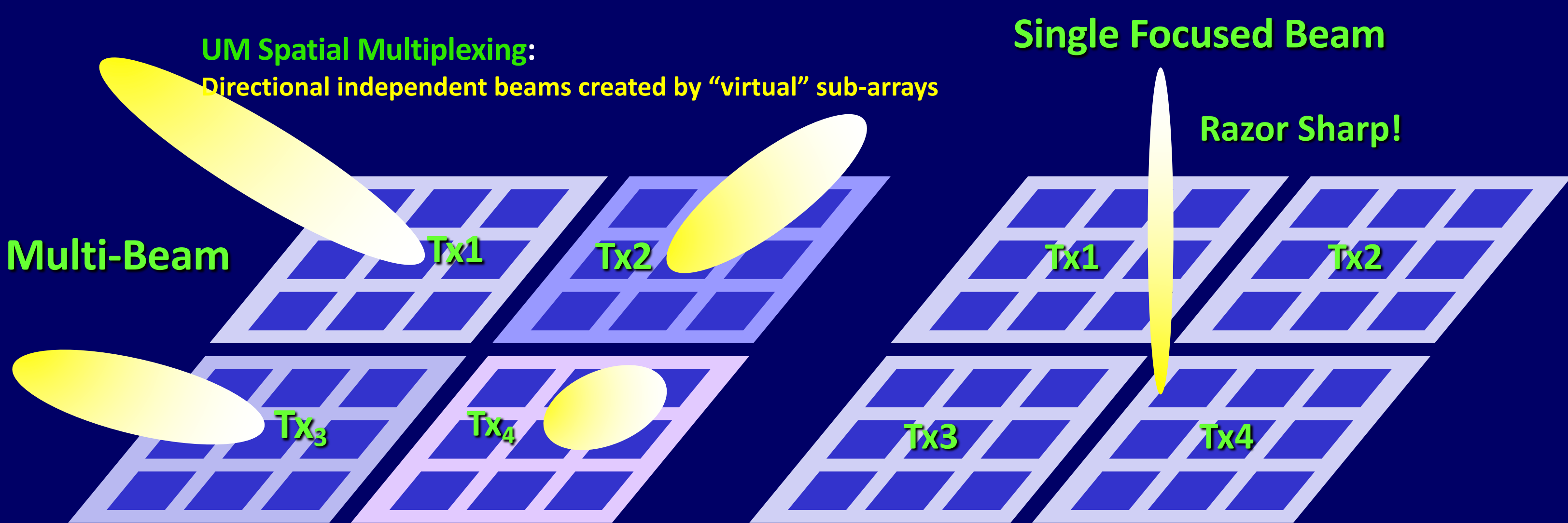


UM-MIMO can achieve at least 10-fold increase in transmission distance at 300 GHz and 1 THz compared to M-MIMO

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

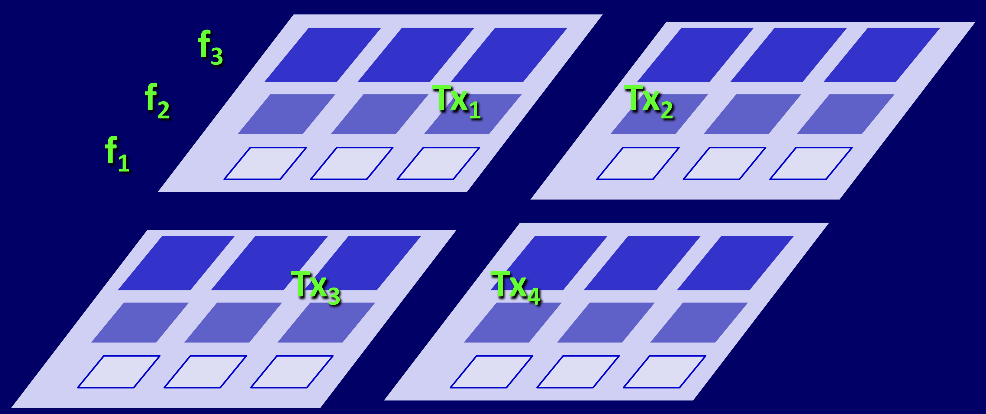
- By properly feeding antenna elements, antenna array can be dynamically switched among different modes
- Increased throughput and multi-user capacity
- Maximum communication range
- Also apply ML algorithms for intelligent beamforming



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)

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

- Fabrication of the UM-MIMO Antennas & Transceivers

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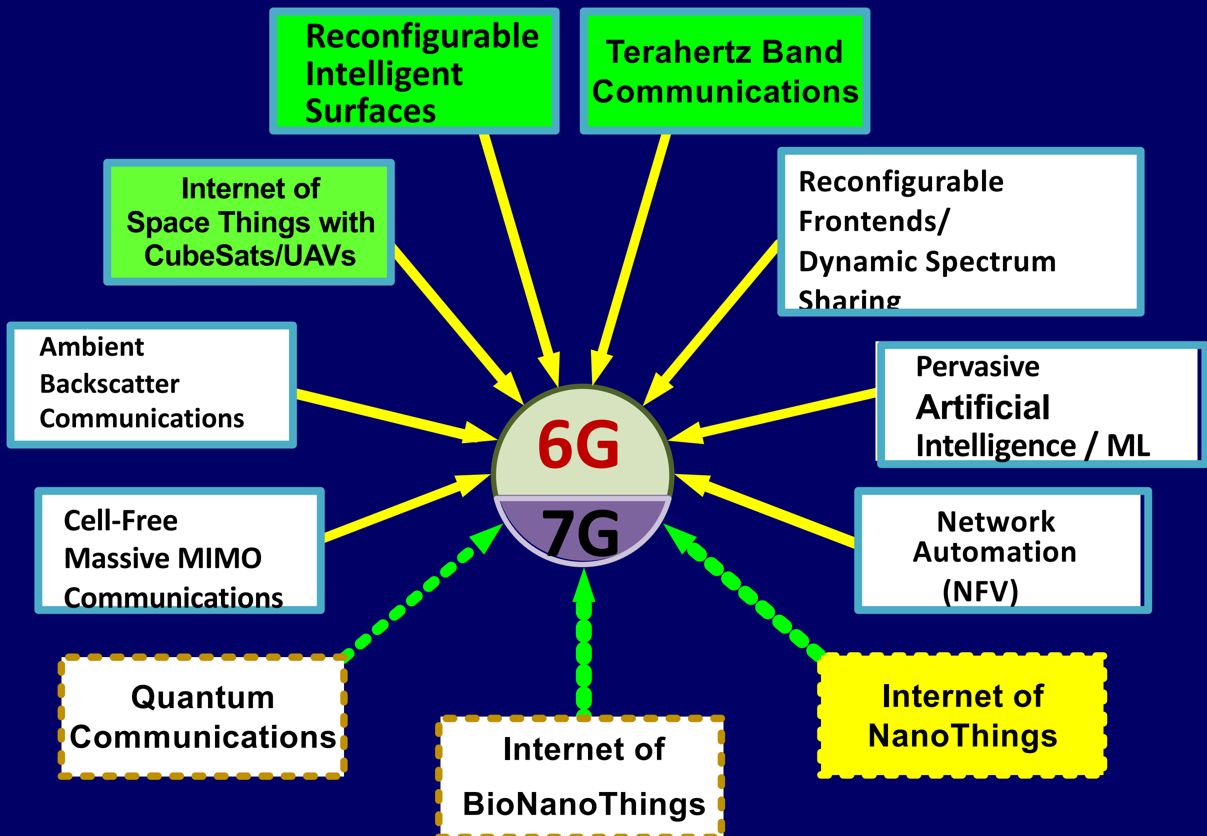

RECONFIGURABLE INTELLIGENT SURFACES
INTELLIGENT ENVIRONMENTS
BASIC REFERENCES

- 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.

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DIFFERENT NOMENCLATURE

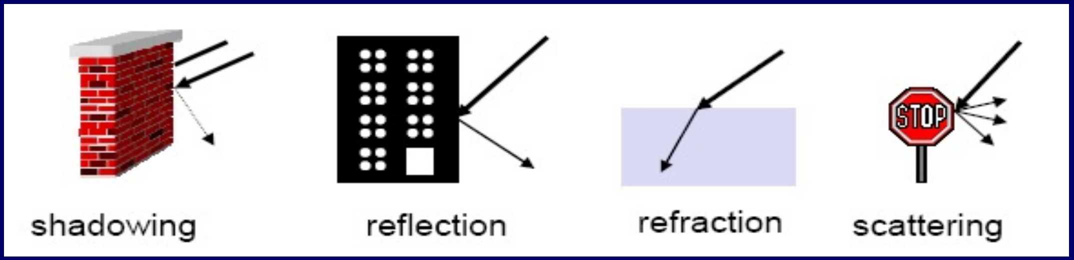
- Intelligent Communication Environments (ICE)
- Intelligent Communication Surfaces (ICF)
- Reconfigurable Intelligent Surfaces (RIS)
- Programmable Wireless Environments (PWE)
- Programmable Metasurfaces
- Hypersurfaces
- Large Intelligent Surfaces (LIS)
- Intelligent Reflecting Surfaces (IRS)
- Smart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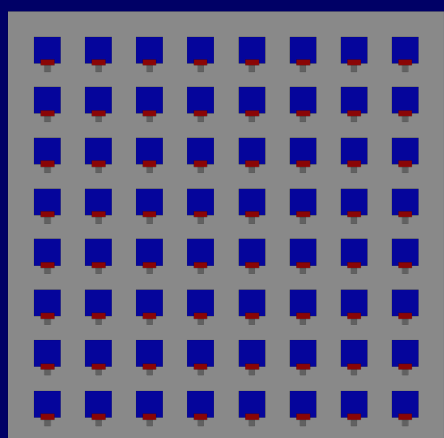
CONVENTIONAL APPROACHES

- 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

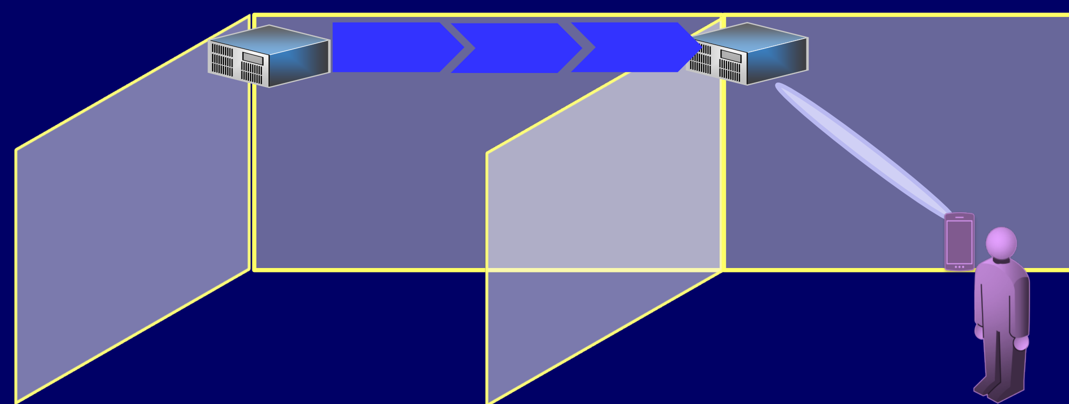
Passive Reflectarrays



Supports only:

