WIRELESS COMMUNICATION SYSTEMS IN THE NEXT DECADE

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EVOLUTION OF CELLULAR SYSTEMS

1G

AMPS
TACS
NMT

1980s

Analog

Different for each country

2.8 kbps – 56 kbps

2G

2.0G 2.5G 2.75G

GSM
cdmaOne
GPRS
EDGE

1990s

Digital

TDMA-based

First data services

15 kbps - 400 kbps

(Narrowband)

3G

3.0G 3.5G 3.9G

UMTS
HSPA
cdma2000
EV-DO
HSPA+

2000s LTE

CDMA-based

(LTE: OFDMA-based)

* Introduction of MIMO
* Mobile Internet – Application Explosion
* Range of Mbps

(Broadband)

4G

LTE-A
LTE-B
LTE-C

2010s

All OFDMA-based

Novel enabling technologies

Range of Gbps

(Mobile Broadband)

xDSL like experience

5G

2020 2030

New Waveforms

mm-Wave access & backhaul

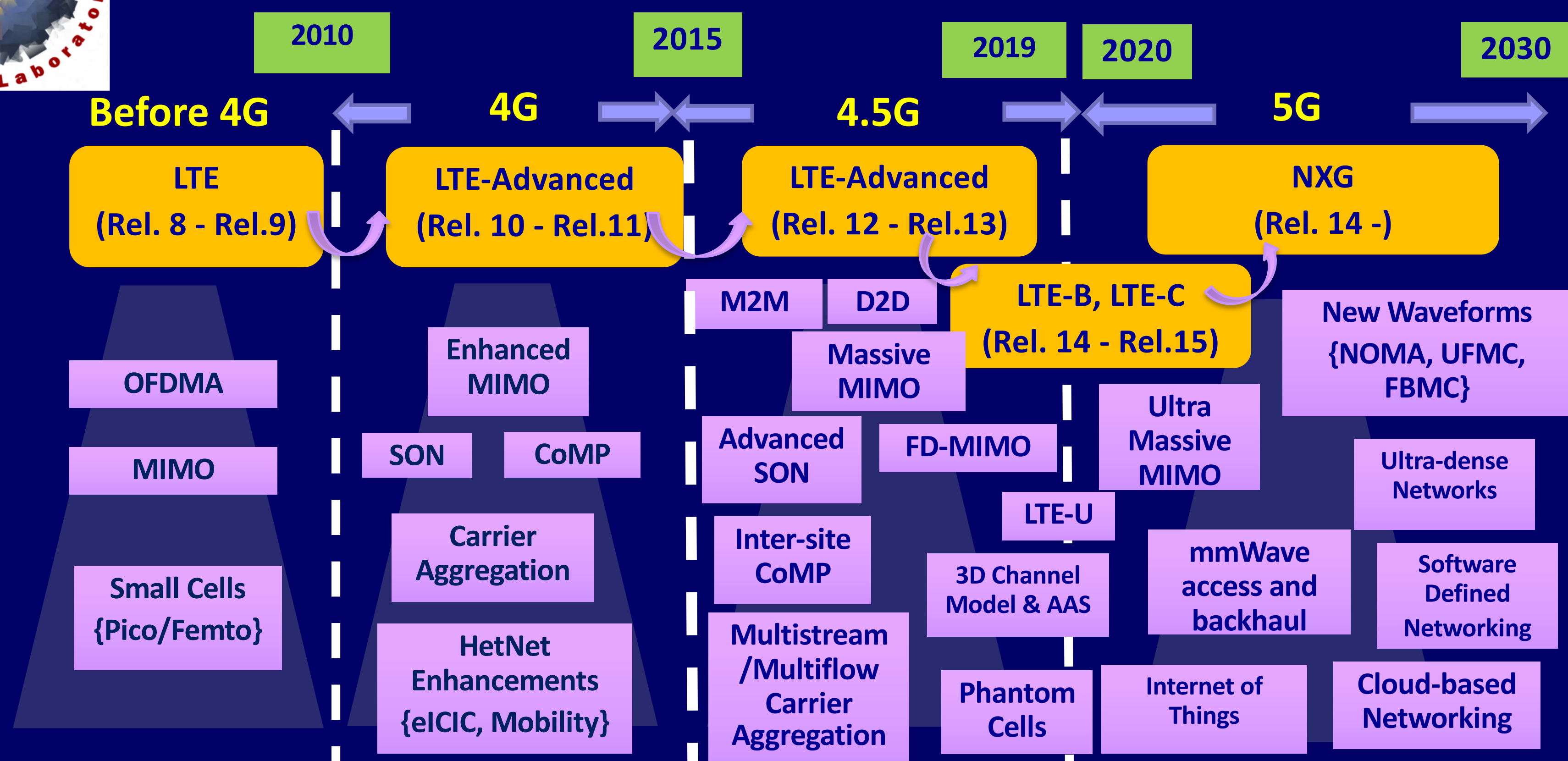
Ultra-dense small cells

Range of tens of Gbps

(Ubiquitous Connectivity)

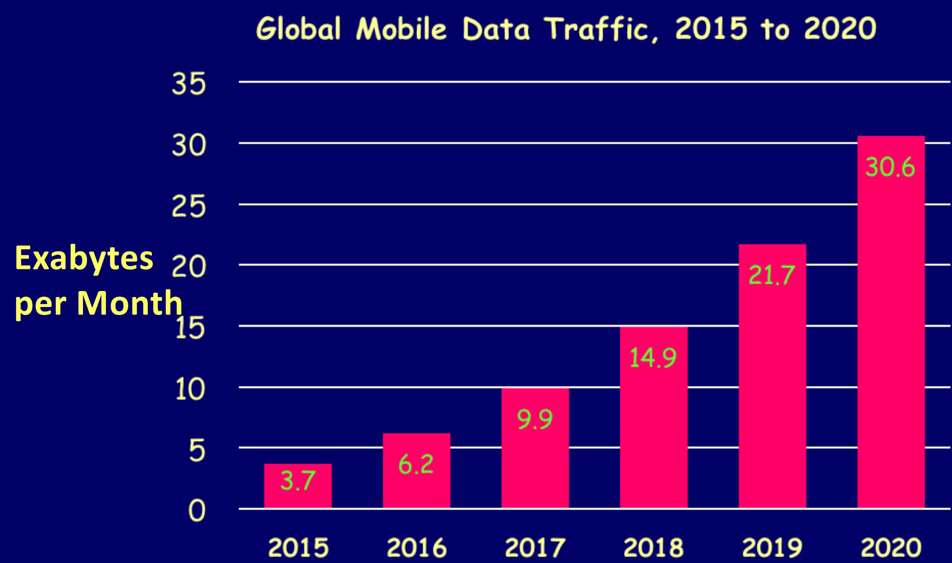
Fiber like experience

DEVELOPMENT OF MAJOR ENABLING TECHNOLOGIES



R&D on enabling technologies start within a certain Release but keep evolving during following Releases of the standard!!!

EVOLUTION OF WIRELESS SYSTEMS



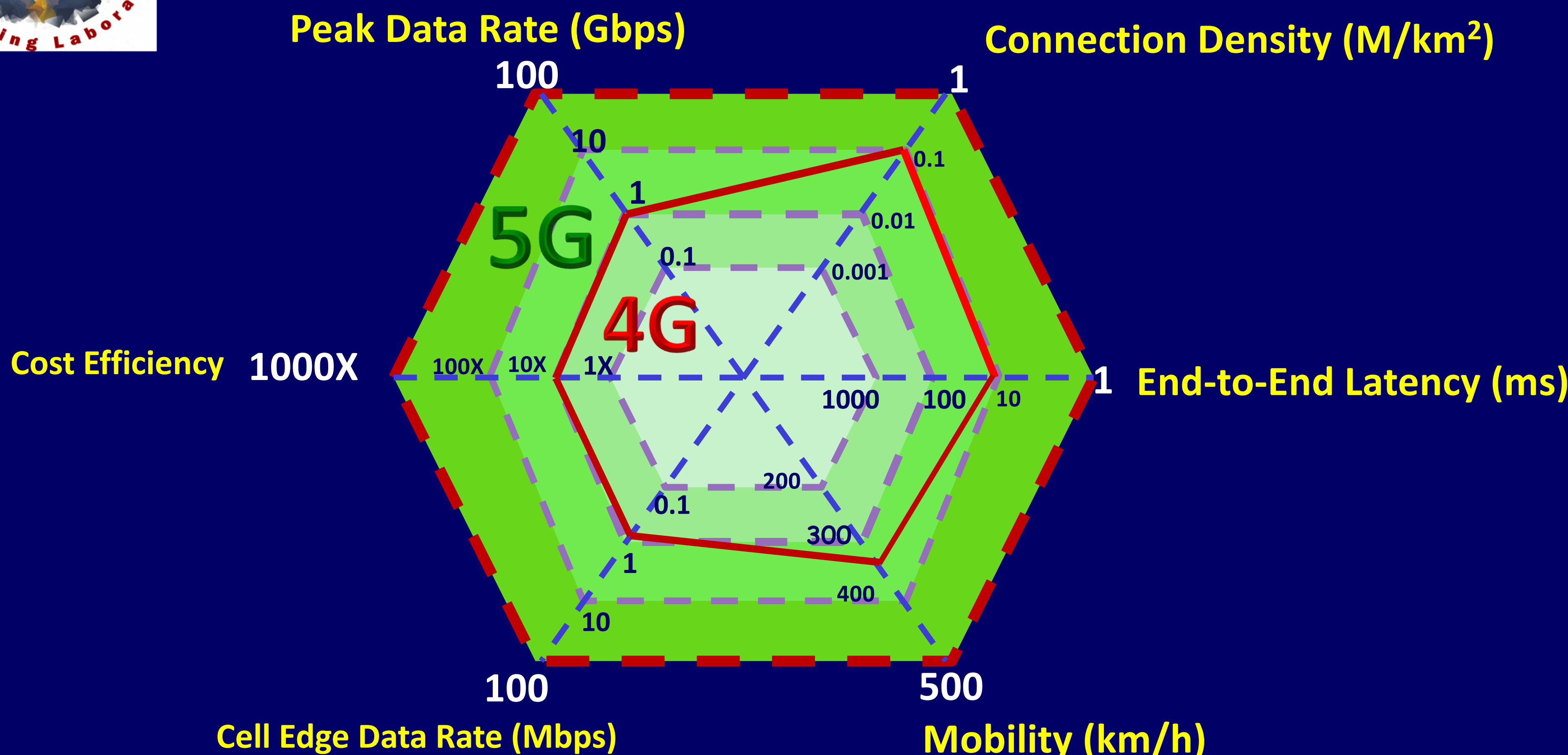
CISCO, "Cisco Visual Networking Index: Mobile Data Traffic Forecast Update, 2015-2020," 2016

1 Exabyte = 10^{18} Bytes

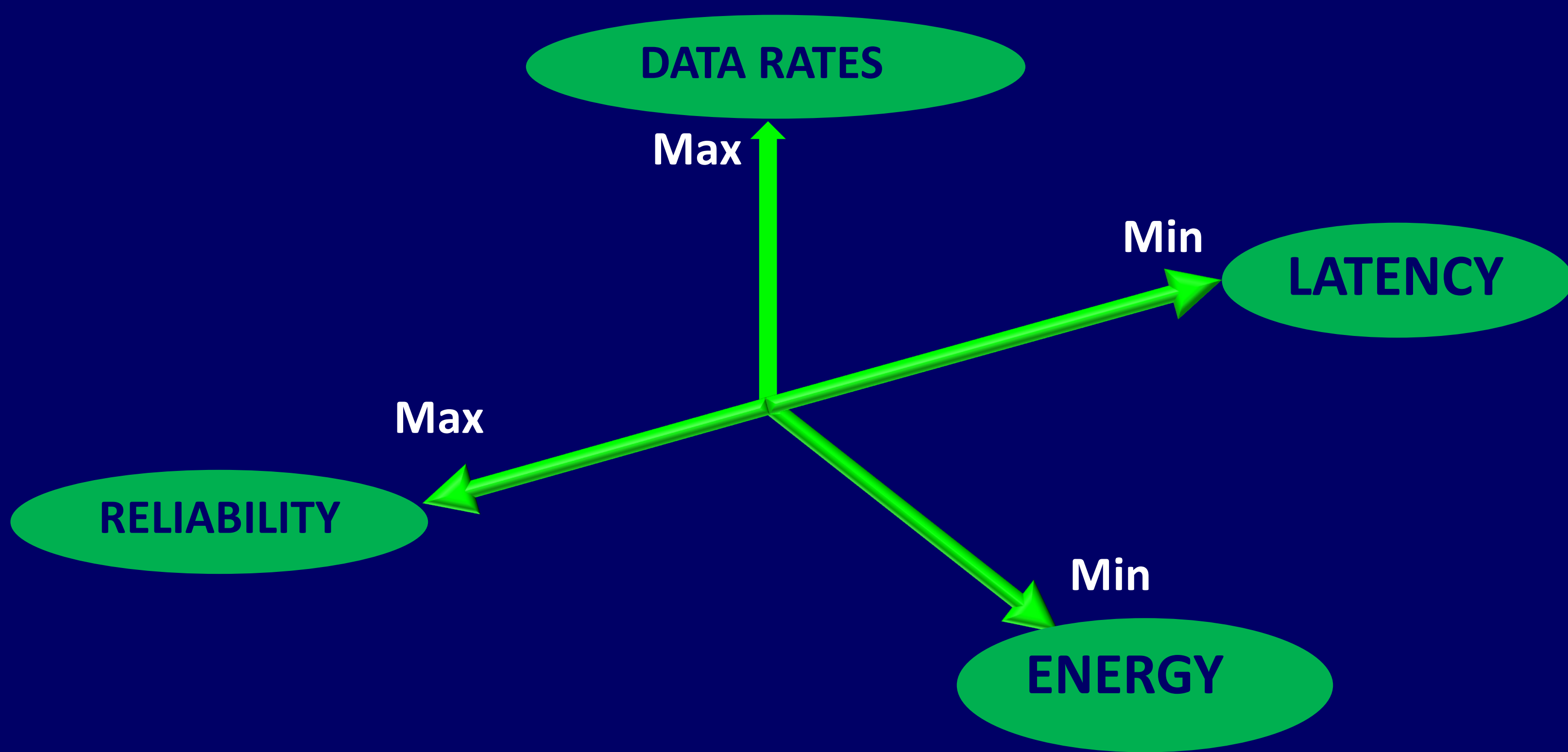
Pictures taken at St. Peter's Square for papal inauguration ceremonies of Pope Benedict (2005) and Pope Francis (2013)