Normal Reflection

Relays

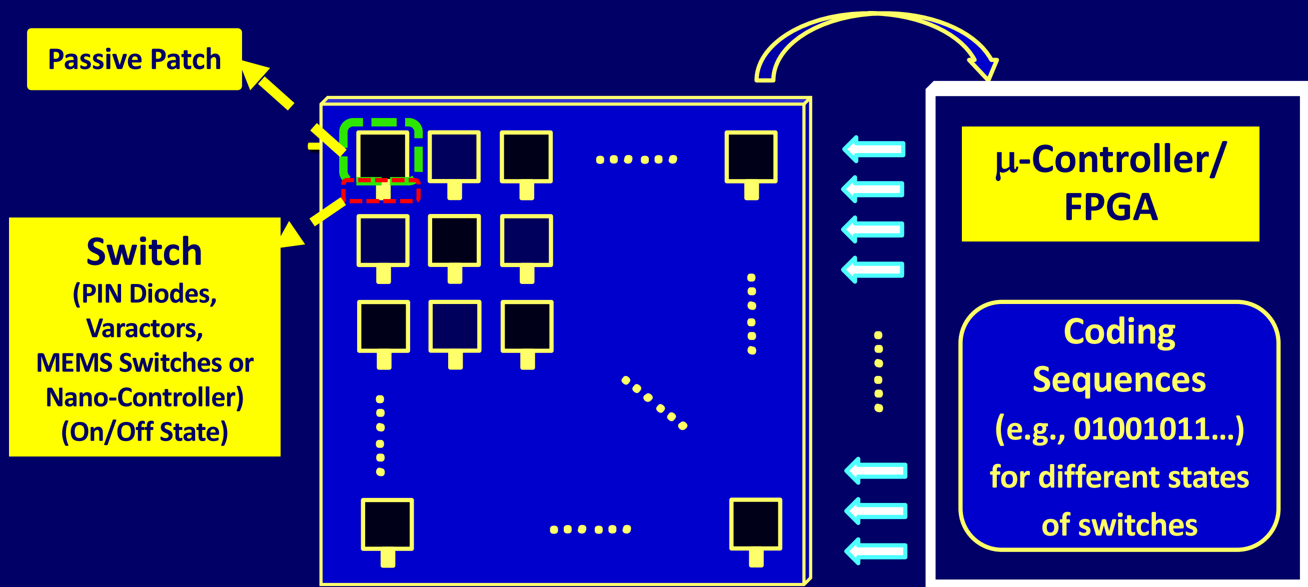


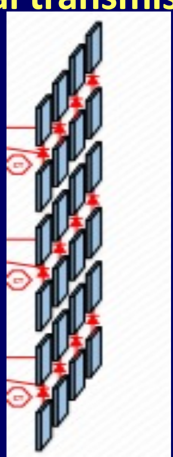
Disadvantages:

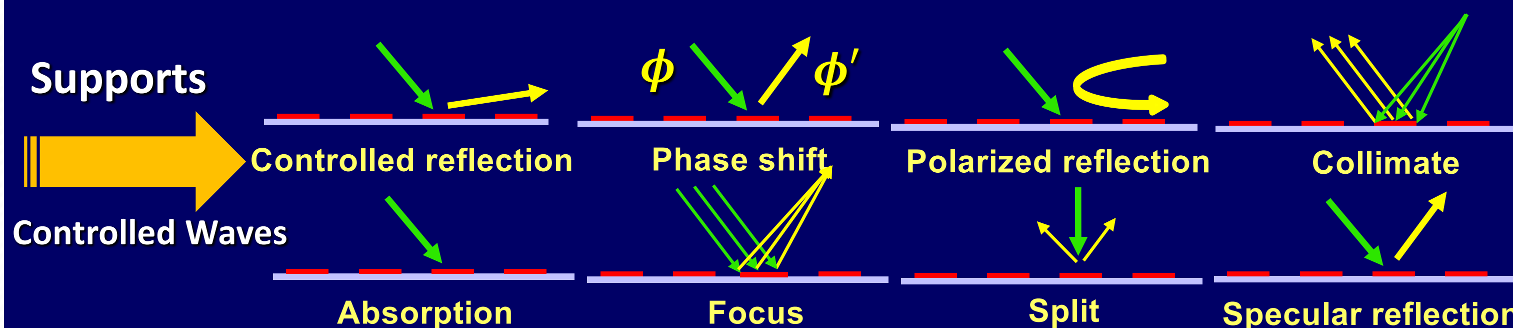
- Longer delays
- More backhaul infrastructure cost;
- Inflexible for existing network layout

RECONFIGURABLE INTELLIGENT SURFACES (RIS)

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







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USE CASES OF RISs
PROPAGATION CHANNEL ENHANCEMENT

Support multiple users and devices for high-throughput links

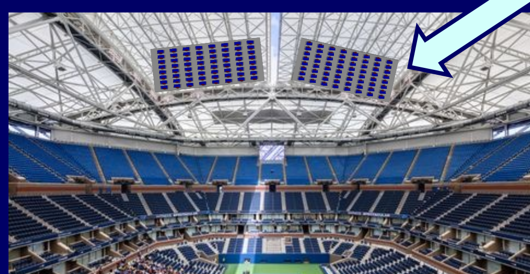
Indoor meeting rooms & offices

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.

CURRENT WORLDWIDE EFFORTS

SURFACES

- **THE WALL**
  Huawei Moscow & RAS-IITP
  Russia
- **HyperSurfaces**
  VisorSurf, EU-FET
- **UM MIMO-based Intelligent Communication Platform**
  BWN LAB, U.SA.
- **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

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!

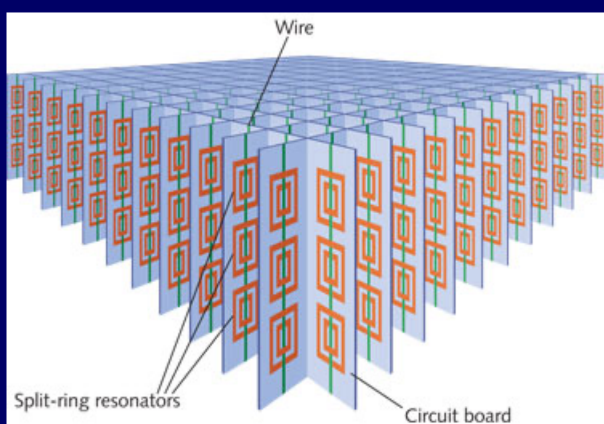
- Start date: 1/1/2017
- Duration: 42 months
- Coordinator: FORTH Crete, Greece
- 8M Euro (2017-2021)

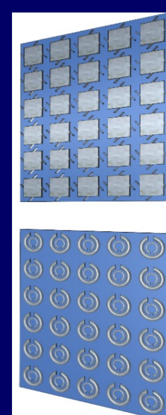
FORTH Foundation for Research & Technology - Hellas
Signal GeneriX Ltd Advanced Signal Solutions
University of Cyprus
Universitat Politècnica de Catalunya BarcelonaTech
Fraunhofer Gesellschaft
Aalto University

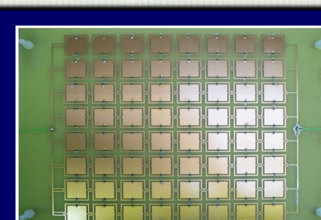
VISORSURF TEAM (FORTH CRETE; AUG. 2019)

METAMATERIALS

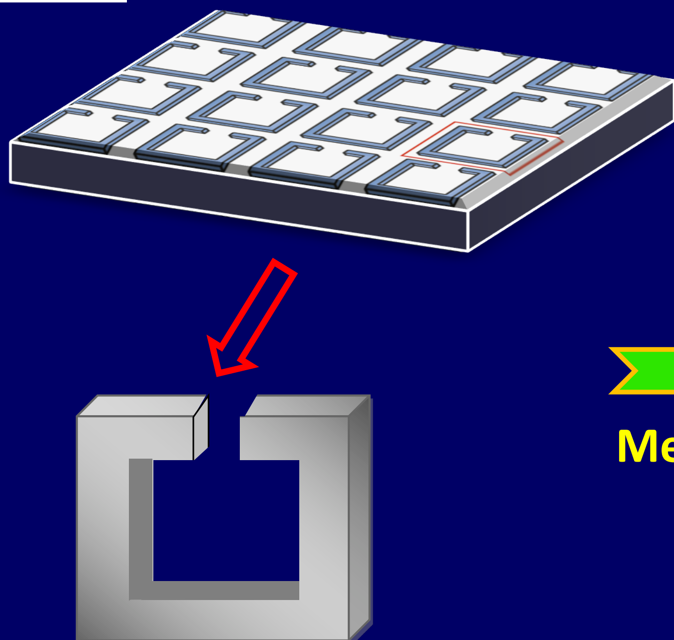
- A metamaterial ("beyond") is a material engineered to have a property that is not found in nature
- Manipulation of EM waves: block, absorb, enhance, or bend waves, to achieve benefits that go beyond what is possible with conventional materials
- Their precise shape, geometry, size, orientation and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







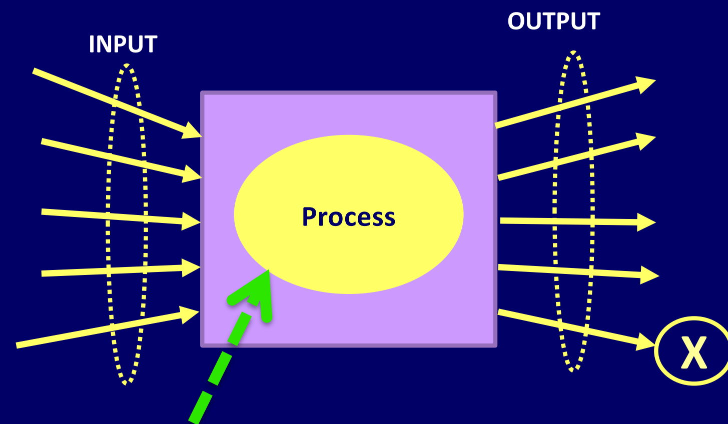
METAMATERIAL BASICS



Schematics of the Elementary Cell

Metasurfaces

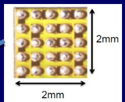
Completely re-engineer incoming EM waves

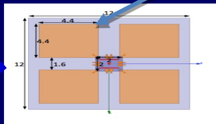


STEER, ABSORB, POLARIZE, SPLIT, FREQ_FILTER,
ALTER_PHASE, FOCUS,
CUSTOM EM/MAG FIELD At output(s)

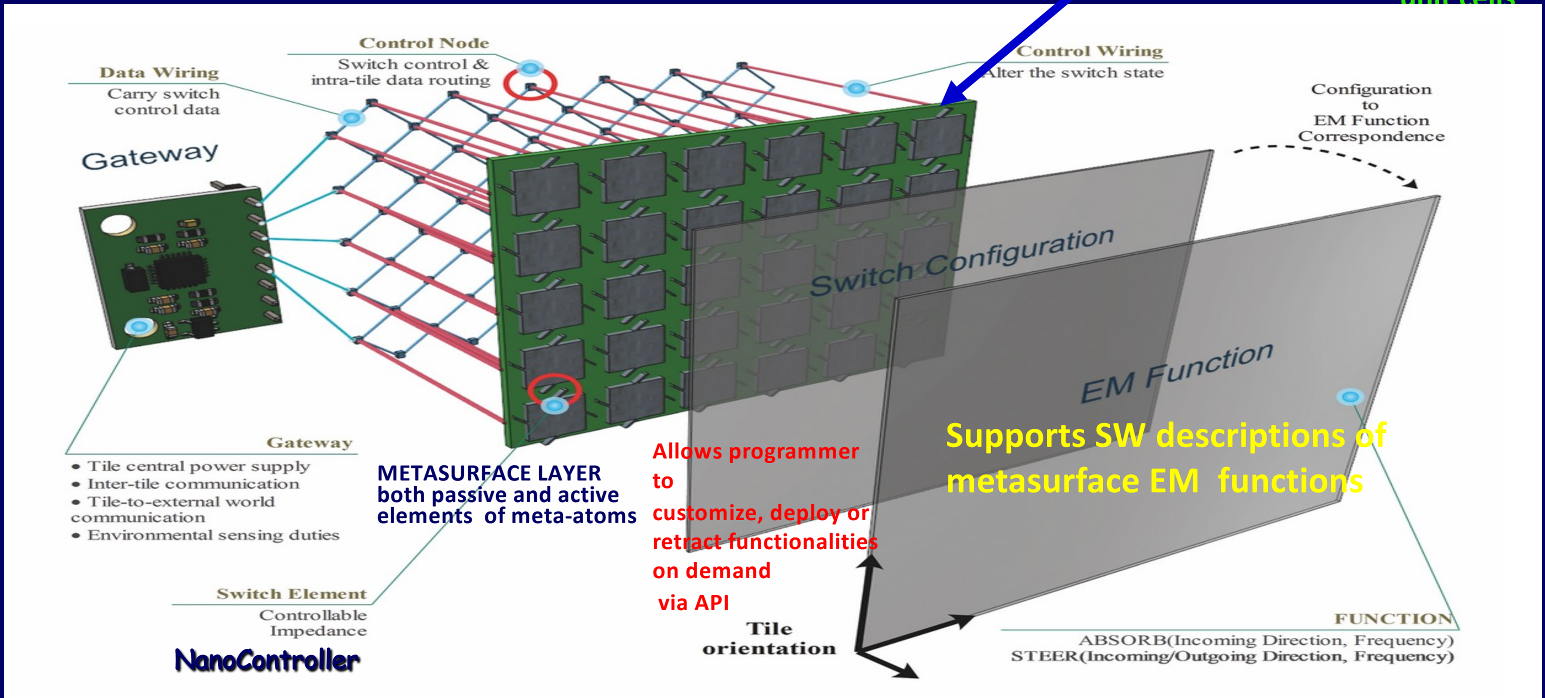
HYPERSURFACES: PROGRAMMABLE (SOFTWARE DEFINED) METASURFACES

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.



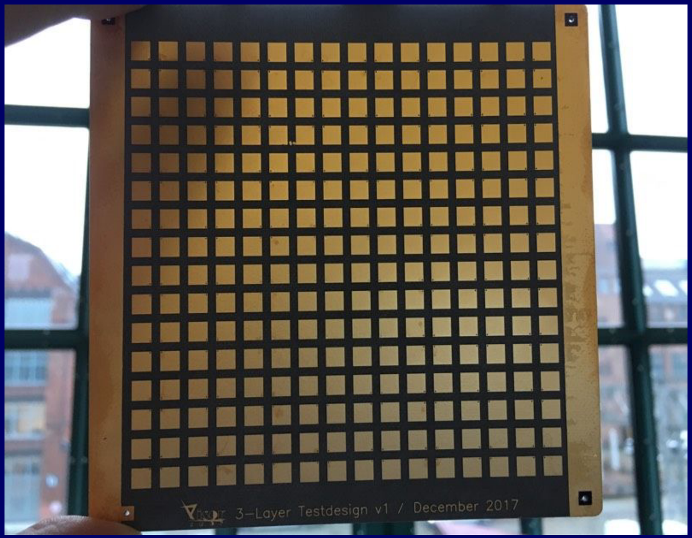


meta atoms/
metallic
patches/
unit cells



PROTOTYPING

COURTESY OF FRAUNHOFER INSTITUTE BERLIN

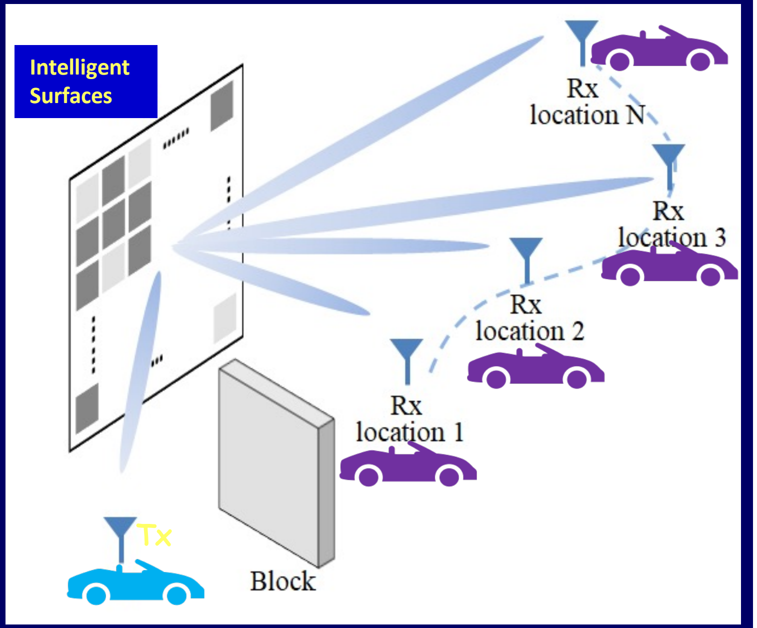


- **First prototype is ready for evaluation**
  - Software & Hardware
- **More prototypes to follow:**
  - Exotic ASIC solutions
  - Graphene-based, THz control

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

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
- Resources in the spatial, temporal, and spectral domains should be allocated in an optimal manner to satisfy per mobile users demand
- Real-time beam tracking scheme for high-speed vehicles and random trajectories

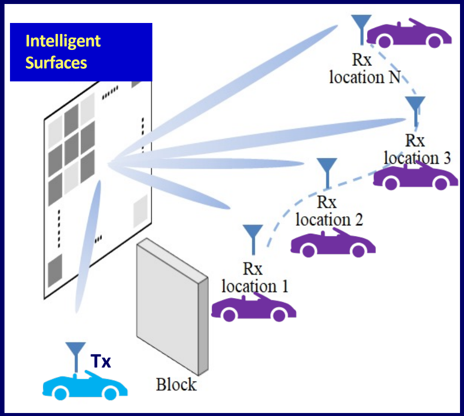


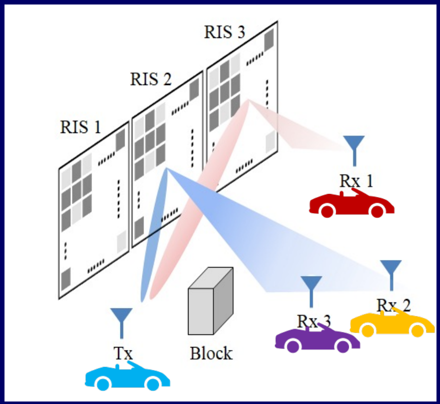
OPEN RESEARCH TOPICS IN INDOOR/OUTDOOR THZ SYSTEMS

- 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





OPEN RESEARCH TOPICS FOR INDOOR/OUTDOOR THZ SYSTEMS

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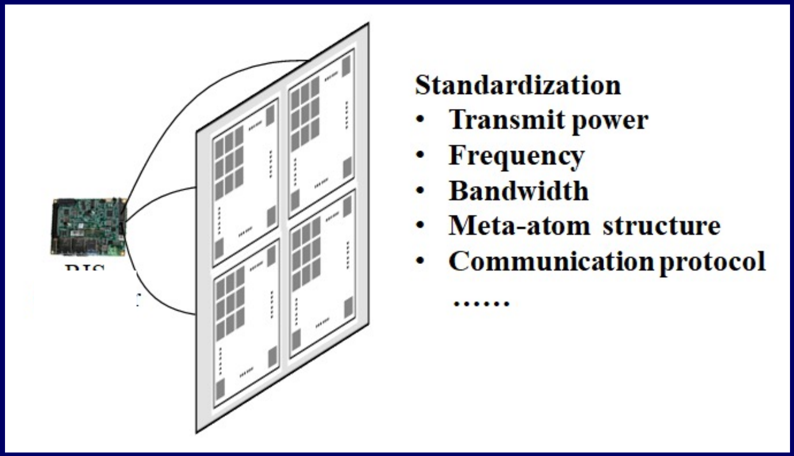
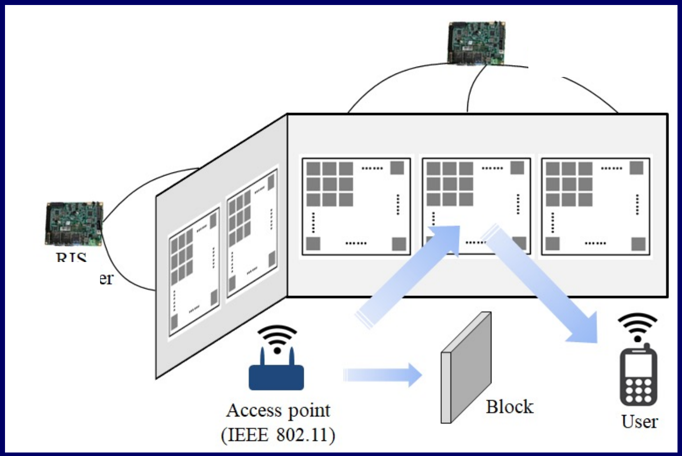
- **Standardization and Assessment**
  - HW structures and communication protocols
  - Integration into existing wireless communication networks (5G, 6G, IEEE 802.11, IoTs)





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

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

STANDARDIZATON (TERAHERTZ BAND)

– THz band is still not regulated
IEEE 802.15 (WPAN) Terahertz Interest Group (IG-thz)
(300 GHz to 3THz)
http://www.ieee802.org/15/pub/IGthz.html

- IEEE Standardization Group created for 100Gbps in 2014.