Mobile World Congress in Barcelona, 2016

EVOLUTION FROM 4G TO 5G

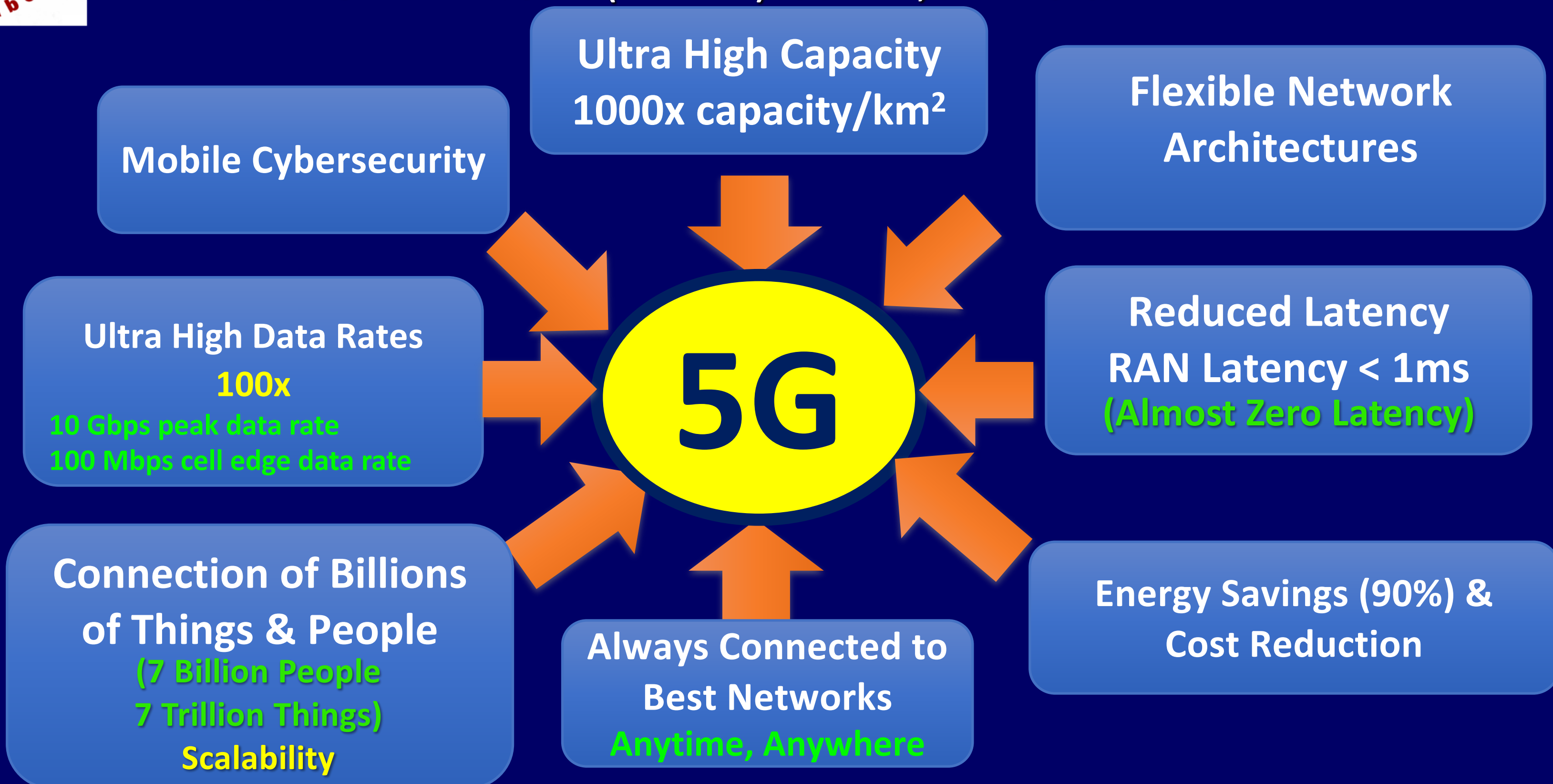


5G PERFORMANCE OBJECTIVES

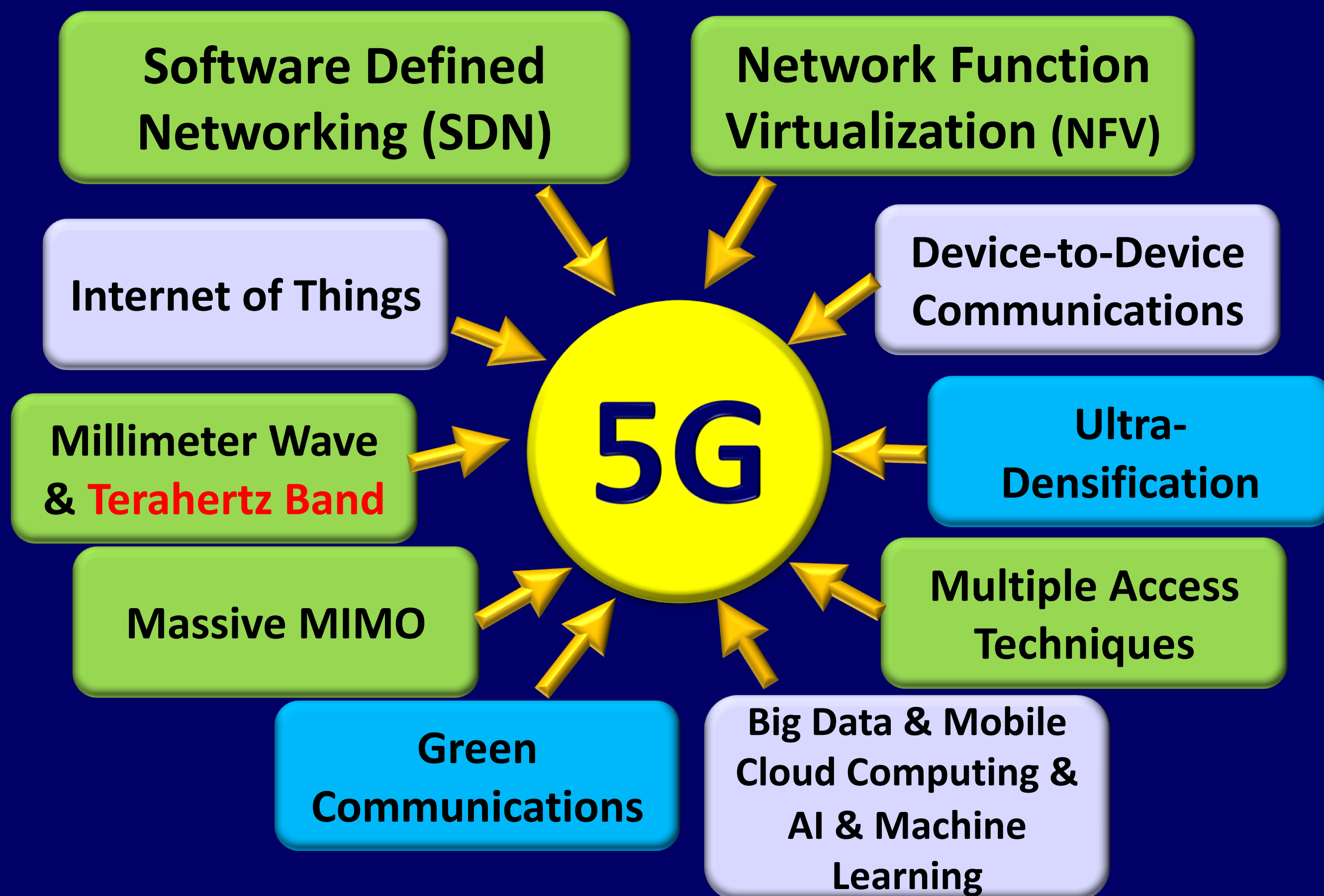


OBJECTIVES OF 5G WIRELESS SYSTEMS

I. F. AKYILDIZ, S. NIE, S. C. LIN, AND M. CHANDRASEKARAN,
"5G ROADMAP: 10 KEY ENABLING TECHNOLOGIES,"
COMPUTER NETWORKS (ELSEVIER) JOURNAL, SEPT. 2016.

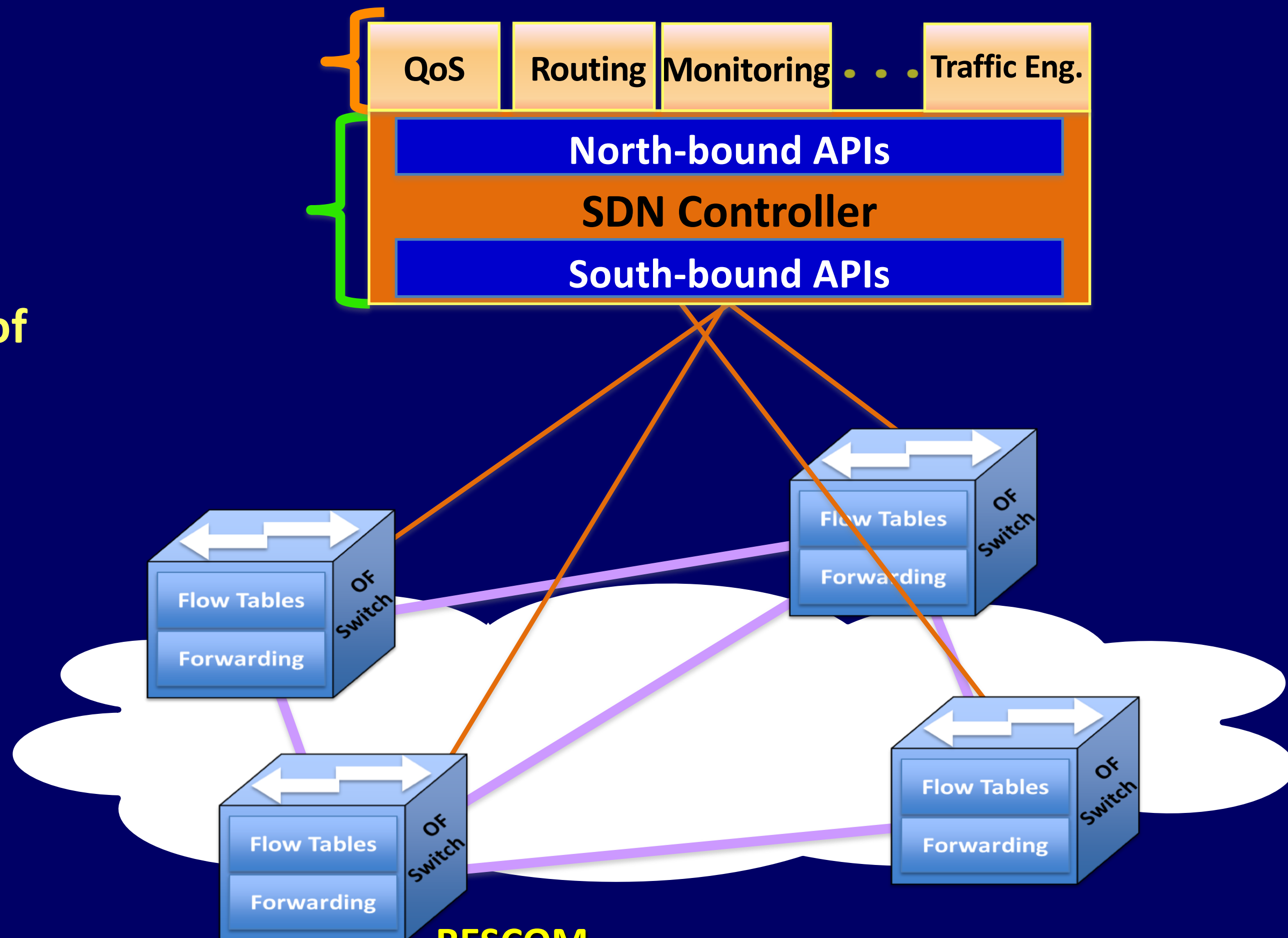


10 KEY ENABLING TECHNOLOGIES FOR 5G



KEYTECH 1: WIRELESS SOFTWARE DEFINED NETWORKING (W-SDN)

* Open Architecture
* Allow Innovation
* Avoidance of Myriad of Heterogenous Software Protocols



SOFTAIR PROJECT (NSF: 2015-2018; HUAWEI HQ: 2012-2016)

I. F. Akyildiz, P. Wang, and S. C. Lin,
"SoftAir: A Software Defined Networking Architecture for 5G Wireless Systems"
Computer Networks (Elsevier) Journal, July 2015.

SoftAir Architecture

1. Scalable Design for SD-RAN & SD-CN (Scalable Cloudification)
2. Network Function Virtualization (NFV)

SoftAir Management Tools

1. Control Traffic Management
2. Network Virtualization
   * Network Hypervisor
   * Wireless Hypervisor
   * Switch Hypervisor
3. Traffic Classifier

SoftAir Traffic Engineering Solutions

1. Dynamic RRH Formation
2. Collaborative Scheduling
3. Mobility Management

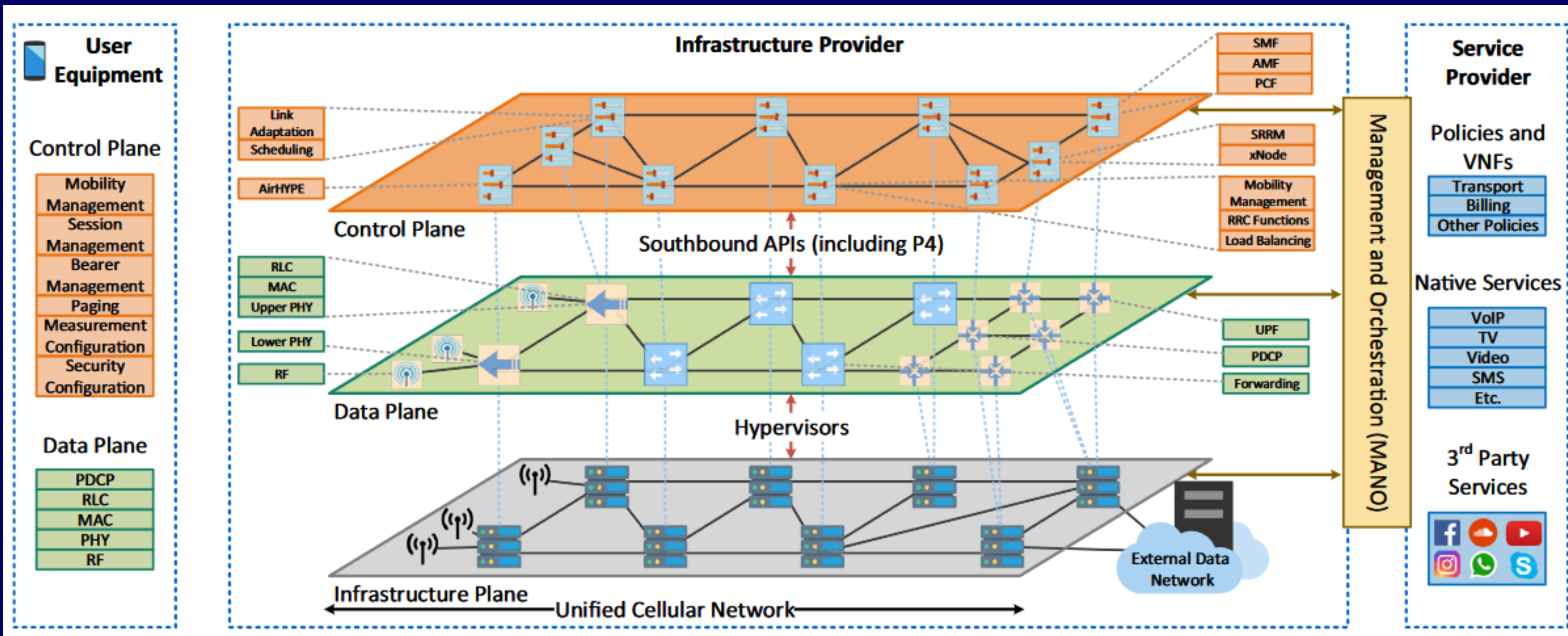
REVIEW OF 2ND GENERATION W-SDN ARCHITECTURES

ARCHITECTURE	CONTROL PLANE	DATA PLANE	SCALABILITY	ADAPTABILITY	MODULARITY	FRONT-HAUL	MEC/CACHE
NGMN (Vodafone, Ericsson, Orange..)	Dynamic Distributed	CU/DU	High	High	NA	Not Addressed	Yes
METIS – II (Nokia-Bell Labs, Ericsson, Huawei, Orange, Samsung et al.)	Dynamic Distributed	CU/DU	High	High	High	Not Addressed	Yes
NORMA (Nokia, NEC, Atos, Nomor et al.)	Dynamic Centralized	CU/DU	Limited	Yes	High	Not Addressed	Yes
X-HAUL (I2CAT/UPC, Huawei, Cosmote, Airrays)	Static Distributed	Transport Node	Architecture Based	Limited	NA	Multiple Functional Splits	Yes
ONF (O-RAN/xRAN +ProgRAN)	Dynamic Distributed	CU/DU + eNB	High	Limited	High	Single Functional Split	NA
TIP vRAN Telecom Infrastructure Project (Facebook)	NFV Only Solution (No SDN)	NFV Only Solution (No SDN)	Limited	Limited	Limited	Multiple PHY Functional Splits	NA
ARBAT (RAS-IITP)	Dynamic Distributed	UND	High	High	High	Multiple Functional Splits	Yes

ARBAT: A Flexible Software Architecture for QoE-Aware Communication in 5G Systems,

I.F. Akyildiz, A. Kak, E. Khorov, A. Krasilov, A. Kureev,

Computer Networks (Elsevier) Journal, Dec. 2018.