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LESSON: DARPA NEWS (2014):

4 DARPA PROJECTS BIGGER THAN THE INTERNET

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

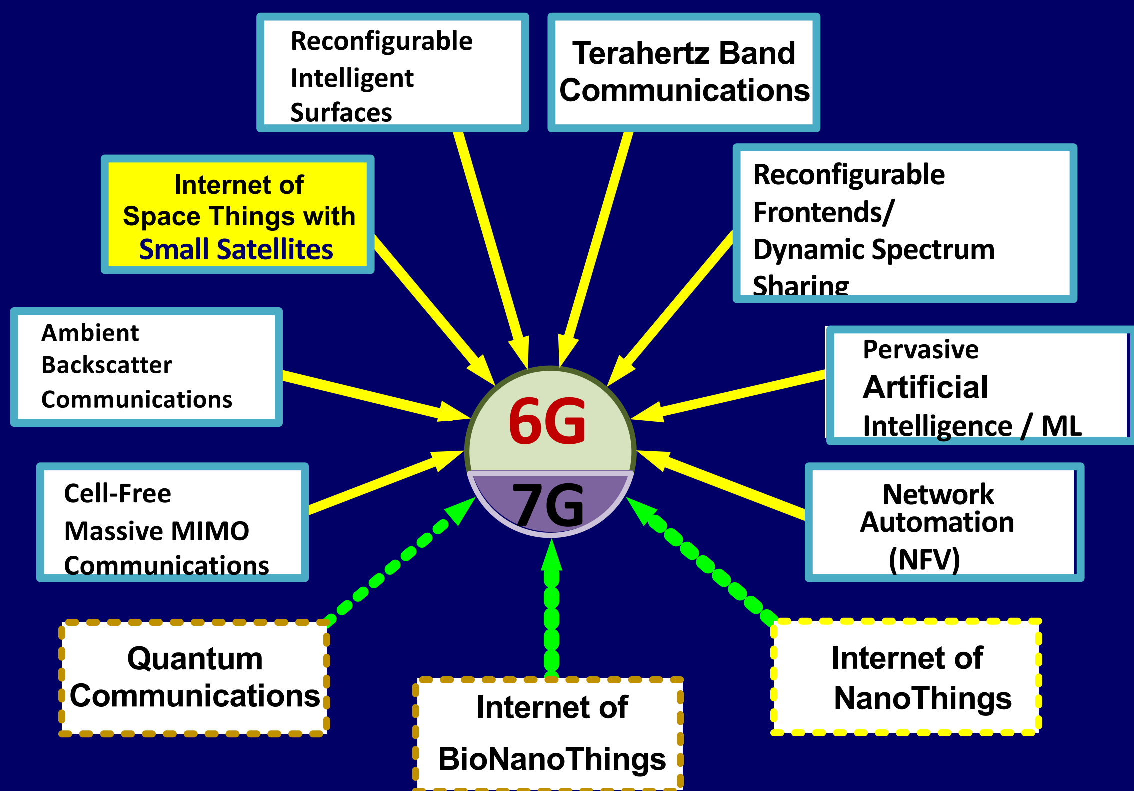
2. Terahertz Frequency Electronics, Devices, Meta-materials and Communication

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

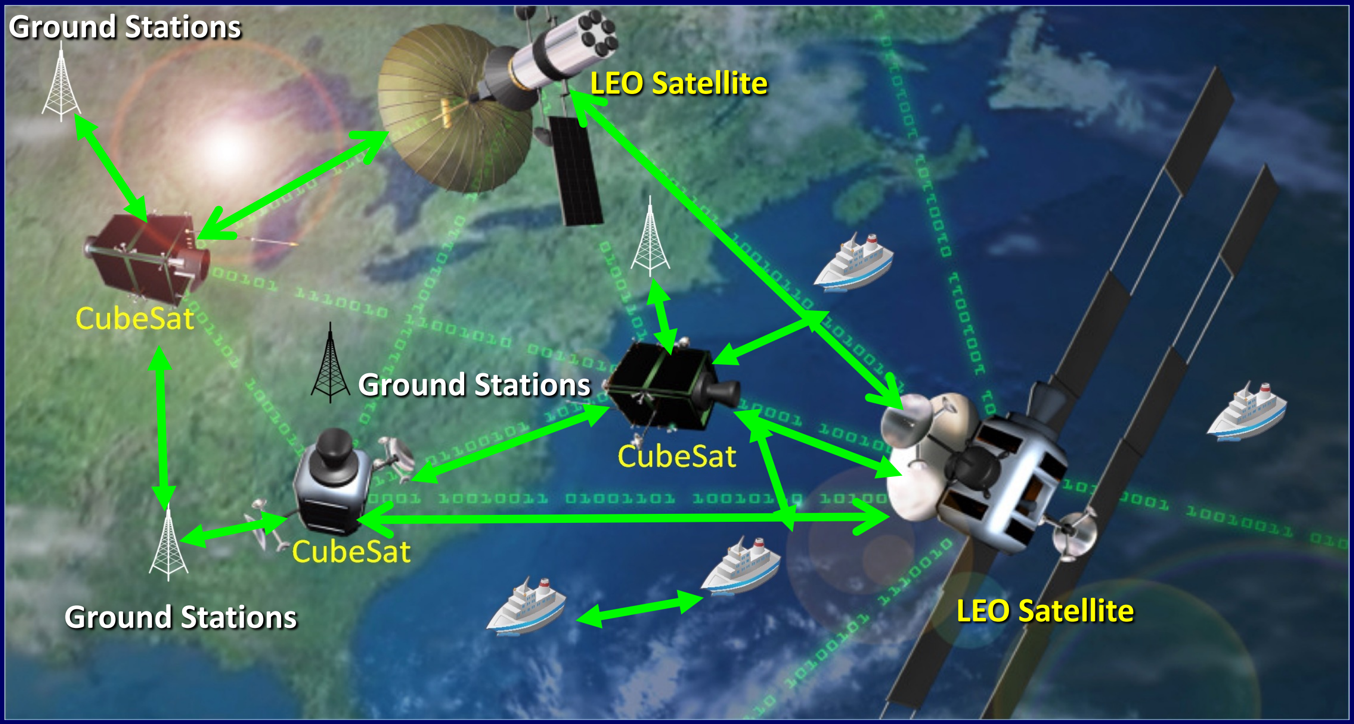
4. Rapid Threat Assessment

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.



INTERNET OF THINGS IN SPACE/CUBESATS



Internet of Space Things/CubeSats

REFERENCES

I. F. Akyildiz, J. M. Jornet and S. Nie,
"A New CubeSat Design with Reconfigurable Multi-Band Radios for Satellite Communication in Dynamic Spectrum Frequencies",
Ad Hoc Networks (Elsevier) Journal), vol. 86, pp. 166-178, April 2019.

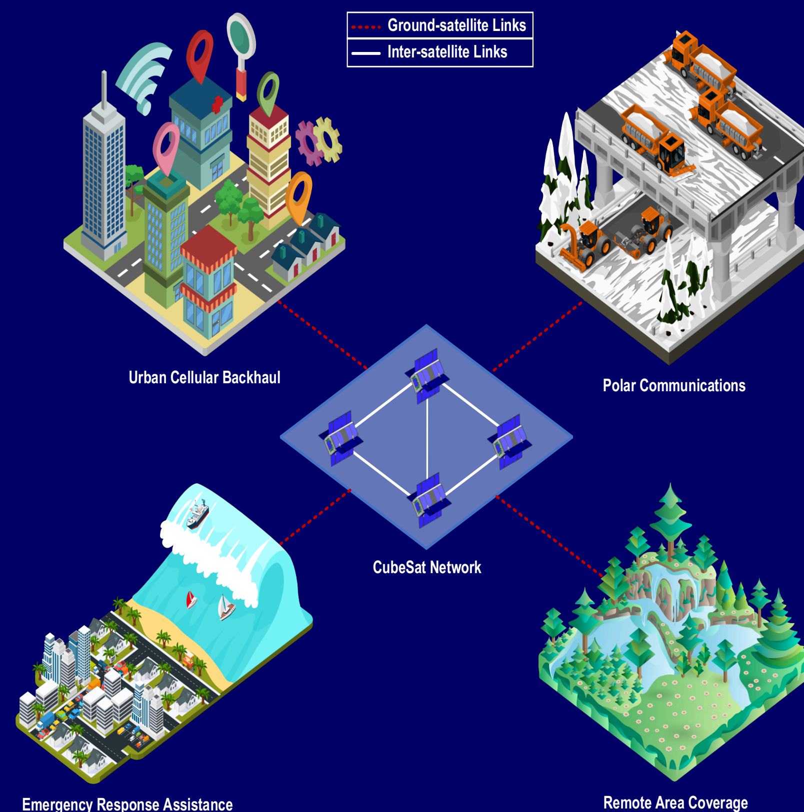
I. F. Akyildiz and A. Kak,
"The Internet of Space Things/CubeSats",
IEEE Network, vol. 33, no. 5, pp. 212-218, Sept.-Oct. 2019

I. F. Akyildiz, A. Kak, and S. Nie,
"Network Employing Cube Satellites,"
US Patent: WO 2020/124076 A1, Fall 2020.
Publication Date: Dec. 14, 2018.

USE CASES OF IoST

Backhaul in the Sky

- Remote areas connectivity (e.g., North and South Poles)
- Pervasive tracking
- Emergency infrastructure after natural disasters (Earthquakes, tsunamis, or tornados)
- Network Security Concern in Terrestrial Networks
- Traffic Offloading from Congested Terrestrial Networks

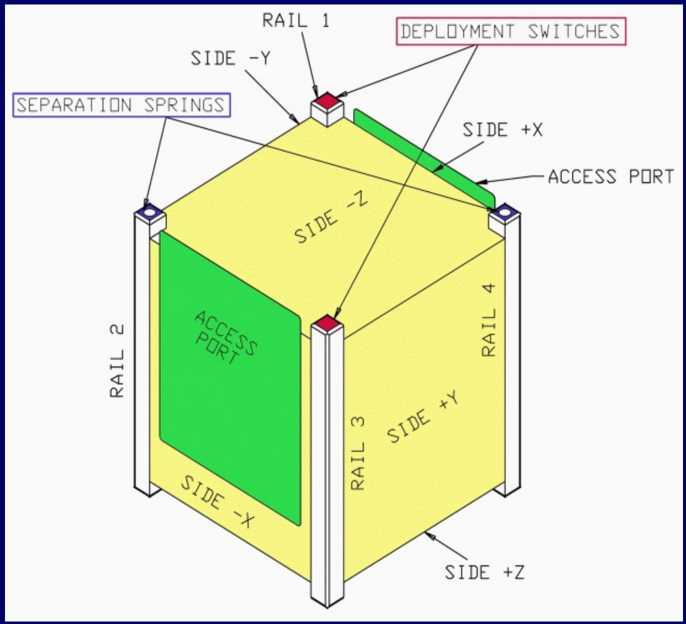


Eyes in the Sky

- Terrain Monitoring
- Disaster Prevention and Monitoring

WHAT IS A CUBESAT?

- Small satellites originally used at CalPoly in 1999
- Also referred as “nano/micro satellites”
- 1U = 10 cm × 10 cm × 10 cm → mug size
- Can be airborne launched



Original CubeSat Specification

Existing CUBESAT Networks

System	Astrocast	Fleet	Kepler	Aistech	Myriota	Planet Dove	Lacuna Space
Developer	Else, Switzerlan d	Fleet, AUS	Kepler, Canada	Aistech, Spain	Myriota, AUS	Planet Labs, US	Lacuna Space, UK
Purpose	IoT and M2M	IoT	Satellite backhauling	IoT, M2M, asset tracking	IoT	Earth imaging	IoT and M2M
ISL Capability	Yes	No	Yes	NA	NA	No	NA
Orbital Altitude	575 km	580 km	600 km	500 km	800 km	420 km	500 km
Orbital Inclination	97.4	NA	98.6	97.8	NA	52	NA
Number of Satellites	64	100	140	102	50	150	32
Weight	8 kg	20 kg	7 kg	NA	NA	NA	11 kg
Operating Frequency	L	NA	Ka and Ku	NA	UHF	S	ISM
Form Factor	3U	12U	3U	2U	3U	3U	6U

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LIMITATION OF EXISTING CUBESAT SOLUTIONS

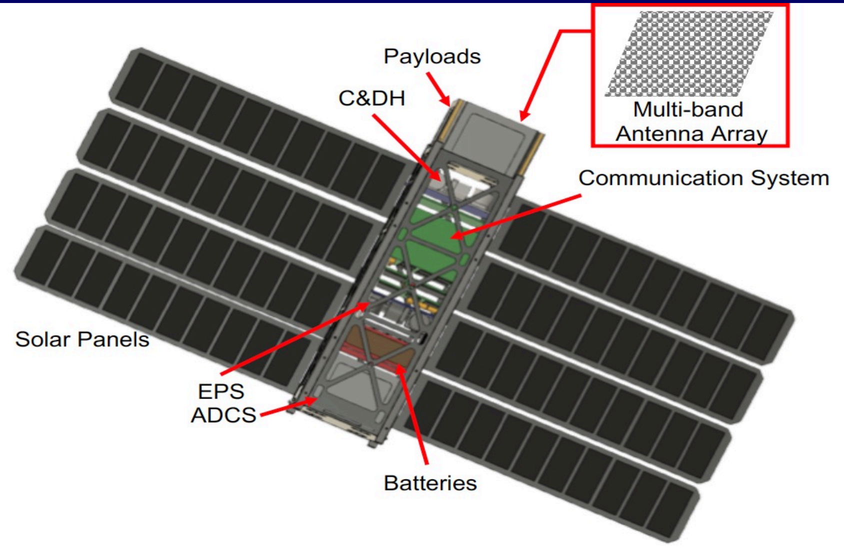
- Lack of continuous global coverage
- Low data rates (kbps; 1 Mbps; Keppler: 1-40Mbos)
- No publicly available solutions for large-scale network constellation design!
- Existing solutions rely far too much on distributed on-board path computation!
- Serving a variety of use cases with differing service requirements
- Data routing for ultra-dense CubeSat systems is a major problem
- mmWave and THz bands are underexplored for active communication in space
- Use conventional satellite communication frequencies → Already very congested with limited BW
  - Iridium NEXT SensorPod: L- and K_a-band
  - AstroCast: L-band
  - Keppler: K_u-band
  - Hiber: S-band

Our Design: UbiCube

I.F. Akyildiz, J. Jornet and S. Nie,
"A New CubeSat Design with Reconfigurable Multi-Band Radios for Satellite Communication in Dynamic Spectrum Frequencies,"
Ad Hoc Networks (Elsevier) Journal, vol. 86, pp. 166-178, April 2019.
Patent Applied in Dec. 2018.

I. F. Akyildiz and A. Kak,
"The Internet of Space Things/CubeSats: A ubiquitous cyber-physical system for the connected world",
Computer Networks, vol. 150, pp. 134-149, February 2019.
Patent applied, Dec. 2018.

- Dimension: 3U (10 cm × 10 cm × 34 cm)
- Weight: 5 kg max.
- No propulsion system
- Solar panels expand 45 minutes at deployed to target orbits
  - 8 independent solar panels flexible to change orientations for max. area of sun exposure



MULTI-FREQUENCY BAND COMMUNICATION

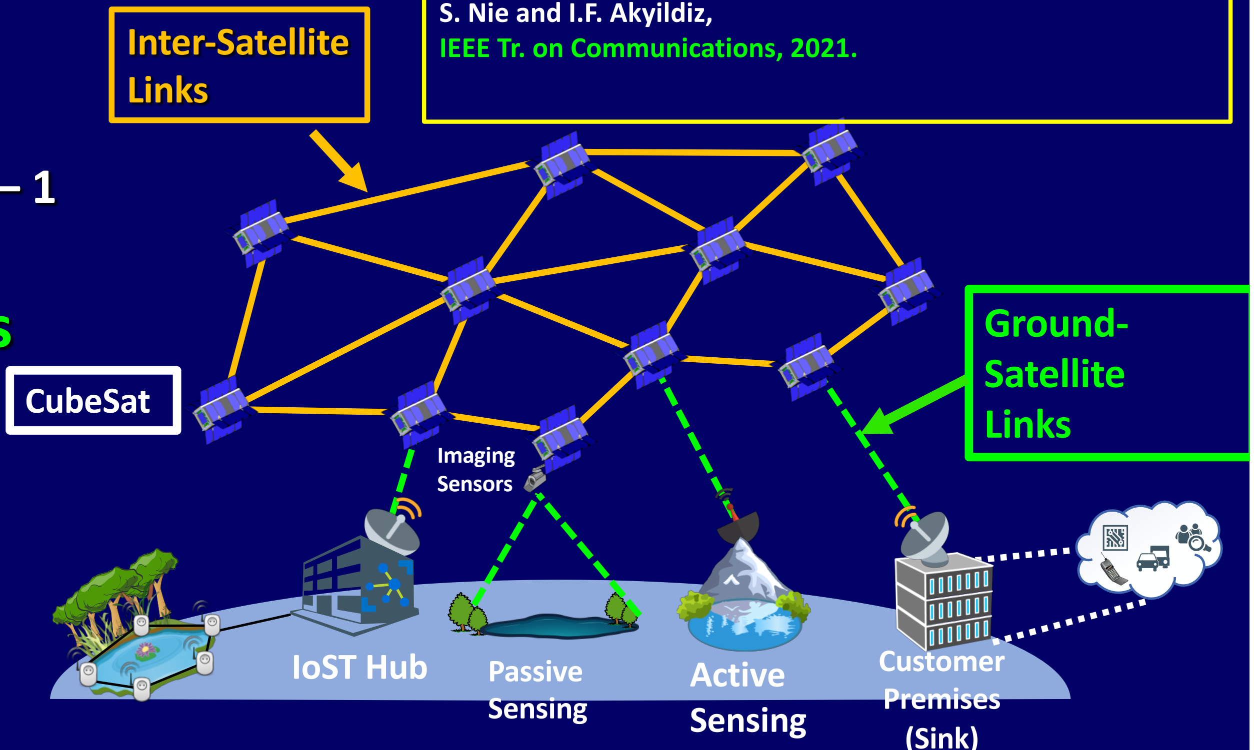
Channel Model and Analysis of Inter-Small-Satellite Links in THz Band Space Networks
S. Nie and I.F. Akyildiz,
IEEE Tr. on Communications, 2021.