MEGA-GRANT PROJECT AT IITP-RAS (2018-2023)

ARBAT Architecture → **ARBAT Management Tools** → **ARBAT Multi RAT Operations** → **NEW RADIO**

ARBAT Architecture

1. Universal Network Device
2. Unified Cellular Network
3. xSTREAM Platform
4. Multi-layer RRM Framework
5. ServiceBRIDGE Orchestration

ARBAT Management Tools

1. Control Traffic Management
2. Diverse Hypervisors
3. Multidimensional Slicing Framework
4. Traffic Classifier

ARBAT Multi RAT Operations

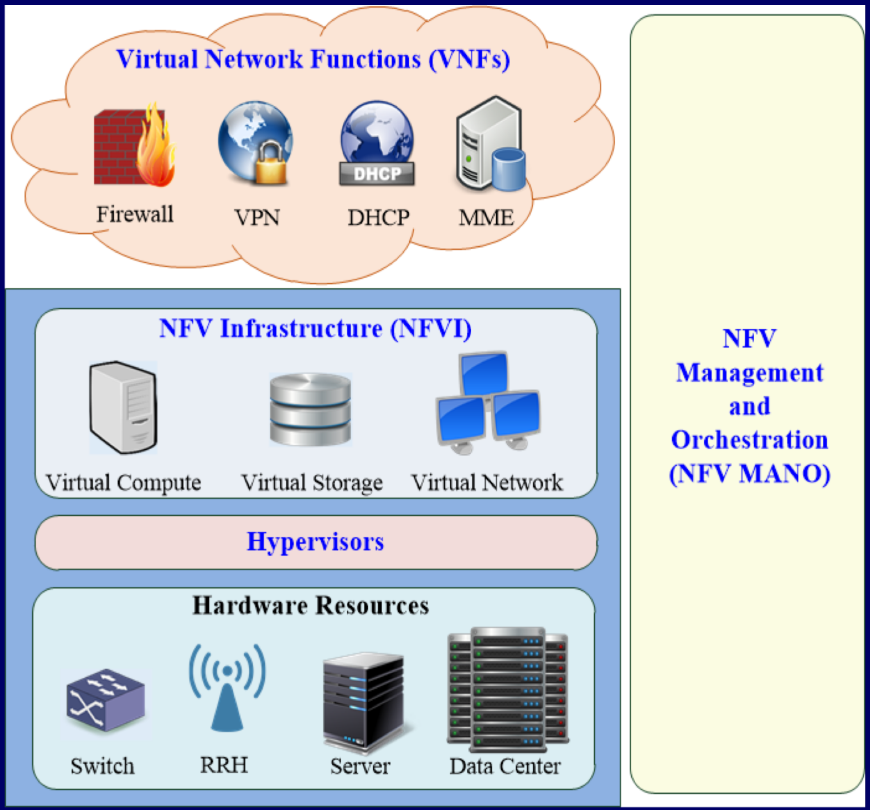
1. RRM in MULTI RAT
2. RRM Coordinated MP Transmission
3. Orchestration of BSs in License exempt Bands
4. Coexistence & Cooperation of different RATs working in license exempt bands
5. Multi-technology RANs

NEW RADIO

1. mm waves
2. URLLC
3. TeraHertz

KEYTECH 2: NETWORK FUNCTION VIRTUALIZATION (NFV). (SLICING)

- Decouple network functions (SW) and physical devices (HW) running them
- Advantages
  - OPEX and CAPEX → reduced
  - Easy deployment of new services
- Key Contributions
  - Decoupling Software from Hardware
  - Elastic NF Deployment
  - Fine-grained Dynamic Scaling

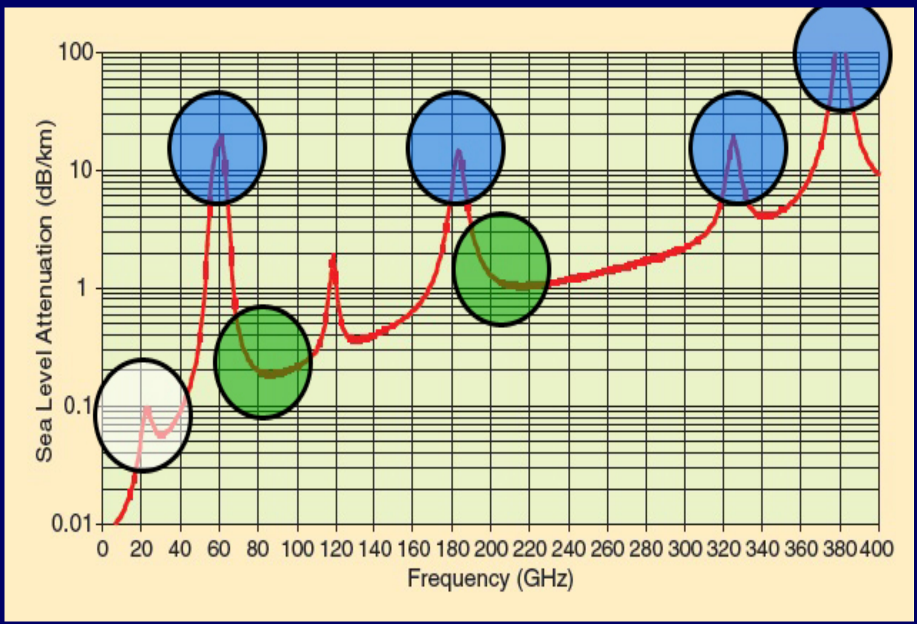


Architecture of NFV

KEYTECH 3: MM-WAVE COMMUNICATIONS

- Frequency spans between 30~300 GHz
- Potential candidate to enable 100-fold data rate increase
- FCC proposed spectrum usage in 2015
  - 28 GHz and 39 GHz for small cells
  - 64~71 GHz for indoor deployment

FACTS ABOUT MM-WAVE ATMOSPHERIC ATTENUATION



- **White**
  - Very low air attenuation at 28 and 38 GHz
- **Blue**
  - High Attenuation at 60 GHz
    - Ultra-short-range indoor communications
- **Green**
  - Low atmospheric attenuation
  - Multi-GHz Bandwidth
  - Directional Antenna Arrays with beamsteering and beam-combining

FACTS ABOUT MM-WAVE PROPAGATION LIMITATIONS

- mm-Wave has high spreading loss and path loss
  - Path-loss increases with the square of the frequency
  - Need to use high-gain directional antennas or antenna arrays for distances above a few meters
- NLOS (very high path losses) and distance limited
  - mm-wave cannot propagate through wall, objects or people
  - Possible solution is using relays to redirect propagation paths → high cost and energy consumption

MM-WAVE COMMUNICATIONS: OPEN PROBLEMS

- **3D Channel Modeling**
  - Lack of uniform 3D channel model
- **Dynamic Power Control Algorithm**
  - Channel condition varies largely
  - Signal strengths drop 15~40 dB from LOS to NLOS
- **User Scheduling and Congestion Control**
  - Multiple users in the same cell
  - Collision avoidance

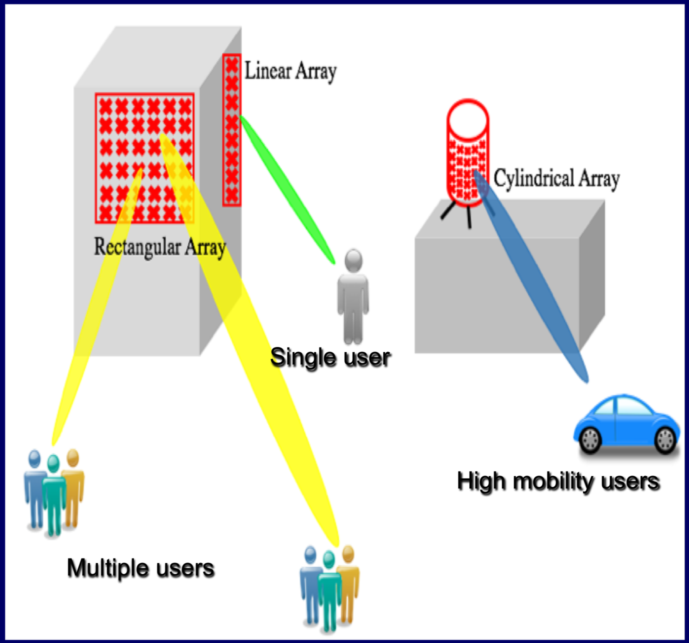
MM-WAVE COMMUNICATIONS: OPEN PROBLEMS

- Gbps Rates (several meters but LOS)
  - Mature mm-wave systems are only able to support few Gbps over several meters with LOS
  - For example, IEEE 802.11 ad (60 GHz): 7 Gbps with 512-OFDM and 64-QAM
- Hardware Limitations
  - mm-Wave transceiver design and mass production
  - High infrastructure costs
- Mobile mm-wave Systems
- Bandwidth Limitation

  (only 7 GHz of BW around 60 GHz systems)

KEYTECH 4: MASSIVE MIMO

- Also known as “Large-Scale Antenna Systems”, “Very Large MIMO”, “Hyper MIMO”
- Large arrays of antennas at BS to overcome path loss
  - Tens/Hundreds of antenna elements at BS
  - Traditional MIMO in LTE-A uses max 64x64
- Three types of antenna array configurations
  - Linear array
  - Rectangular array
  - Cylindrical array
- Can serve single user, multiple users, and high mobility users



Three types of antenna array configurations in massive MIMO

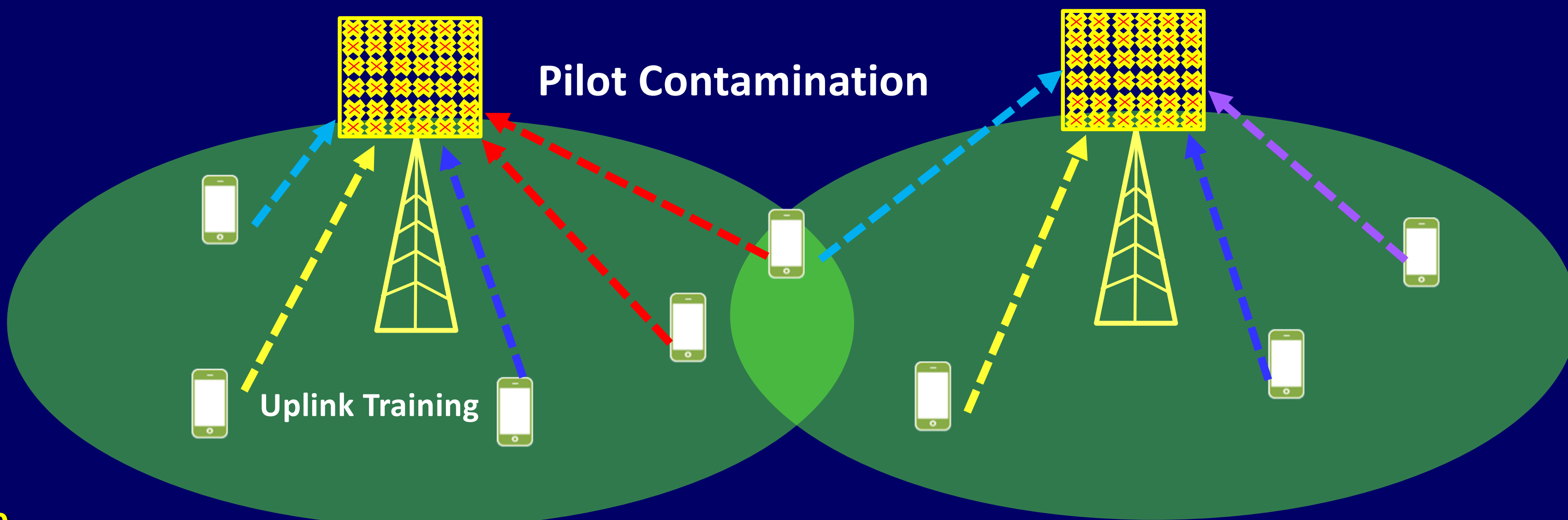
ADVANTAGES OF MASSIVE MIMO

- **Increased Transmission Distance**
  - High antenna array gain compensates path loss
- **Increased Spectral Efficiency**
  - High spatial usage from spatial multiplexing and beamforming
- **Reduced Latency**
- **Scalable Air Interface**

KEYTECH 4: MASSIVE MIMO: OPEN PROBLEMS

- Pilot Contamination Problem
  - Occurs in pilot training stage
  - Caused by the reuse of pilot sequences of co-channel cells

- Cause severe performance degradation



KEYTECH 4: MASSIVE MIMO: OPEN PROBLEMS

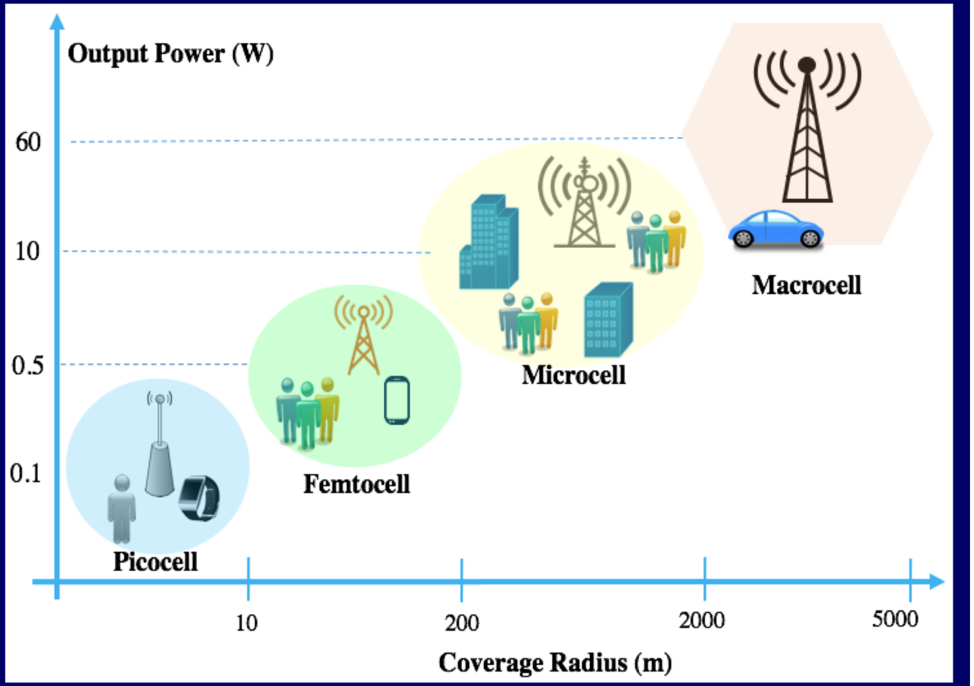
- **Derivation of Accurate 3D Channel Models**
  - Near-field and far-field problem
- **Design of Very Large Antenna Arrays**
  - Analog, digital, and hybrid architectures proposed
- **Cooperation Mechanisms**
  - Distributed massive MIMO
  - Maximum ratio combining (MRC) algorithm

KEYTECH 4: MASSIVE MIMO: OPEN PROBLEMS

- **Channel Estimation**
- **Hardware Constraints**
  - Imperfection of hardware → channel estimation error
- **Energy Consumption of Signal Processing**
  - High energy for hundreds of RF chains, ADC/DAC,…

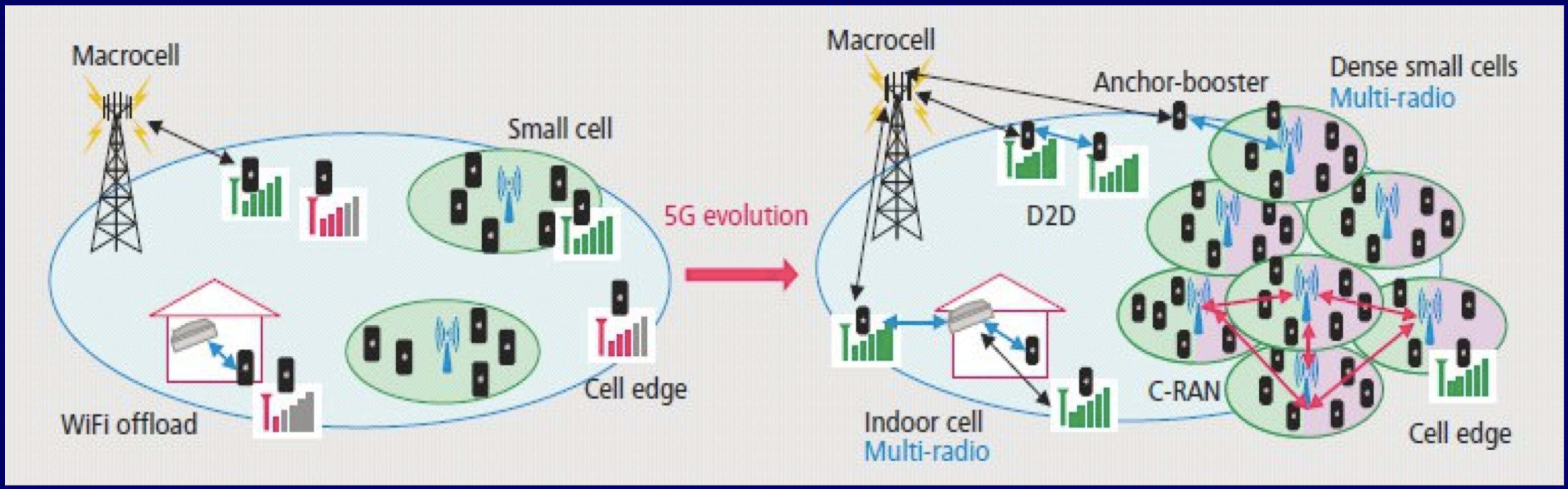
KEYTECH 5: ULTRA-DENSIFICATION (HETNETS)

- **Spatial Densification**
  - Femtocells and picocells
  - Small Cells → reduce load factor of macrocells
- **Spectral Aggregation**
  - To facilitate efficient use of fragmented spectrum
  - Spectrum sharing techniques
    → offer great flexibility



SPATIAL-DENSIFICATION

- **Heterogeneous Networks (HetNets) introduce**
  - Multiple layers of cells
  - Better coverage for edge users
- **UEs will be scheduled to the best cell available**



Evolution of HetNet Architecture

SMALL CELLS

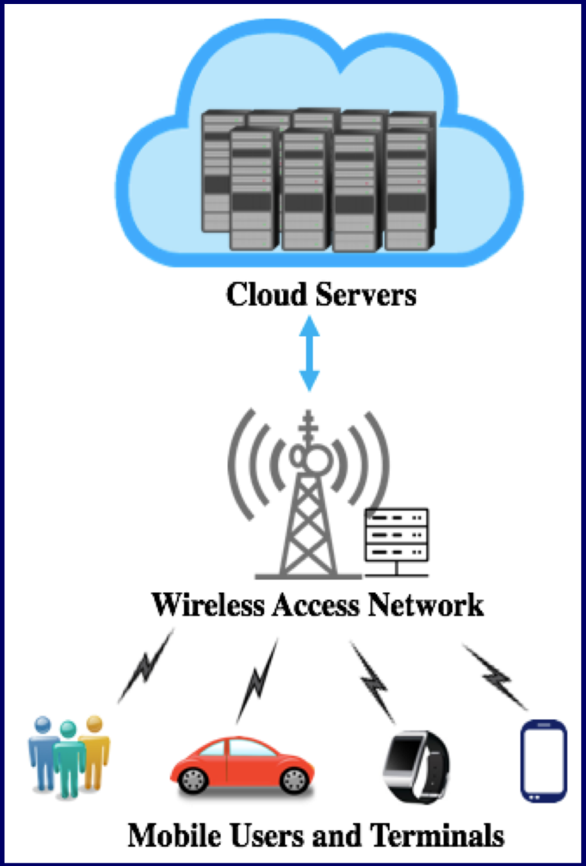
- Small Cells initially introduced in 4G LTE-A
- Low-powered radio access node with coverage of 1~2 km
- Three types
  – Microcell
  – Picocell
  – Femtocell (most commonly deployed in homes and small business)
- Challenges
  – Management issues
  – Pricing issue
  – Cost of small cell infrastructures

KEYTECH 5: ULTRA-DENSIFICATION: OPEN PROBLEMS

- Interference Management and Cancellation
  - Intra-layer and inter-layer interference
  - New algorithms for intercell interference coordination (ICIC) needed
- User Association Criteria
- New Handoff Algorithms needed
  - Same user can connect to multiple layers of cells, how to find the best connectivity?

KEYTECH 6: BIG DATA & AI/ML: BIG DATA AND MOBILE COMPUTING

- **Computation Offloading**
  - Allow remote servers to share computation load from local mobile device
  - Save local storage on device and battery life
- **Smart Data Management**
  - Useful for D2D links on small-size devices (e.g. smart watches)
  - Energy efficiency on intelligent data management



KEYTECH 6: BIG DATA & AI/ML: BIG DATA AND MOBILE COMPUTING

- **Big Data Analytics can be used for business support system**
  - Customer-related data
    - Network contract, location, service consumption, personal devices, etc.
  - Environmental context
    - Weather, news, etc.
  - Network operator-related data
    - Revenue, subscribers, etc.

KEYTECH 6: BIG DATA & AI/ML: BIG DATA AND MOBILE COMPUTING OPEN PROBLEMS

- **Limited network resources**
  - Regulations are needed for open access network
- **Security techniques**
  - Cloud data storage should be safely managed without being hacked
- **Data transmission delay in WAN (wide area network)**
  - Better routing algorithms are needed

KEYTECH 6: AI AND MACHINE LEARNING FOR WIRELESS

DATA CLASSIFICATION
- k-Nearest Neighbor
- Naïve Bayes
- Support Vector Machines

DATA REGRESSION
- Linear Regression
- Support Vector Regression

DATA CLASSIFICATION/ REGRESSION
- Classification and Regression Trees
- Random Forests
- Bagging

DATA CLUSTERING
- k-Means
- Density-Based Spatial Clustering of Applications with Noise

FEATURE EXTRACTION
* Principal Component Analysis
* Canonical Correlation Analysis

Data Regression/ Classification/ Clustering/ Feature Extraction
- Feed Forward Neural Network

Data Anomaly Detection
- One-class Support Vector Machines

KEYTECH 6: BIG DATA & AI/ML: AI AND MACHINE LEARNING OPEN ISSUES

- ML is just simple math
- ML is not programmed but taught with data
- ML output value is a function of the quality of the data you feed it
- You can have a neural network recognize faces, but you cannot ask it to describe any of the faces it knows.
- If you teach a ML system two skills, it cannot combine them to create a third skill.
- There is no autonomy in ML systems
- Reliability problem

- GRAND CHALLENGE: MAP BRAING FUNCTIONALITIES TO A NEW ML CONCEPT?

KEYTECH 7: INTERNET OF THINGS CHALLENGES

- Support massive number of devices (Scalability)
- Low power consumption
- Handling massive data storage and processing
- Signaling overhead if SDN/NFV used
- A Virus Shield for IoT (Grand Challenge)
- Standardization and Interoperability (Grand Challenge)

KEYTECH 7: OVERVIEW OF ML ALGORITHMS AND THEIR USE CASES IN IoT

Machine Learning Algorithm	IoT, Smart City Use Cases	Metric to Optimize
Classification	Smart Traffic	Traffic Prediction, Increase Data Abbreviation
Clustering	Smart Traffic, Smart Health	Traffic Prediction, Increase Data Abbreviation
Anomaly Detection	Smart Traffic, Smart Environment	Traffic Prediction, Increase Data Abbreviation, Finding Anomalies in Power Dataset
Support Vector Regression	Smart Weather Prediction	Forecasting
Linear Regression	Economics, Market analysis, Energy usage	Real Time Prediction, Reducing Amount of Data
Classification and Regression Trees	Smart Citizens	Real Time Prediction, Passengers Travel Pattern
Support Vector Machine	All Use Cases	Classify Data, Real Time Prediction
K-Nearest Neighbors	Smart Citizen	Passengers' Travel Pattern, Efficiency of the Learned Metric
Naive Bayes	Smart Agriculture, Smart Citizen	Food Safety, Passengers Travel Pattern, Estimate the Numbers of Nodes
k-Means	Smart City, Smart Home, Smart Citizen, Controlling Air and Traffic	Outlier Detection, fraud detection, Analyze Small Data set, Forecasting Energy Consumption, Passengers Travel Pattern, Stream Data Analyze

KEYTECH 7: OVERVIEW OF ML ALGORITHMS AND THEIR USE CASES IN IoT

Machine Learning Algorithm	IoT, Smart City Use Cases	Metric to Optimize
Density-Based Clustering	Smart Citizen	Labeling Data, Fraud Detection, Passengers Travel Pattern
Feed Forward Neural Network	Smart Health	Reducing Energy Consumption, Forecast the States of Elements, Overcome the Redundant Data and Information
Principal Component Analysis	Monitoring Public Places	Fault Detection
Canonical Correlation Analysis	Monitoring Public Places	Fault Detection
One-class Support Vector Machines	Smart Human Activity Control	Fraud Detection, Emerging Anomalies in the data

KEYTECH 7: BIG DATA IN IOT → DATA ANALYTIC ALGORITHMS

- Algorithms must be able to analyze
  - Data coming from a variety of sources
  - In real time

- Solution:

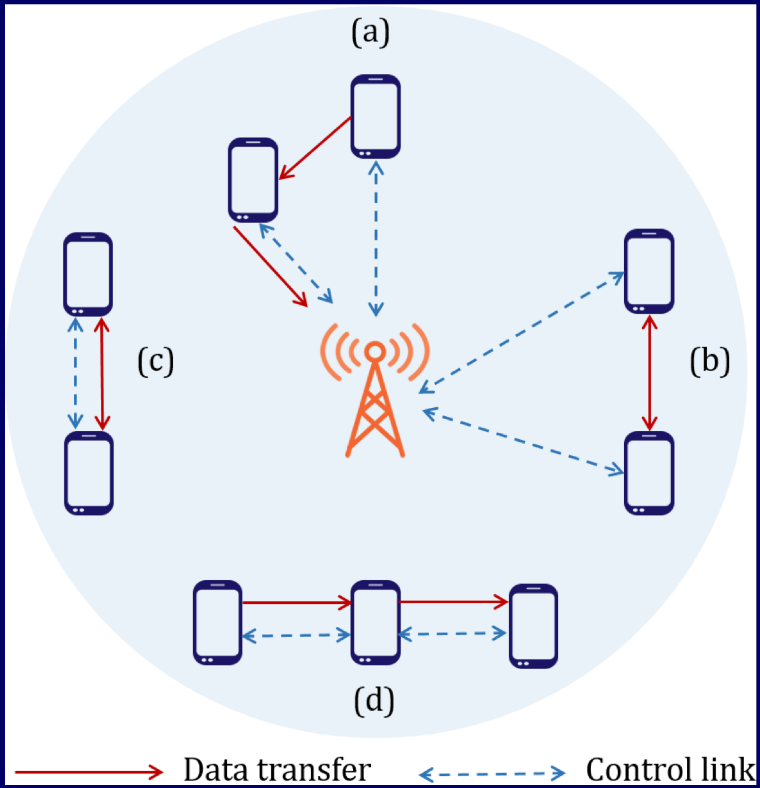
  Deep learning algorithms can reach high accuracy if they have enough data and time
  - Cons:
    - Easily influenced by noisy smart data
    - Neural network based algorithms lack interpretation

      (Data scientist cannot understand the reasons for the model results)
    - Semi-supervised algorithms can assist

      which model a small amount of labeled data with a large amount of unlabeled data

KEYTECH 8: DEVICE TO DEVICE (D2D) COMMUNICATIONS

- **Application Scenarios**
  - Relaying on the link established by BS
  - Direct D2D communication on the link established by BS
  - Direct D2D communication on the link established by device
  - Relaying on links established by device



KEYTECH 8: DEVICE TO DEVICE (D2D) COMMUNICATIONS

- **High-efficiency local communications**
  - Direct high-data-rate and low-latency connection
  - Improve spectrum utilization
- **Increase coverage through relaying**
  - Offload base station traffic
- **Brings scope for innovative applications**
  - Possibly new type of social networking
  - Intelligent vehicles that talk to each other

KEYTECH 8: D2D COMMUNICATION CHALLENGES

- D2D Co-Existence with underlaying cellular network (Interference Problems)
- Spectrum Sharing and Allocation
- Dynamic Power Control
- Resource Allocation
- Intelligent Routing Algorithms
- Security and Privacy
- Who will get charged when used as relay?
- Need global standardization on 5G D2D

KEYTECH 9: GREEN COMMUNICATIONS

- Reduction on carbon emissions and operating expenditure (OPEX) costs
- Power consumption to achieve 100-fold reduction
- Examine alternatives to current network structure
  - Energy efficient Base Stations and Network Topology
  - Distributed antennas, BS cooperation, strategic placement of small cells)
  - Harvesting renewable energy (solar panels)
  - Energy saving hardware (e.g., all-in-one solutions, fanless, etc.)
  - Energy efficient communication techniques (e.g., MIMO, beam-forming)
  - Energy efficient network deployment (e.g., femtocells vs macrocells)
  - Energy management functionalities (e.g., sleep schedules, cooperation)

KEYTECH 10: MULTIPLE ACCESS TECHNIQUES

- **Support multiple types of devices with varying requirements**

  High data rates (10Gbps); low latency (1ms); MIMO; less interference; robustness to timing Offsets & CSI Imperfections, power constraints.

- **Higher requirements on**
  - Data rate, Latency, Out-of-band emissions, Spectral efficiency, MIMO compatibility
- **5G-New Radio**
  - DL Waveform: CP-OFDM
  - UL Waveform:
    - CP-OFDM (high throughput scenarios)
    - DFT-s-OFDM (power limited scenarios)
- **Industry is reluctant to change from tried and tested OFDM**

  Standard adopted will be some modified version of OFDM

  (e.g., Rel. 15 only supports orthogonal multiple access and not NOMA)

KEYTECH 10: MULTIPLE ACCESS TECHNIQUES
FULL DUPLEX COMMUNICATIONS

- **Simultaneous Transmission and Reception**
  - In the same frequency slot at the same time
- **Bidirectional Transmission Between UE and BS**
  - Reuse factor improvement

PROBLEMS:

- **Reduction in computational complexity**
  - Current solutions → complex to implement in low power devices
- **Robustness to timing and frequency misalignments**

CURRENT 5G STANDARDS:

Key Features in Release 15 (June 2018): 5G Phase 1

Operation in Licensed Bands between 600 MHz – 39 GHz

Non-standalone (with LTE Core/EPC), and Standalone (with 5G/NG-Core) Operations

Basic URLLC Support

Massive MIMO

Network Slicing

Virtualization Support

CURRENT 5G STANDARDS:

Looking Forward: Release 16 (2020): 5G Phase 2

Complete Alignment with IMT-2020, i.e., the “full” 5G

Support for Higher Frequencies (> 52.6 GHz)

Additional Access (Wireline-Wireless Convergence, Satellites, etc.)