– Inter-Satellite Links

- Mm-wave (30 – 300 GHz)
- THz Frequency Band (0.3 – 1 THz)

– Ground-Satellite Links

- L-band (1–2 GHz)
- S-band (2–4 GHz)
- C-band (4–8 GHz)
- X-band (8–12 GHz)
- K_u-band (12–18 GHz)
- K_a-band (26.5–40 GHz)
- Mm-wave (30 – 300 GHz)
- THz frequency band (0.3 – 1 THz)



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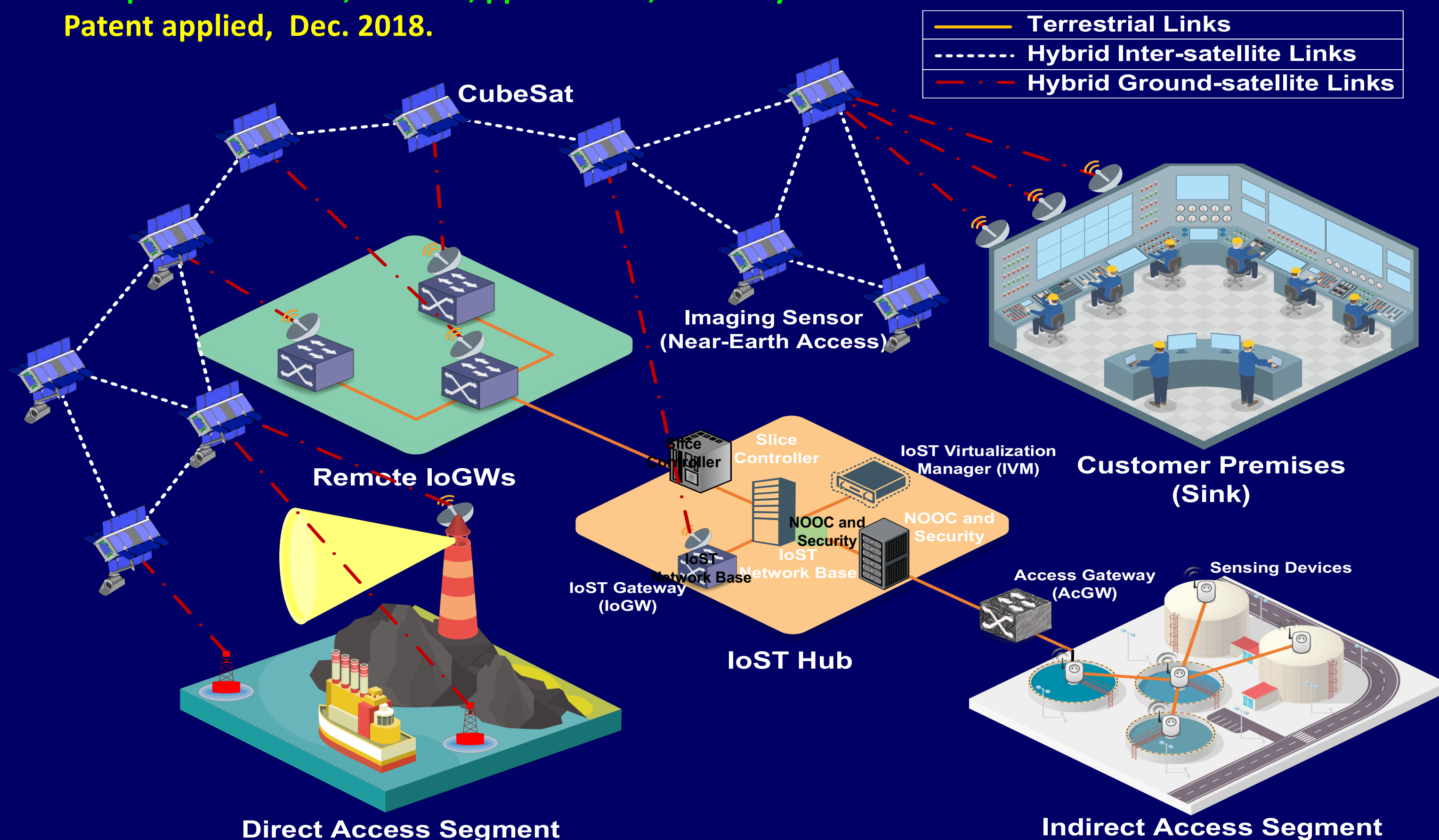
SDN AND NFV-BASED SYSTEM ARCHITECTURE

I. F. Akyildiz and A. Kak,

"The Internet of Space Things/CubeSats: A ubiquitous cyber-physical system for the connected world",

Computer Networks, vol. 150, pp. 134-149, February 2019.

Patent applied, Dec. 2018.



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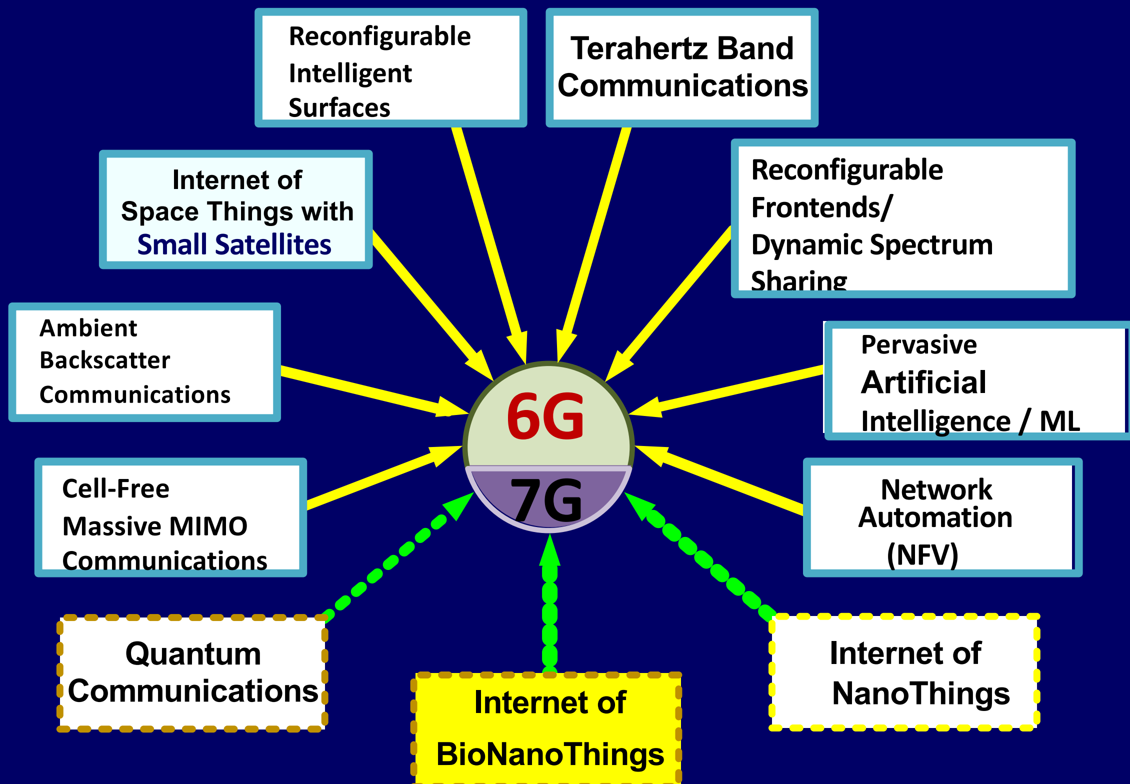
IEEE ACCESS JOURNAL, VOL. 8, PP. 133995-134030, JULY 2020.



REFERENCES

- I.F. Akyildiz, M. Pierobon, S. Balasubramaniam, Y. Koucheryavy,
  "The Internet of Bio-NanoThings",
  IEEE Communications Magazine, March 2015.

- I. F. Akyildiz, M. Ghovanloo, U. Guler, T. Ozkaya-Ahmedov, P. Rather, F. Sarioglu, B. Unluturk,
  "PANACEA: An Internet of Bio-NanoThings Application for Early Detection and Mitigation of Infectious Diseases",
  IEEE Access, July 2020.

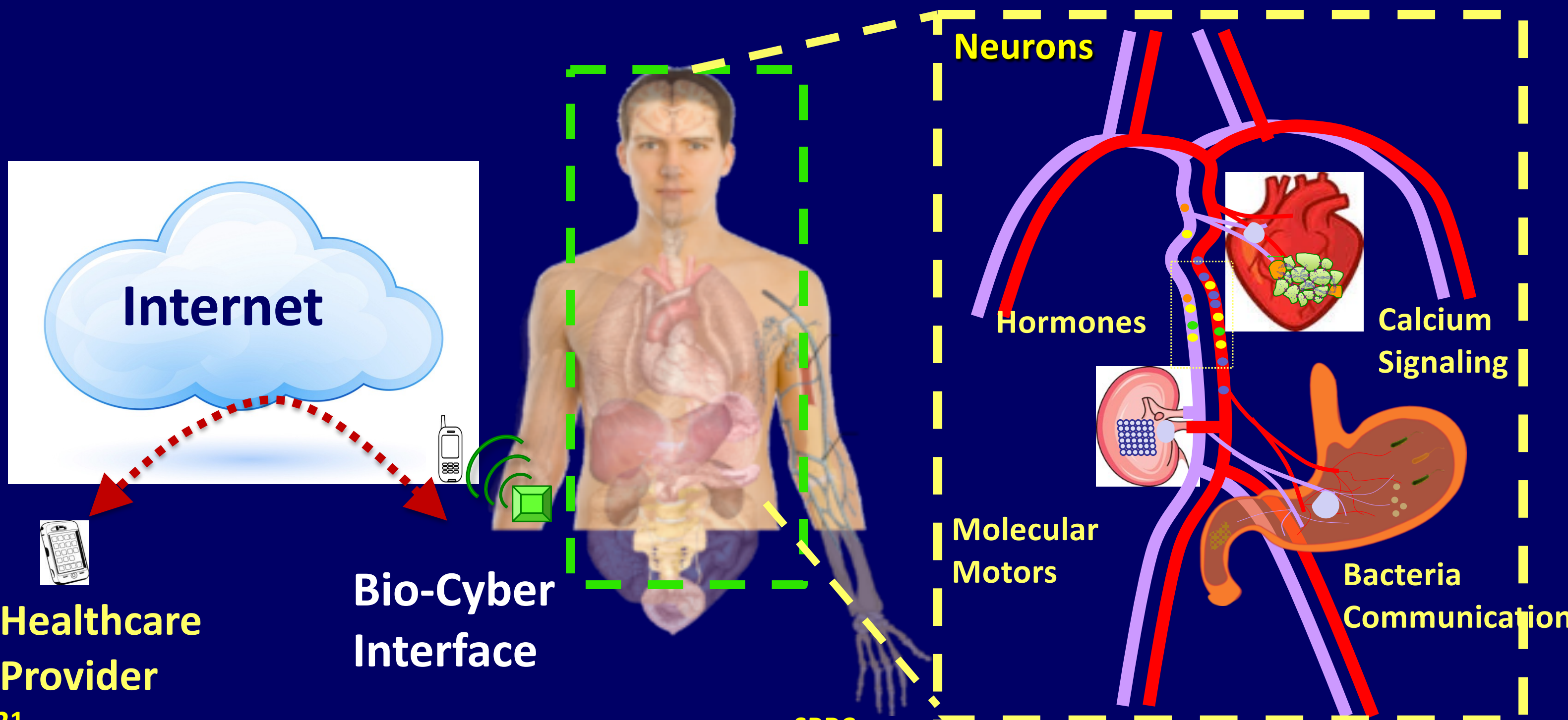
- I. F. Akyildiz, M. Pierobon, S. Balasubramaniam,
  "Moving Forward with Molecular Communication: from Theory to Human Health Applications",
  Proceedings of IEEE, Point of View paper, May 2019.