Enhanced Massive MIMO

Support for Unlicensed Bands

Multimedia Priority Services

CURRENT 5G OPERATOR DEPLOYMENTS

PREAMBLE:

- AT&T, Sprint, T-Mobile and Verizon will provide mobile 5G services by 2019.
- A major milestone for the US mobile industry !
- In most of Europe, the operators are targeting a 2020 launch !
- Vodafone → 5G trials with Huawei in Spain, but they are using LTE core network.
- SK Telecom (South Korea):
  - Next-generation core deployment scheduled for 2019
- NTT Docomo (Japan), Telenor (Norway), EE (UK):
  - Launch targeted for 2020

CURRENT 5G OPERATOR DEPLOYMENTS: AT&T (USA)

- 5G technology is an evolution, not a single event.
- Deployments in e.g., Dallas, Atlanta, plus Charlotte, Raleigh, and Oklahoma City
- Trials in South Bend, IN; Waco and Austin, TX; and Kalamazoo, MI.
- FirstNet the nationwide public safety broadband platform !
- Mobile 5G:
  - Based on mmWave using Ericsson, Nokia, and Samsung equipment
  - Deployment schedule: Late 2018/Early 2019 onwards
  - 19 cities including Atlanta

CURRENT 5G OPERATOR DEPLOYMENTS: Verizon Wireless (USA)

- First commercial 5G network in Sacramento, Houston, LA, and Indianapolis.
- mmWave based fixed-wireless access launched in Oct. 2018
- In Sacramento small cells installations on more than 200 utilities poles and street lights
- 5G-based fixed wireless services in 3-5 cities in 2018, targeting a 20–30% penetration rate in these markets.
- 14 Broader fixed wireless rollout is expected in 2019
- Verizon has acquired spectrum in the 28 GHz and 39 GHz bands.

CURRENT 5G OPERATOR DEPLOYMENTS: T-Mobile (USA)

- Deploying mobile 5G in 2019 with 30 cities named so far; starting with NYC, LA, Dallas, Vegas.
- To cover two-thirds of the US with "over 25-Mbs" by 2021, and 90% by 2024.
- 5G nationwide coverage by 2020, utilizing the 600 MHz spectrum
- First 5G smartphones in early 2019
- Agreement signed with Ericsson for providing 5G NR equipment in Sept. 2018
- mmWave deployment started in late 2018

SPRINT

- Launch mobile 5G in the first half of 2019 in Atlanta, Chicago, Dallas, Houston, Kansas City, LA, NYC, Phoenix and Washington, D.C.
- Access to a beautifully designed 5G phone
- In 2019 deploy thousands of massive MIMO radios, significantly increasing data speeds and network capacity for millions of customers across the country.
- Upgrade existing towers to leverage all 3 spectrum bands (800 MHz, 1.9 GHz and 2.5 GHz)
- Small cells → > 100,000 Sprint Magic Boxes deployed in about 200 cities

5G FORECAST IN THE USA

- 100 million mobile connections in 2023
- > 190 million by 2025
- 5G-based Fixed Wireless Access

PRIORITY USE CASES IN 5G DEPLOYMENTS

Enhanced Mobile Broadband

74%

- Ultra-fast Internet (Gigabytes/s)
- Enhanced Video (4K, 8K, 3D, 360-degree video, ultra HD live streaming on mobile)
- Integrated mobile/video customer experience
- Early Augmented and Virtual Reality
- Work and Play in the Cloud

Massive IoT

21%

- Smart Homes
- Smart Cities
- Smart Buildings
- Multiple Vertical Industries

Ultra-Reliable, Low-Latency Communications

5%

- Advanced AR and VR
- Connected and Autonomous Vehicles
- Industrial and Vehicular Automation
- Mission Critical Broadband (e.g., Emergency Services)

+

Fixed Wireless (launch in the second half of 2018)

Alternative to Fixed Broadband Connectivity !

RISE OF NEW TECHNOLOGIES AND HORIZONTAL PLATFORMS

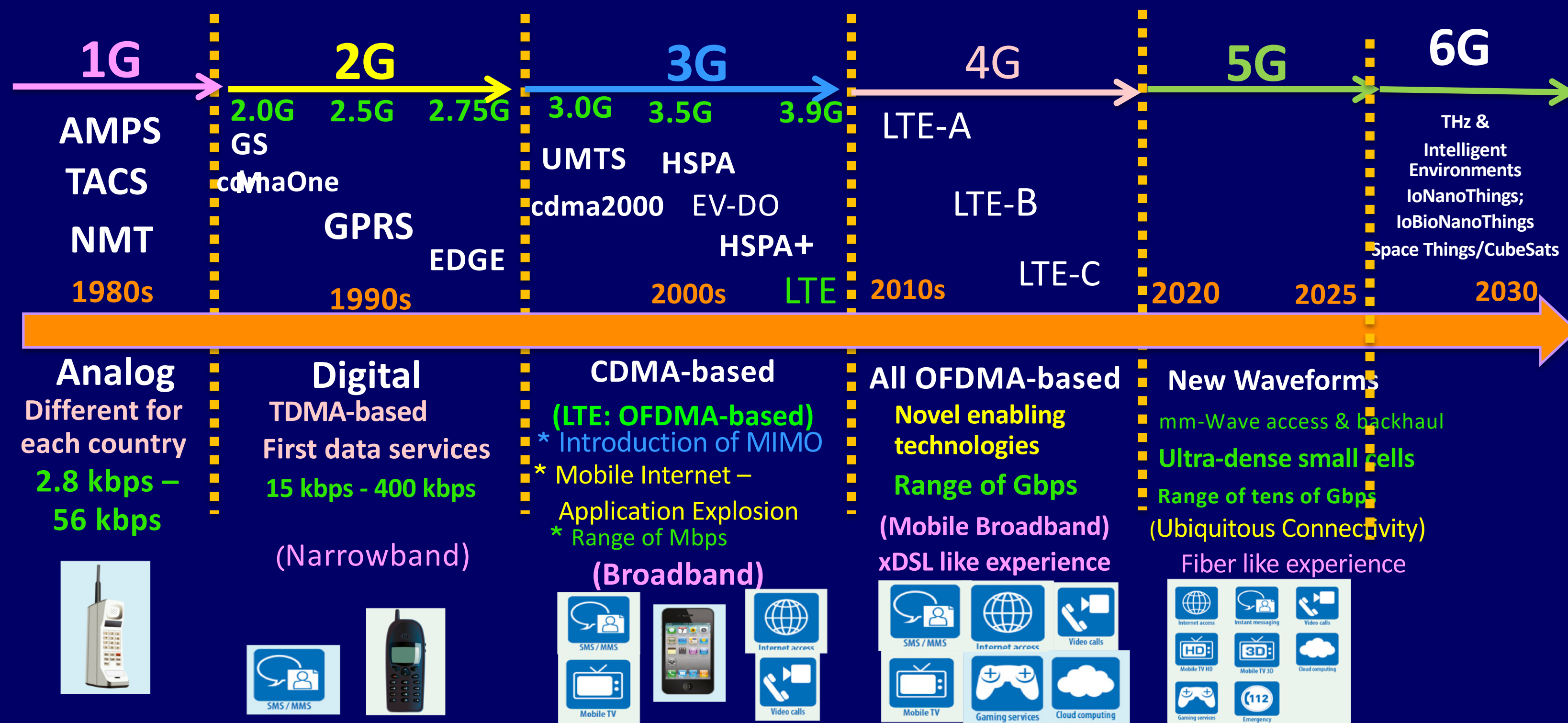
Robotics	Augmented Reality	Virtual Reality
Voice-based home devices	Drones	5G
Data Analytics	Edge Computing	Network Slicing
Blockchain	NG Vehicles	Machine Learning