INTERNET OF BIO-NANOTHINGS:

I.F. AKYILDIZ, M. PIEROBON, S. BALASUBRAMANIAM, Y. KOUCHERYAVY,
"THE INTERNET OF BIO-NANOTHINGS",
IEEE COMMUNICATIONS MAGAZINE, VOL. 53, NO. 3, PP. 32-40,MARCH 2015

Objective:

To interconnect the heterogeneous Bio-NanoThing Networks to the Internet



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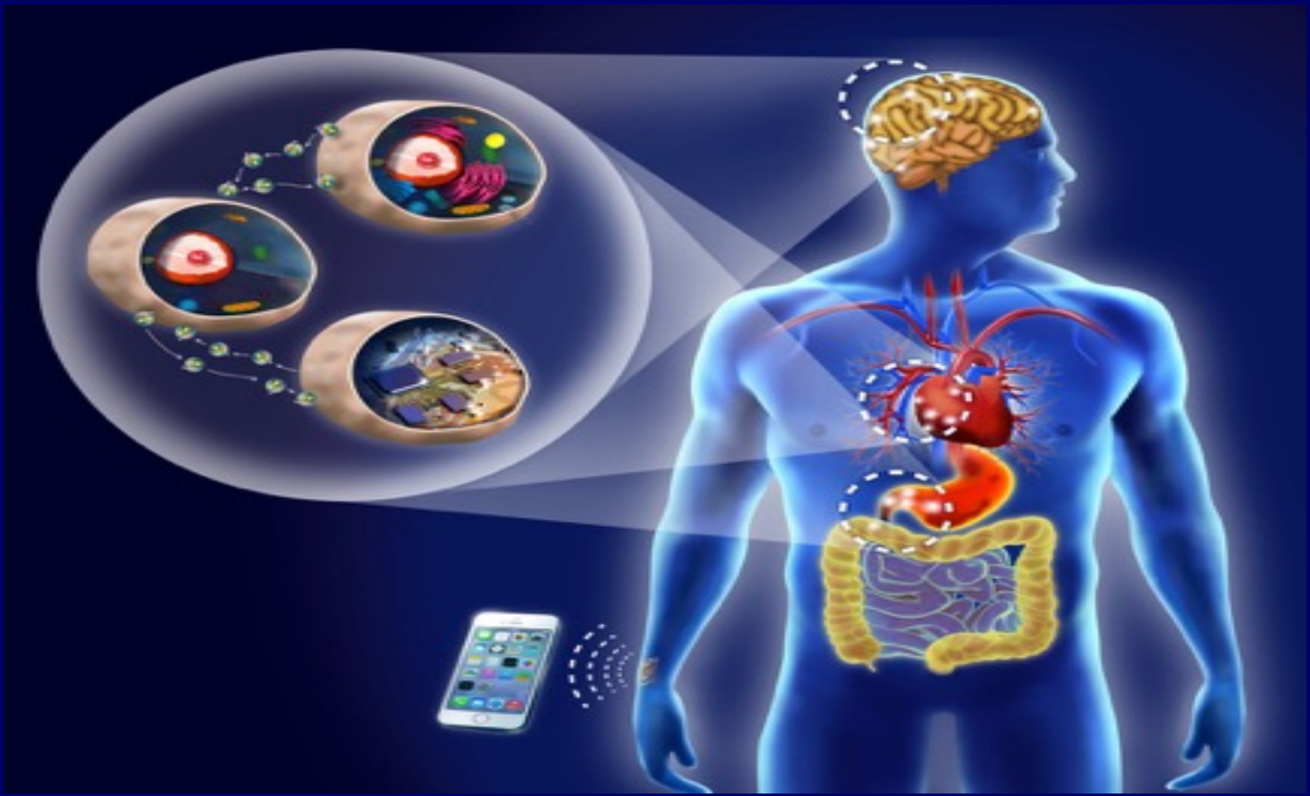
Internet of Bio-NanoThings:
Network Architecture



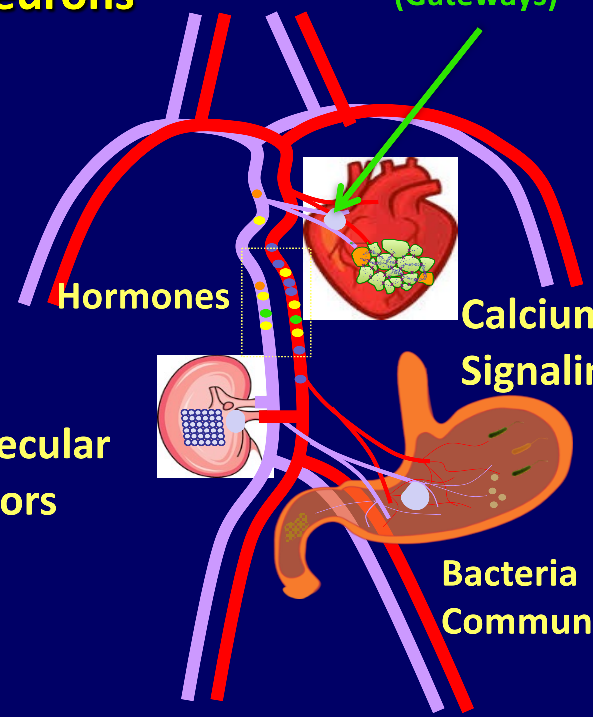
HETEROGENEOUS BIO-NANOTHINGS NETWORK

Challenge

- Translating information between the different Bio-NanoThings networks.

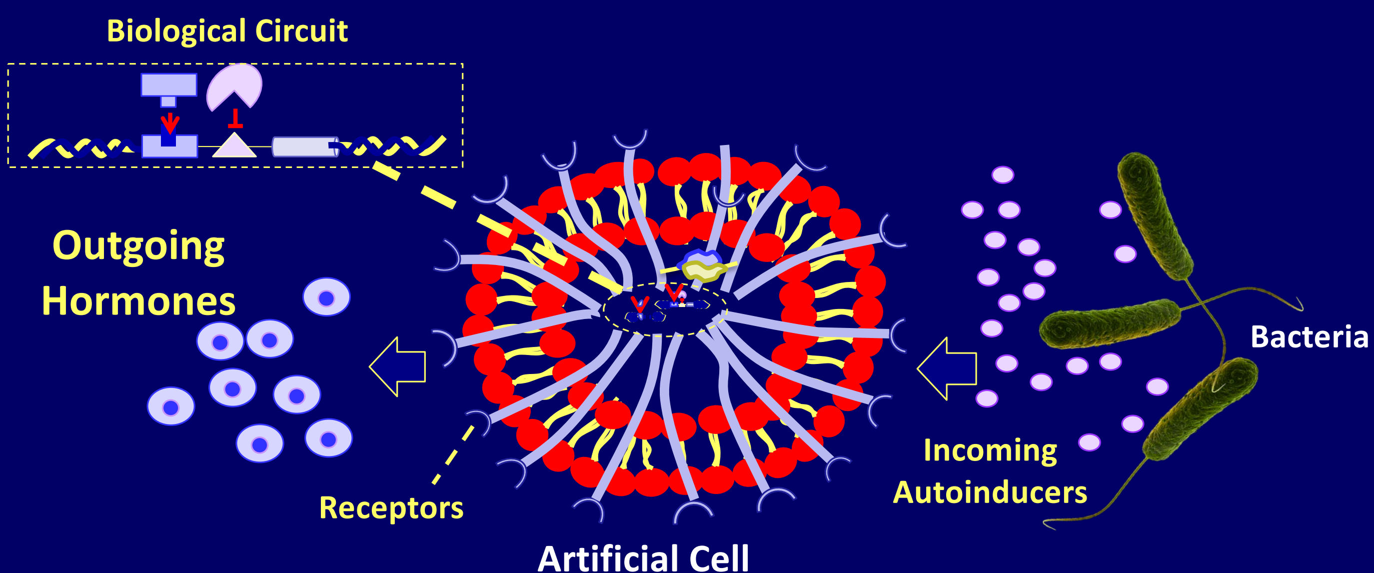
Approach

- Design Artificial Cells (GATEWAYS) for translating between different molecule types.



ARTIFICIAL CELLS AS GATEWAYS

- Receptors intercept the incoming molecules (e.g.,autoinducers from bacteria).
- Activates Biological Circuit to synthesize outgoing molecules (e.g., hormones)



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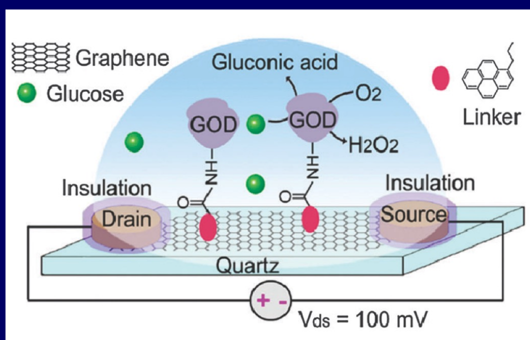
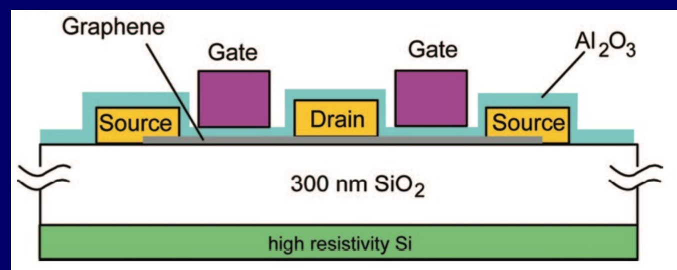
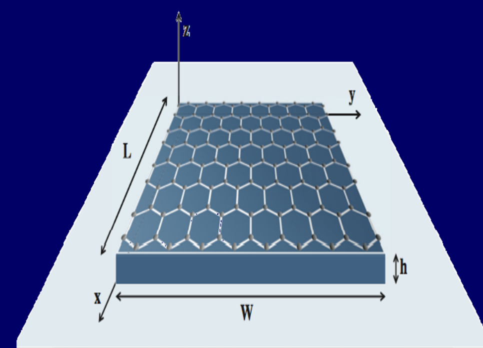
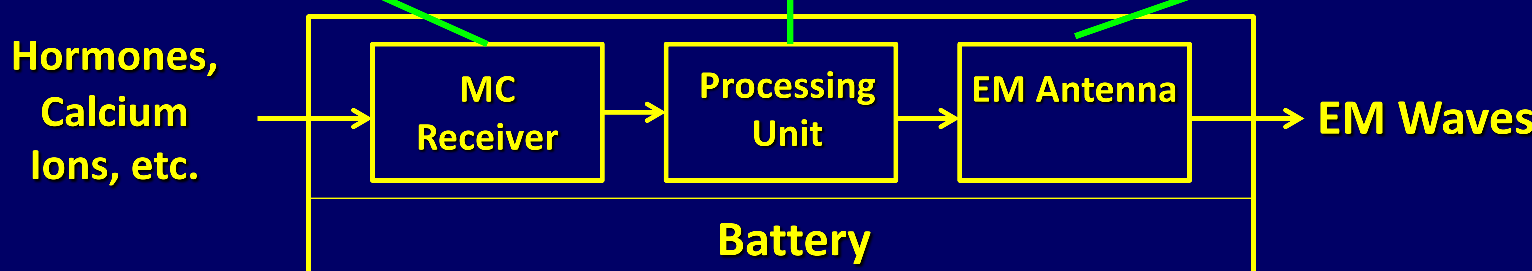
BIO-CYBER INTERFACE:
EM NANOMACHINE GATEWAYS WITH GRAPHENE

- Graphene-based sensors for biological detection of MC signals
- Graphene-based transistors for information processing
- Graphene–based plasmonic nano-antenna









FURTHER CHALLENGES

I. F. Akyildiz, M. Pierobon, and S. Balasubramaniam,
"Moving Forward With Molecular Communication: From Theory to Human Health Applications,"
Proceedings of the IEEE, vol. 107, no. 5, pp. 858 - 865, May 2019.