Big Tech Players are becoming Horizontal Platforms

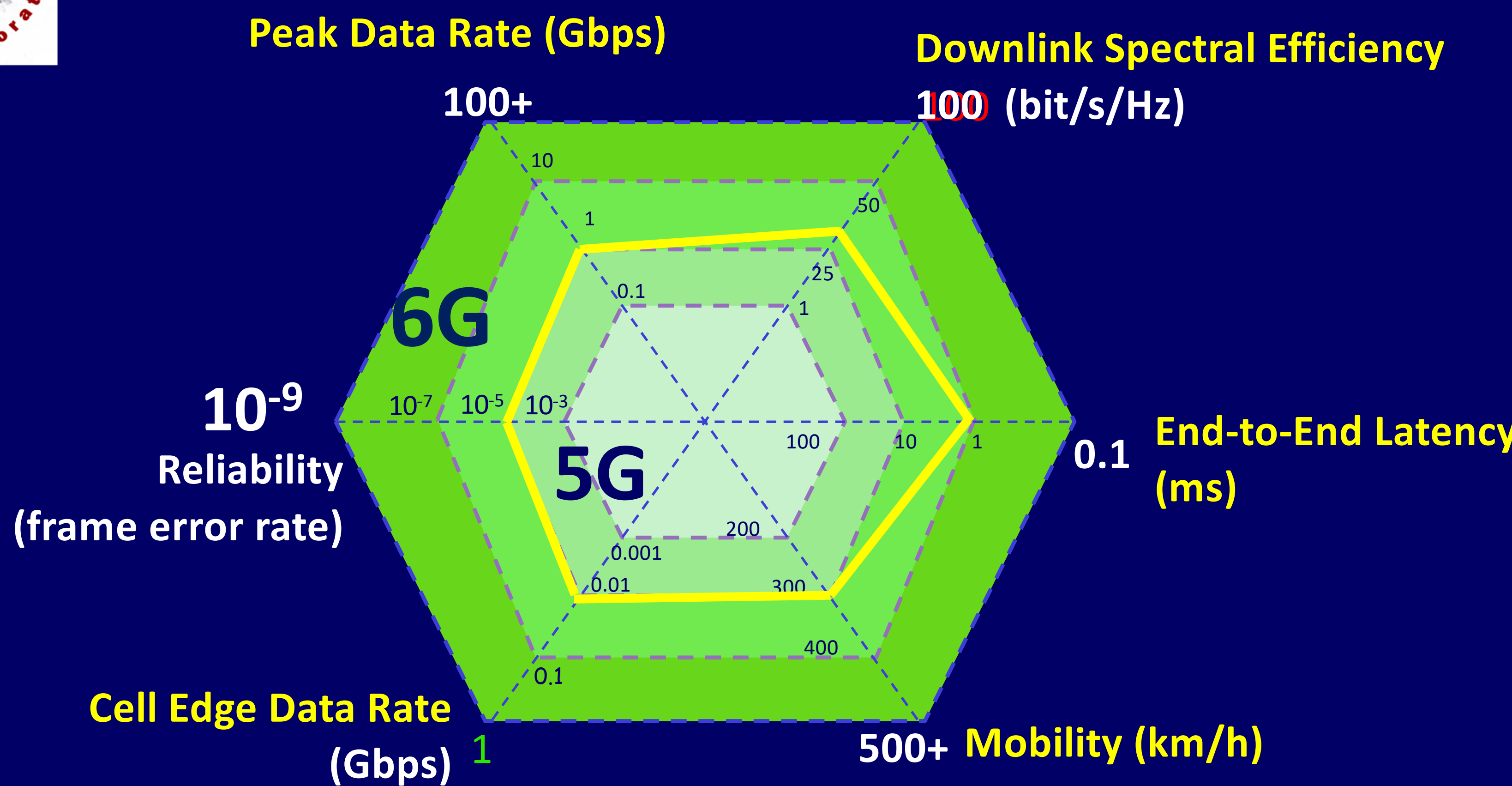
Google Microsoft Facebook

Amazon Apple

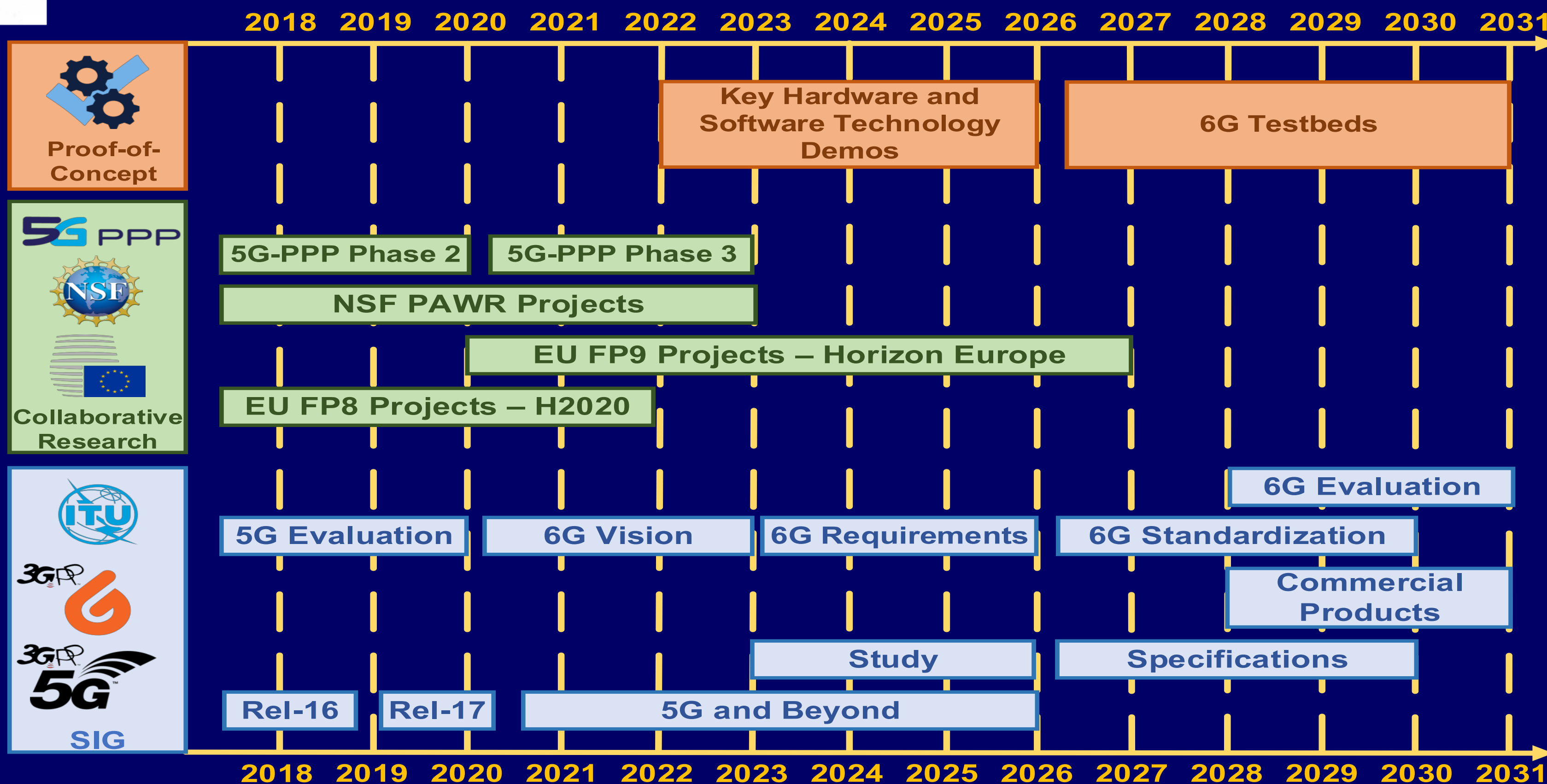
EVOLUTION OF WIRELESS SYSTEMS



EVOLUTION FROM 5G TO 6G

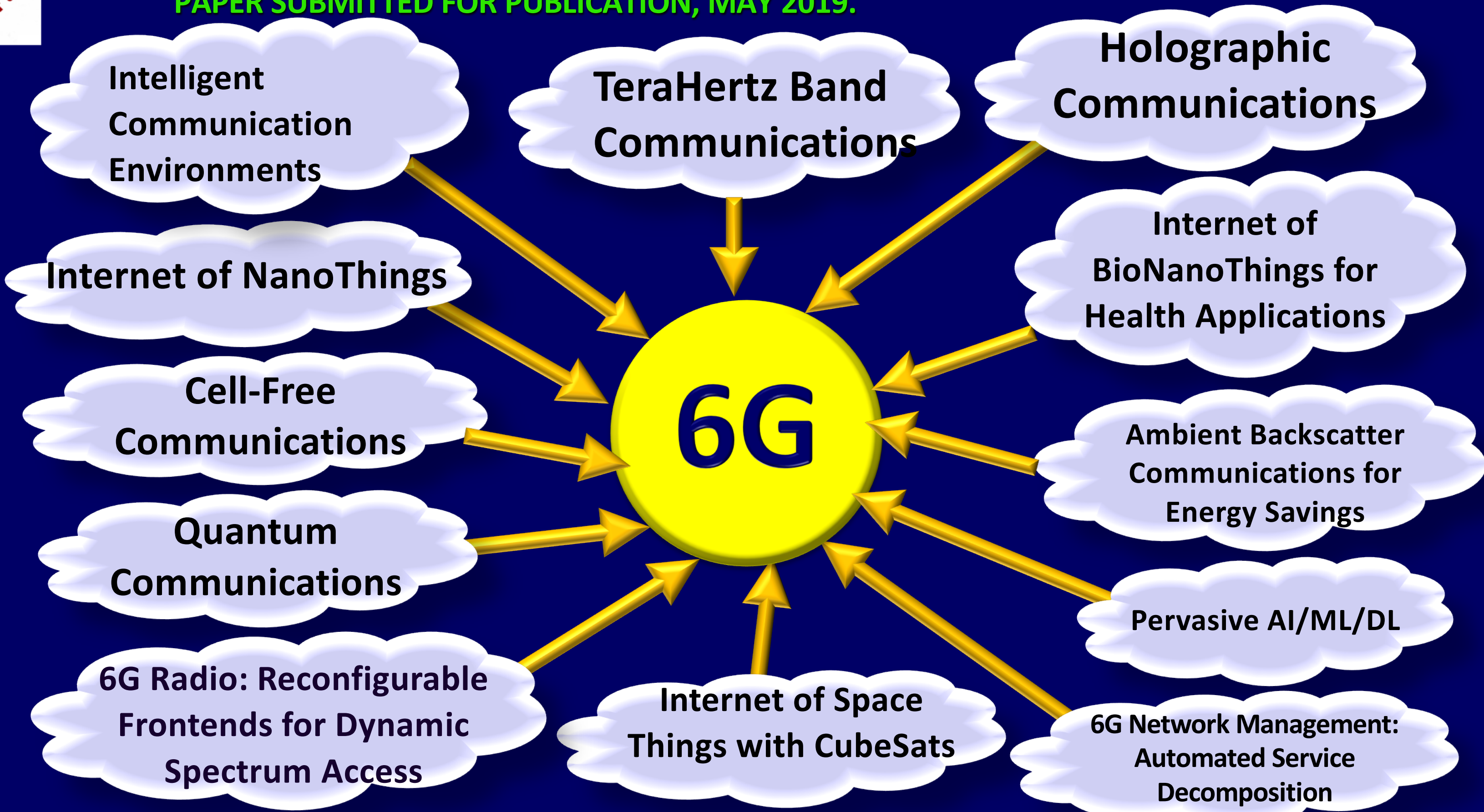


PROJECTED 6G TIMELINE



KEY TECHNOLOGIES FOR 6G

I. F. AKYILDIZ AND S. NIE,
"6G: NEXT FRONTIER IN WIRELESS COMMUNICATIONS"
PAPER SUBMITTED FOR PUBLICATION, MAY 2019.



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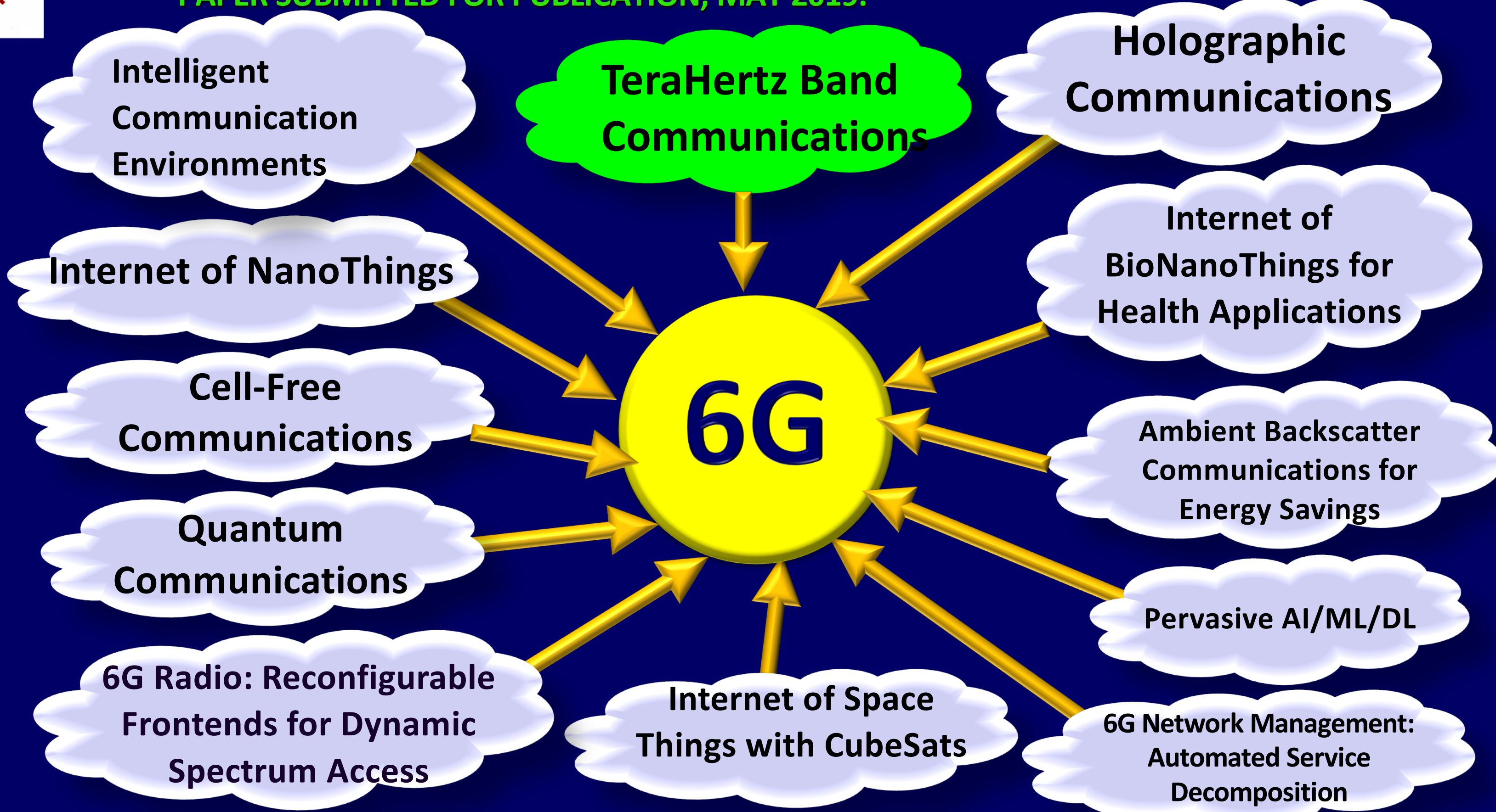


WHY TERAHERTZ??

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

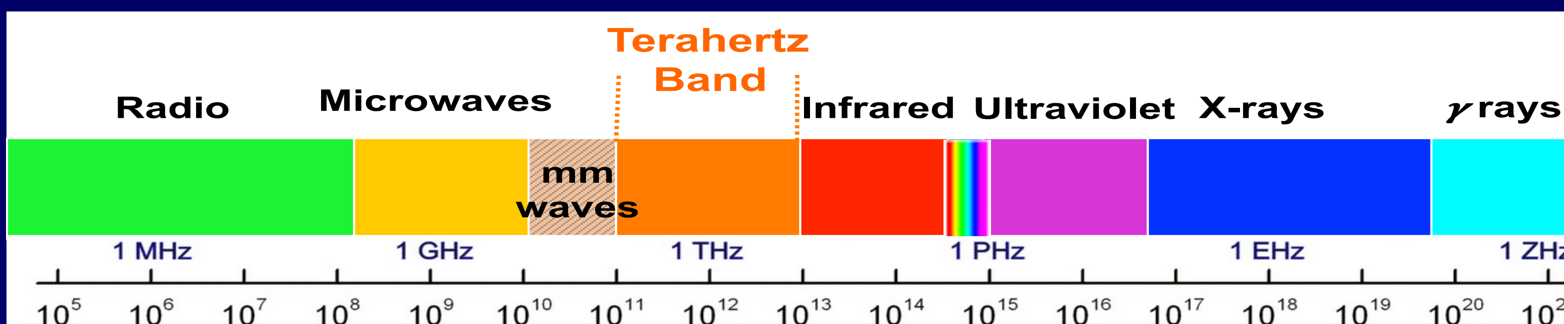
- **Exponential growth of wireless data traffic:**
  - **More Devices → 11.6 billion mobile-connected devices by 2020**
  - **Faster Connections → Wireless data rates have doubled every 18 months over the last three decades**

→ **Wireless Terabit-per-second (Tbps) links will become a reality within the next 5 years → HOW??? → Explore high frequencies !!**

WHY TeraHertz?

Everything: Radio, TV, Cellular Systems, Wi-Fi, Bluetooth, mm-Wave, Radar, GPS, etc.

No man's land!!!



TERANETS (FORMERLY GRANET; 2008-2013):

GRAPHENE BASED NANO SCALE COMMUNICATION NETWORKS IN THZ BAND

NSF; 2013-2016 & 2016-2020; US ARMY-TERATACTICS (2019-2024)

- **Objectives:**
  - To establish the theoretical and experimental foundations of ultra-broadband com nets in the (0.1-10) THz band

THz Materials & Devices

- THz Source/Detector ✓
- THz Modulator/ Demodulator ✓
- THz Antennas and Arrays ✓
- Fabrication
- Experimental Measurements

THz Channel

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

THz Communications

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

THz Networks

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

Experimental and Simulation Testbeds

TERAHERTZ CHANNEL CHARACTERISTICS

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.

- Developed path loss and noise models for EM communications in the THz band (0.1-10 THz) by means of radiative transfer theory
- Proposed different power allocation schemes and computed the channel capacity as a function of distance and channel composition

TOTAL PATH-LOSS

$$A(f,r)[dB] = A_{spread}(f,r)[dB] + A_{loss}(f,r)[dB]$$

- **Spreading Loss (A_{spread}):**
  Attenuation due to the expansion of the wave as it propagates through the medium

- **Absorption Loss (A_{abs}):**
  Attenuation due to molecular absorption

SPREADING LOSS

- Depends on the frequency of the wave and the transmission distance:

$$A_{spread}\left(f,r\right)=20\log\left(\frac{4\pi fr}{c}\right)$$

f = frequency

r = distance

c = speed of light in vacuum

ABSORPTION LOSS

- **Depends on the frequency of the wave, the total path length and the molecular composition of the channel:**

$$A_{abs}\left(f,r\right)=e^{\sum_i \frac{p}{p_0}\frac{T_{STP}}{T}Q^i s^i(f)r}$$

f = frequency
r = distance
p = system pressure
p_0 = reference pressure (1 atm)

T_{STP} = reference temperature at 1 atm (273 K)
T = system temperature
Q^i = molecular volumetric density of each gas "i"
σ^i = molecular absorption cross-section of each gas "i"

MOLECULAR ABSORPTION NOISE

- Depends on the frequency of the wave, the total path length and the molecular composition of the channel:

$$N(f,r) = k_B T_0 \left(1 - e^{-\sum_i \frac{p}{p_0} \frac{T_{STP}}{T} Q^i \sigma^i (f) r} \right)$$

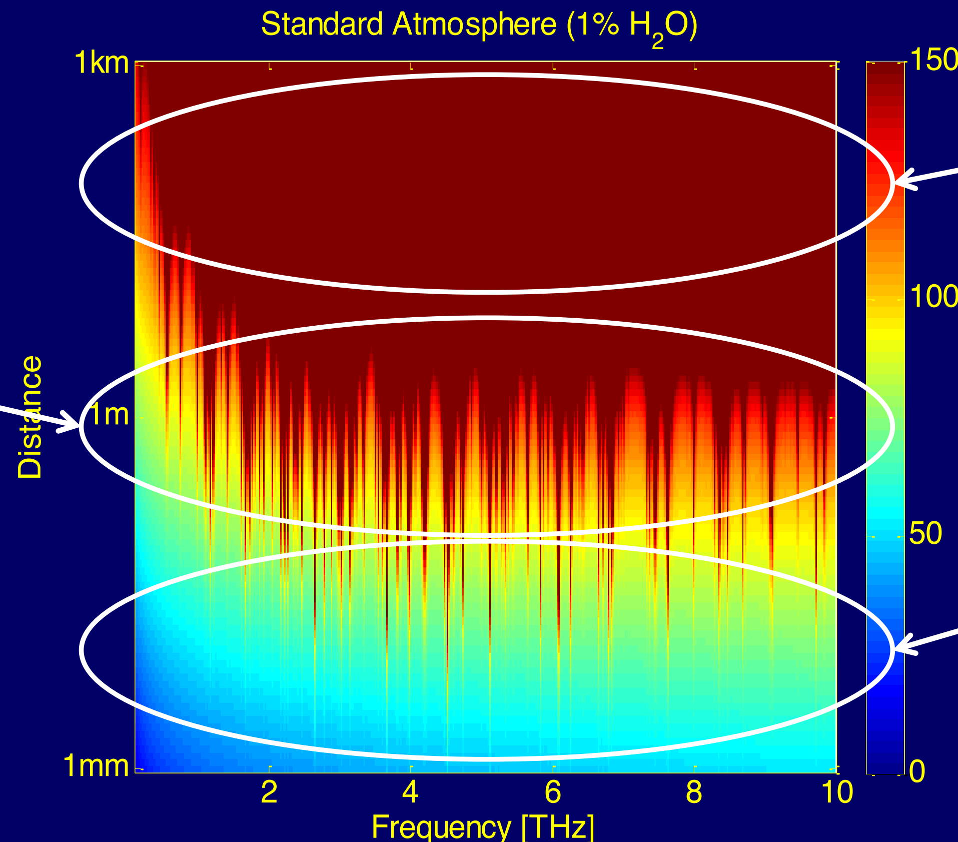
f = Frequency
r = Distance
k_B = Boltzmann constant
T_0 = Reference temperature
p = System pressure

p_0 = Reference pressure
T_{STP} = Reference temperature at 1 atm
T = System temperature
Q^i = Molecular volumetric density of each gas "i"
σ^i = Molecular absorption cross-section of each gas "i"

TOTAL PATH LOSS

For the middle range, there are several windows TENS OF GIGAHERTZ WIDE.

Can we exploit this in SMALL CELLS?



We cannot go far in distance

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

WHAT DID WE LEARN?