Interconnecting IoBNT to IoNT to IoT

* Interconnection will:
  – Escalate "Big Data" to a new level.
  – Require new services to semantically map data from IoBNT and IoNT to IoT.
  – Require new service discovery required to search deep into the biological environment to collect information.

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PANACEA: IoBNT for Early Detection of Infections

I. F. Akyildiz, M. Ghovanloo, U. Guler, T. Ozkaya-Ahmedov, P. Rather, F. Sarioglu, B. Unluturk,
"PANACEA: An Internet of Bio-NanoThings Application for Early Detection and Mitigation of Infectious Diseases",
IEEE Access, July 2020.

- **Problem: Early Detection of Infections critical for patients**
  - Cancer: Chemo patients are very vulnerable to serious bacterial infections
  - Cystic Fibrosis: Infections come wave by wave especially for young children

- **Solution: Project PANACEA**

Continuous monitoring of bacterial infections with IoBNT

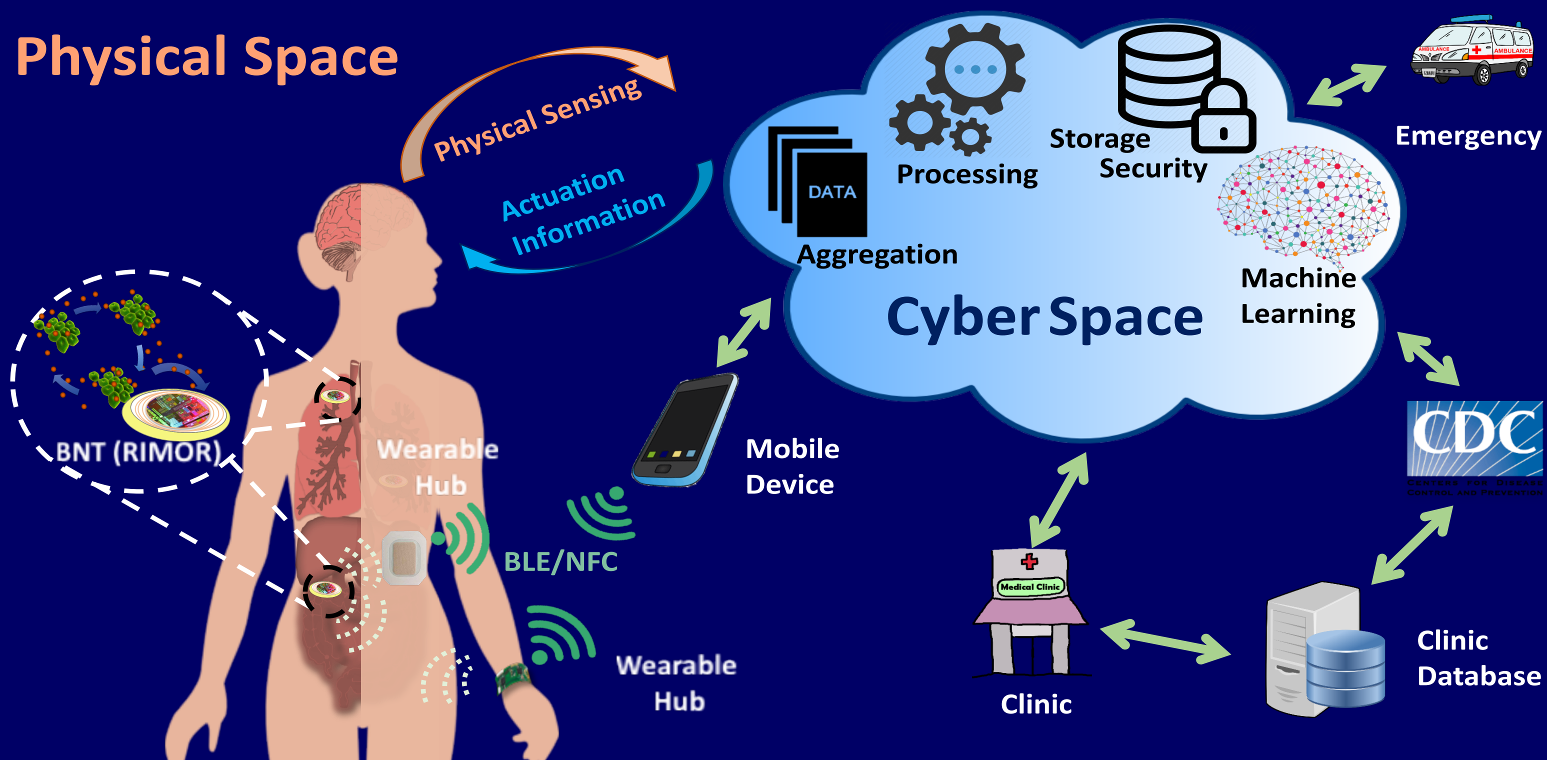
- Early detection of infections
- Timely administration of antibiotics
- Tracking efficiency of antibiotics

}

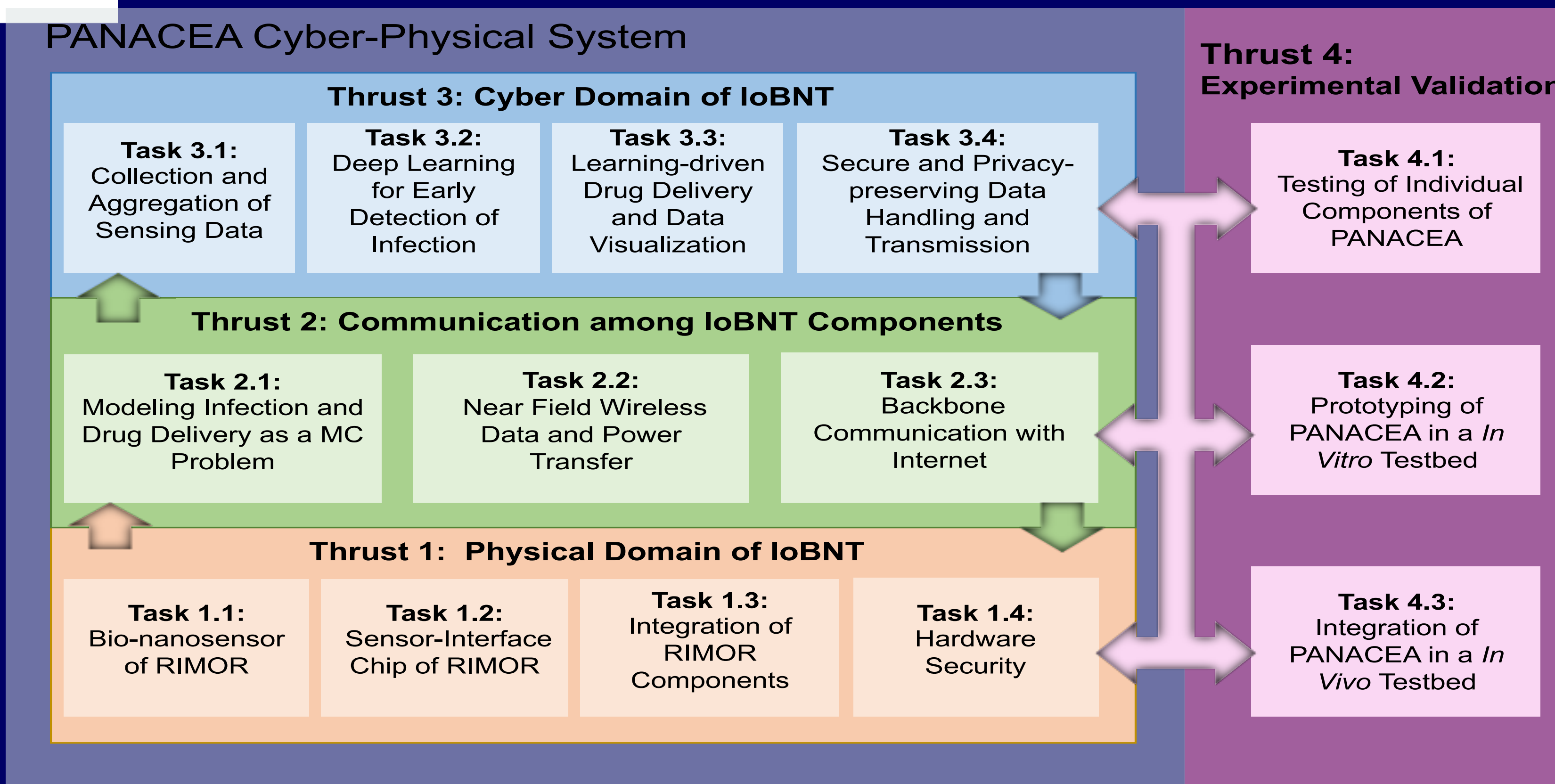
Reducing mortality and hospital costs !

PANACEA: ARCHITECTURE

- Approach: Develop and integrate a novel cyber-physical system



FRAMEWORK OF THE PROJECT



CONCLUSION

- 6G is under development right now and will be commercialized in the coming decade
- Wireless communication networks will experience great revolution in 6G
  - Especially on the PHY with Intelligent Communication Environments and pervasive AI
- The 12 key enabling technologies will make 6G become reality
  - Many open challenges need to be addressed