- THz channel has a strong dependence on
  - Transmission distance
  - Medium molecular composition
- Main factor affecting the performance
  - Presence of water vapor molecules
- Incredibly huge BWs for short ranges (< 1m):
  - 100 Tbps rates are feasible

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

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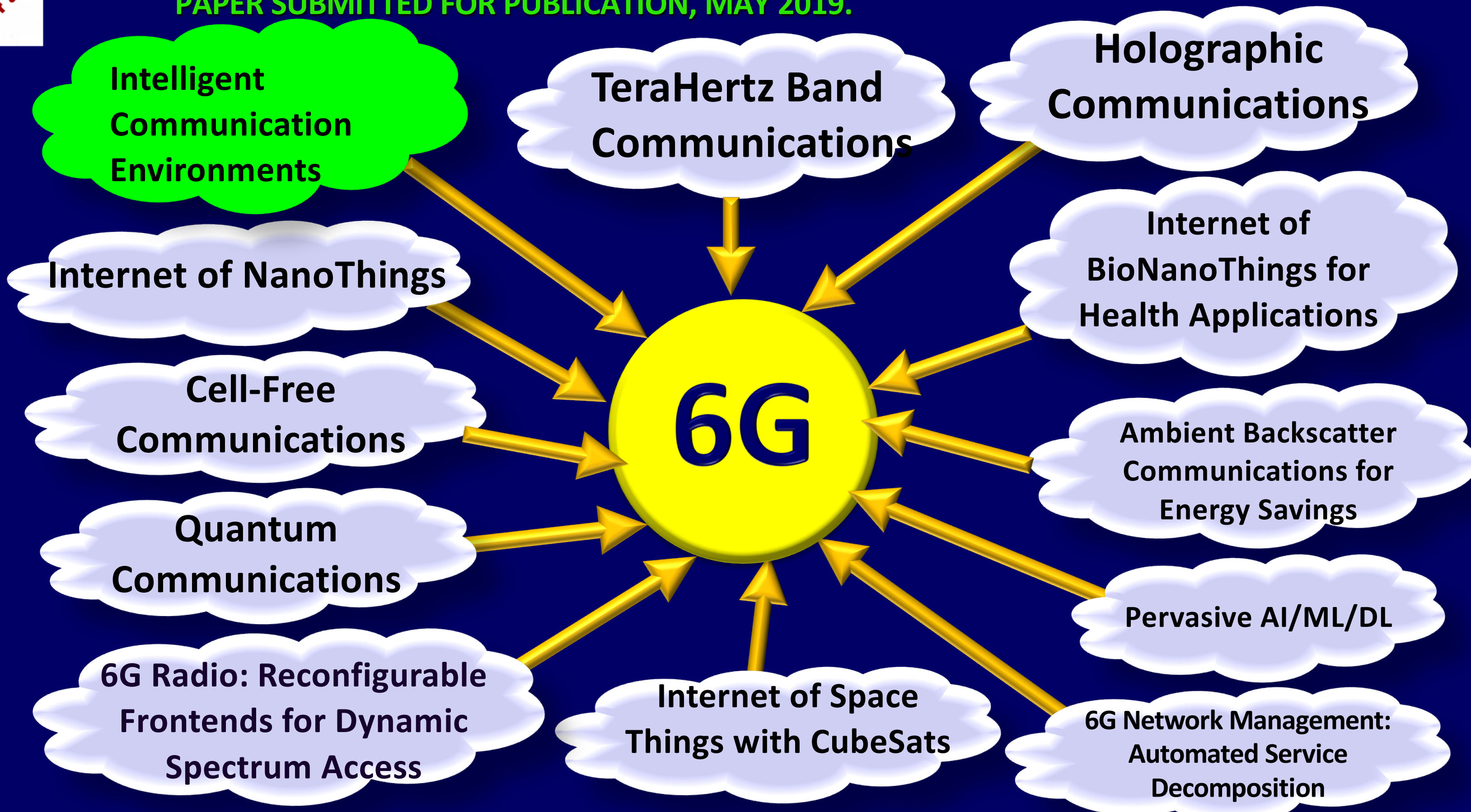
PAPER SUBMITTED FOR PUBLICATION, MAY 2019.



Intelligent Communication Environments
REFERENCES

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

C. Liaskos, A. Tsioliaridou, A. Pitsillides, S. Ioannidis, I. F. Akyildiz.
"Using any Surface to Realize a New Paradigm for Wireless Communications"
Communications of the ACM, Nov. 2018.

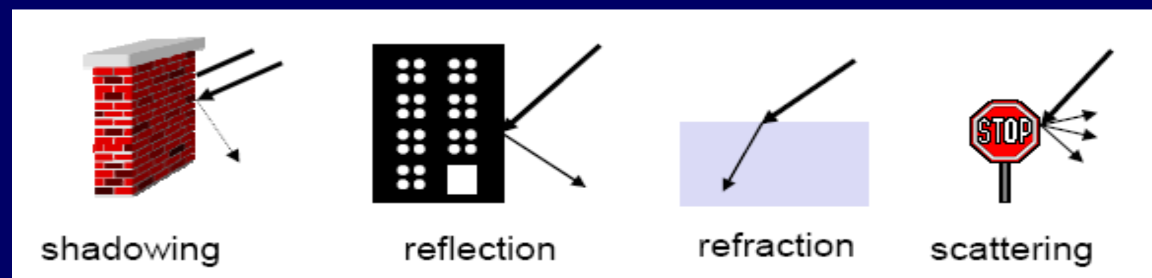
Patent applied for.

WHY INTELLIGENT 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 (Eavesdropping)

CONVENTIONAL APPROACHES

- PHY Layer solutions, e.g., adaptive antenna, MIMO, beamforming, adaptive modulation, dynamic spectrum allocation, encoding and plethora of MAC and ROUTING protocols

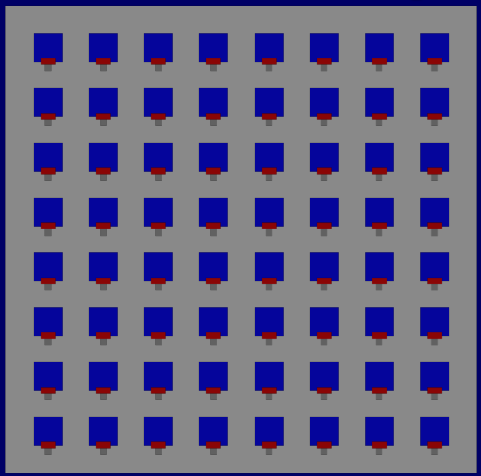
- Although successful, they all have separate degrees of efficiency

- Also the random channel behavior still greatly affects the performance !!

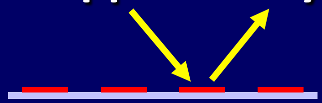
- mm-Wave and THz bands → Distance problem !
  (MIMOs may help but not solve the problem)

POSSIBLE SIMPLE SOLUTIONS

Reflectarrays

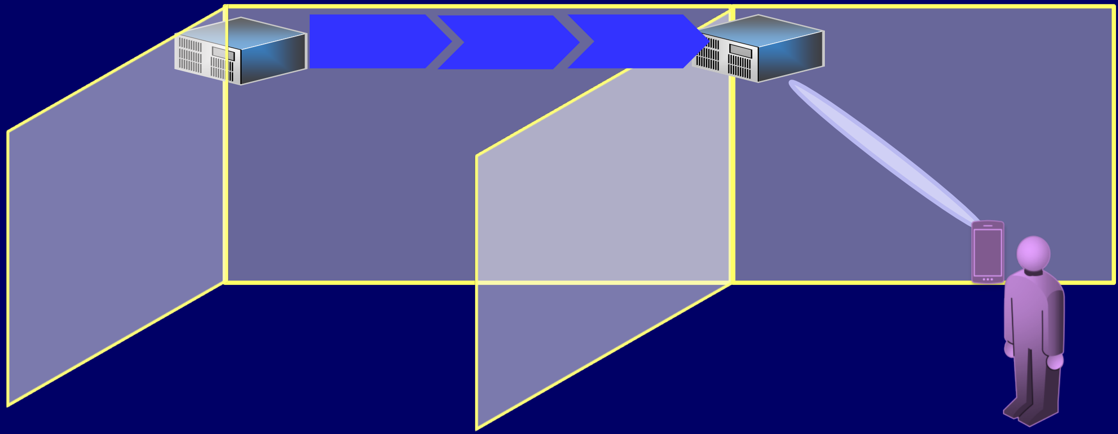


Supports only:



Normal Reflection

Relays

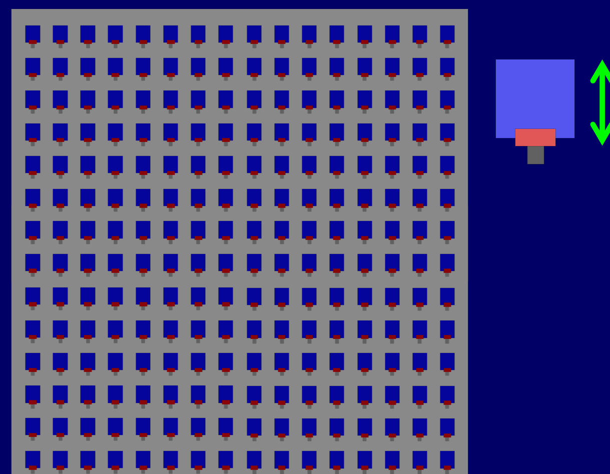


Disadvantages:

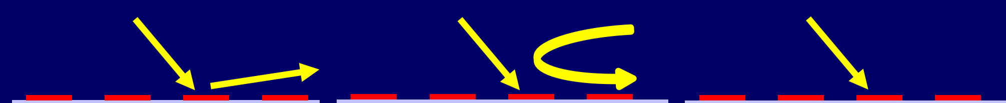
- Extra delays in signal transmission
- Dissipate more energy
- Inflexible for existing network layout

OUR SOLUTION: INTELLIGENT WALLS

TILES



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



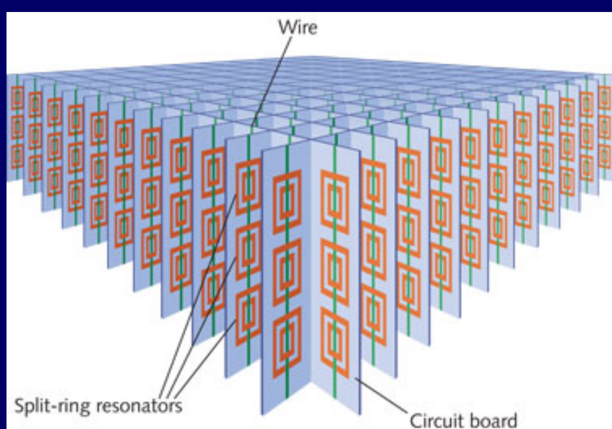
Controlled reflection Polarized reflection Absorption

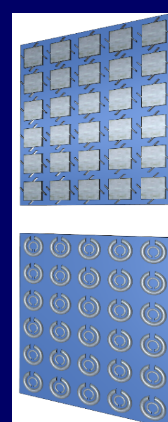
TWO TRACKS FOR TILE DESIGN

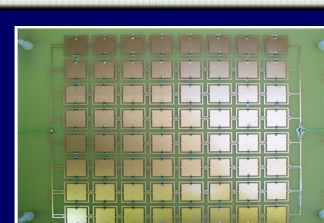
HYPERSURFACES Programmable Metamaterials	Ultra Massive MIMO based Intelligent Environments
EU-FET Project: VisorSurf Programmable Metasurfaces http://www.visorsurf.eu (2017-2021)	The WALL Project NSF (2018 – 2021)
Partners: • Forth Crete, Greece • University of Cyprus • UPC Barcelona • Aalto Univ, Finland • Fraunhofer Institute Berlin • SignalGenerix, Cyprus	Georgia Tech

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

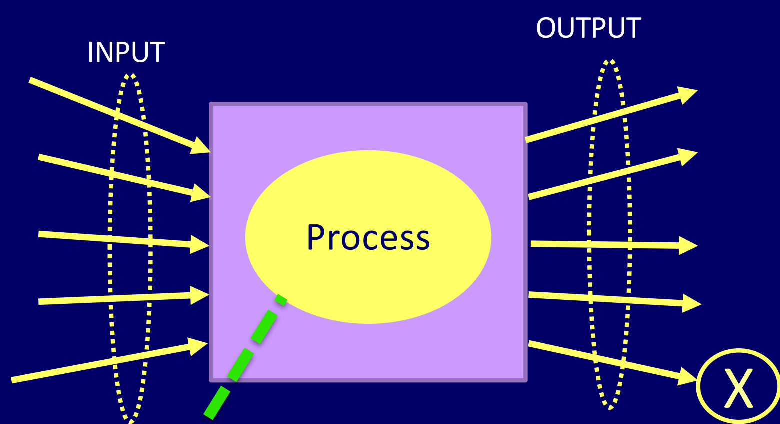






RESULT: METASURFACES

Completely re-engineer incoming EM waves



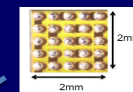
STEER, ABSORB, POLARIZE, SPLIT, FREQ_FILTER, ALTER_PHASE, FOCUS, CUSTOM EM/MAG FIELD at output(s)

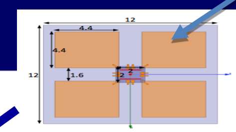
DESIGN 1: HYPERSURFACES: PROGRAMMABLE METASURFACES

C. LIASKOS, S. NIE, A. TSIOLIARIDOU, A. PITSILLIDES, S. IOANNIDIS, I. F. AKYILDIZ.
"A NEW WIRELESS COMMUNICATION PARADIGM THROUGH SOFTWARE-CONTROLLED METASURFACES"
IEEE COMMUNICATION MAGAZINE, SEPT. 2018.

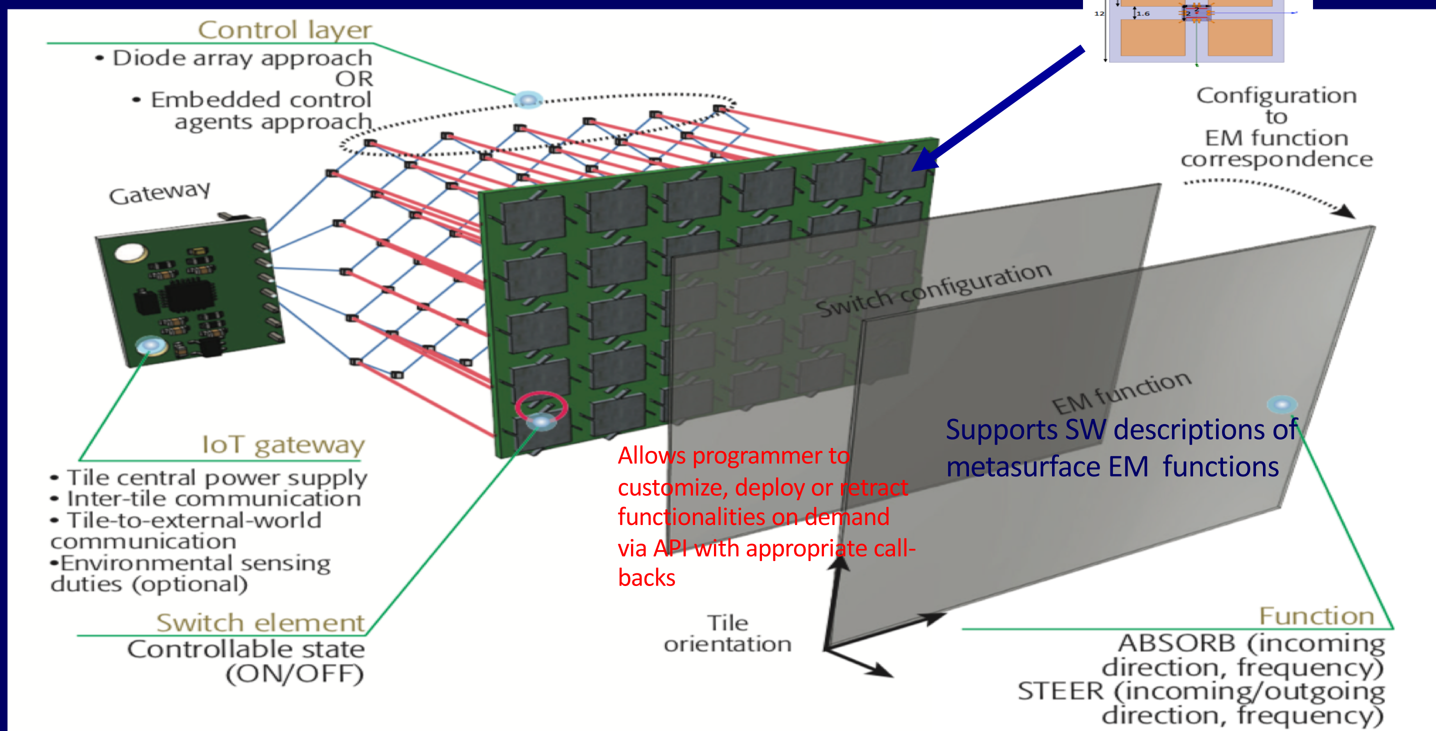
C. LIASKOS, A. TSIOLIARIDOU, A. PITSILLIDES, S. IOANNIDIS, I. F. AKYILDIZ.
"USING ANY SURFACE TO REALIZE A NEW PARADIGM FOR WIRELESS COMMUNICATIONS"
COMMUNICATIONS OF THE ACM, NOV. 2018.

PATENT APPLIED FOR.

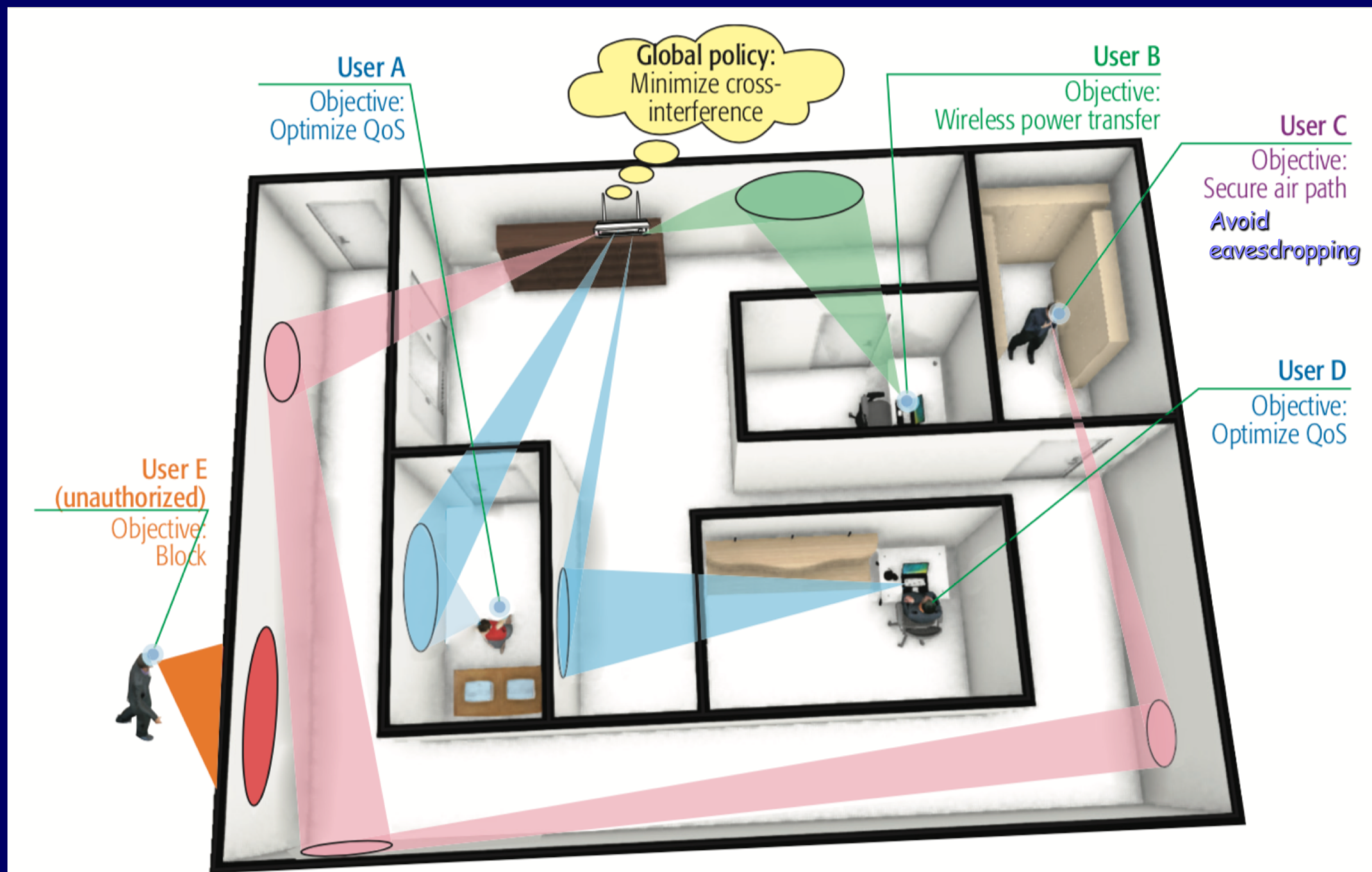




meta atoms/metallic patches/unit cells

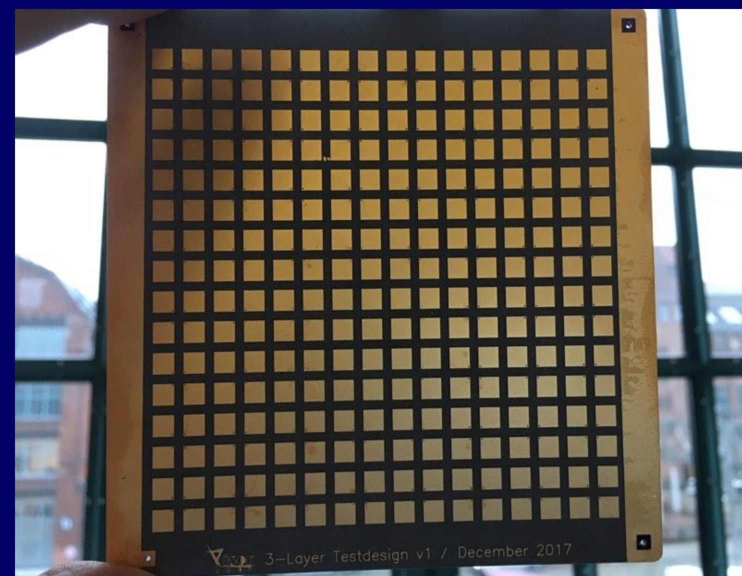


EXAMPLE: HYPERSURFACES USE CASES



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
  - Internet of Materials

DESIGN 2: TILE DESIGN BASED ON ULTRA-MASSIVE MIMO

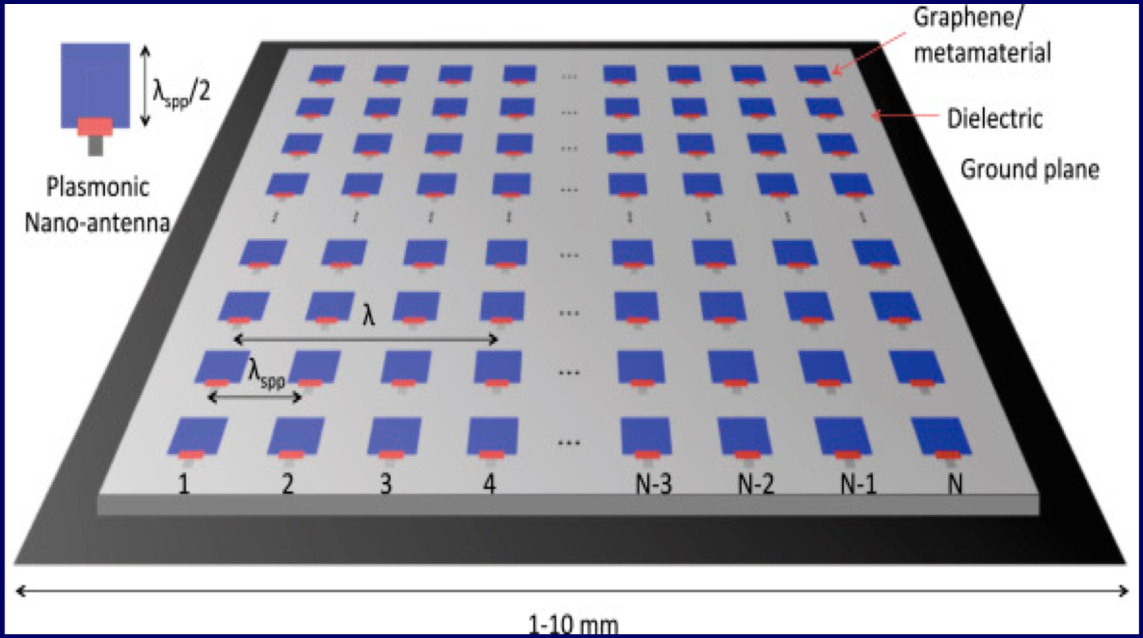
I. F. Akyildiz and J. M. Jornet

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

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

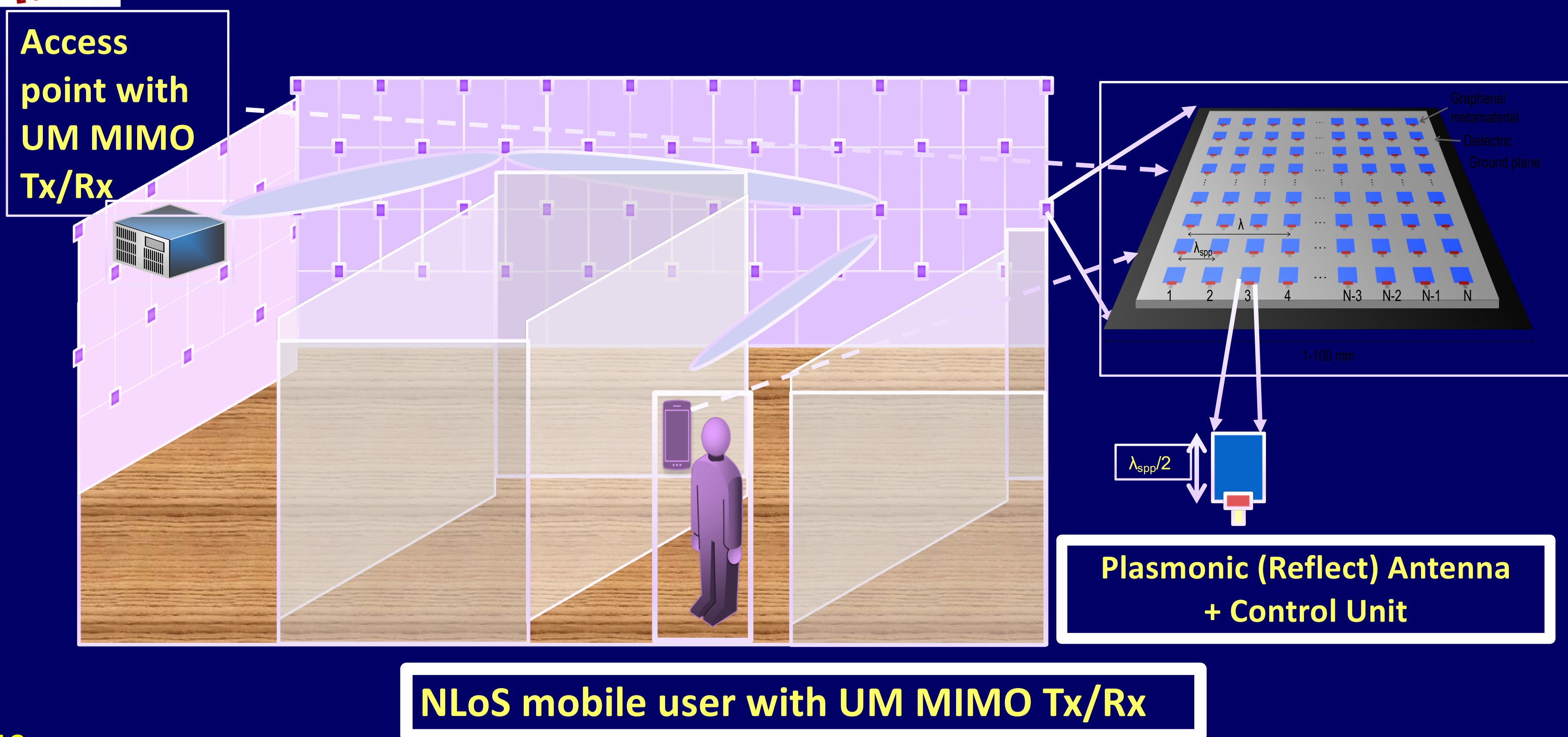
U.S. Patent 15/211,503 awarded on Sept. 7, 2017.

- 1024x1024 Antenna Element Array



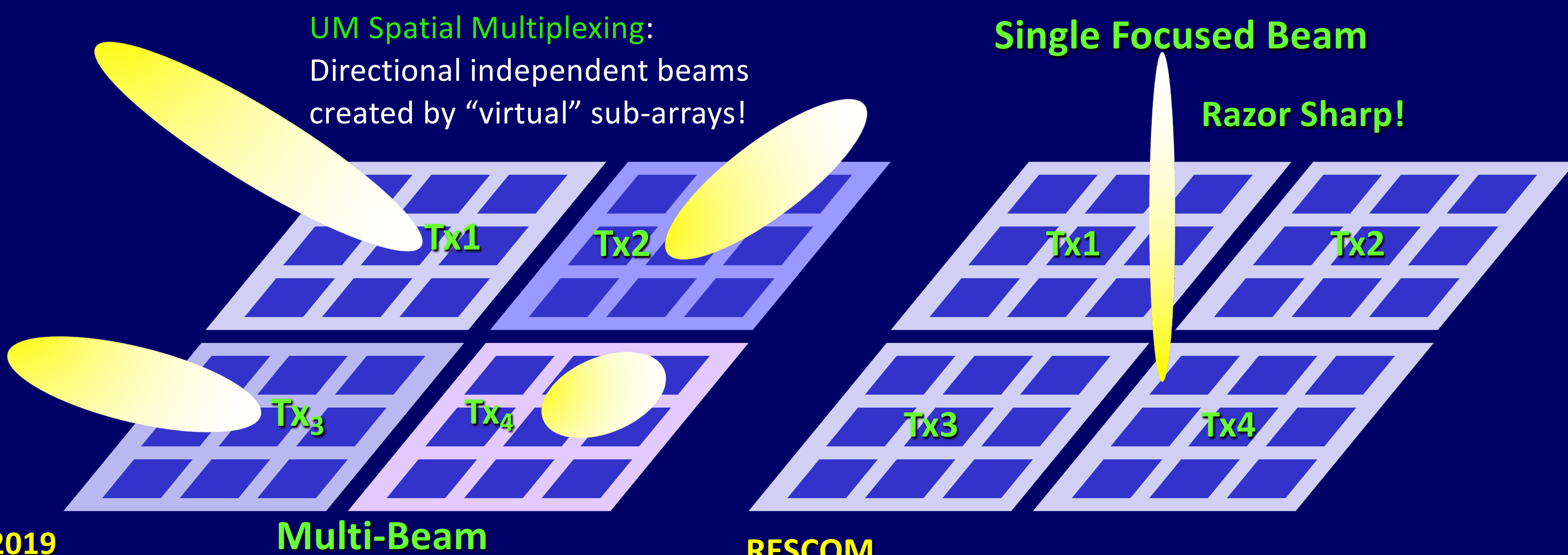
A square uniform plasmonic nano-antenna array
RESCOM

UM MIMO BASED INTELLIGENT ENVIRONMENTS



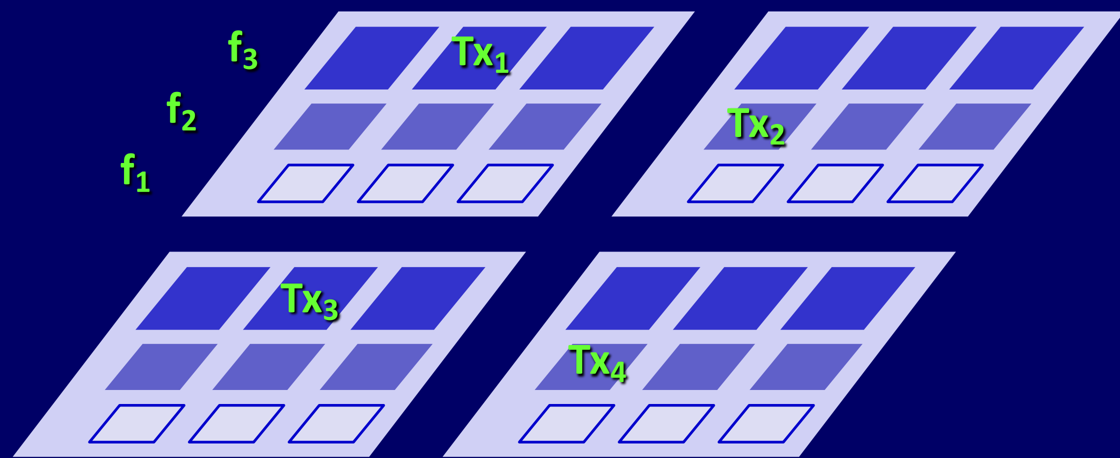
DYNAMIC MASSIVE MIMO

By properly feeding the antenna elements, the antenna array can be dynamically switched among different modes



MULTI-BAND MASSIVE MIMO

A nano-antenna array designed to communicate over multiple transmission windows simultaneously by electronically tuning the response of fixed-length plasmonic nano-antennas

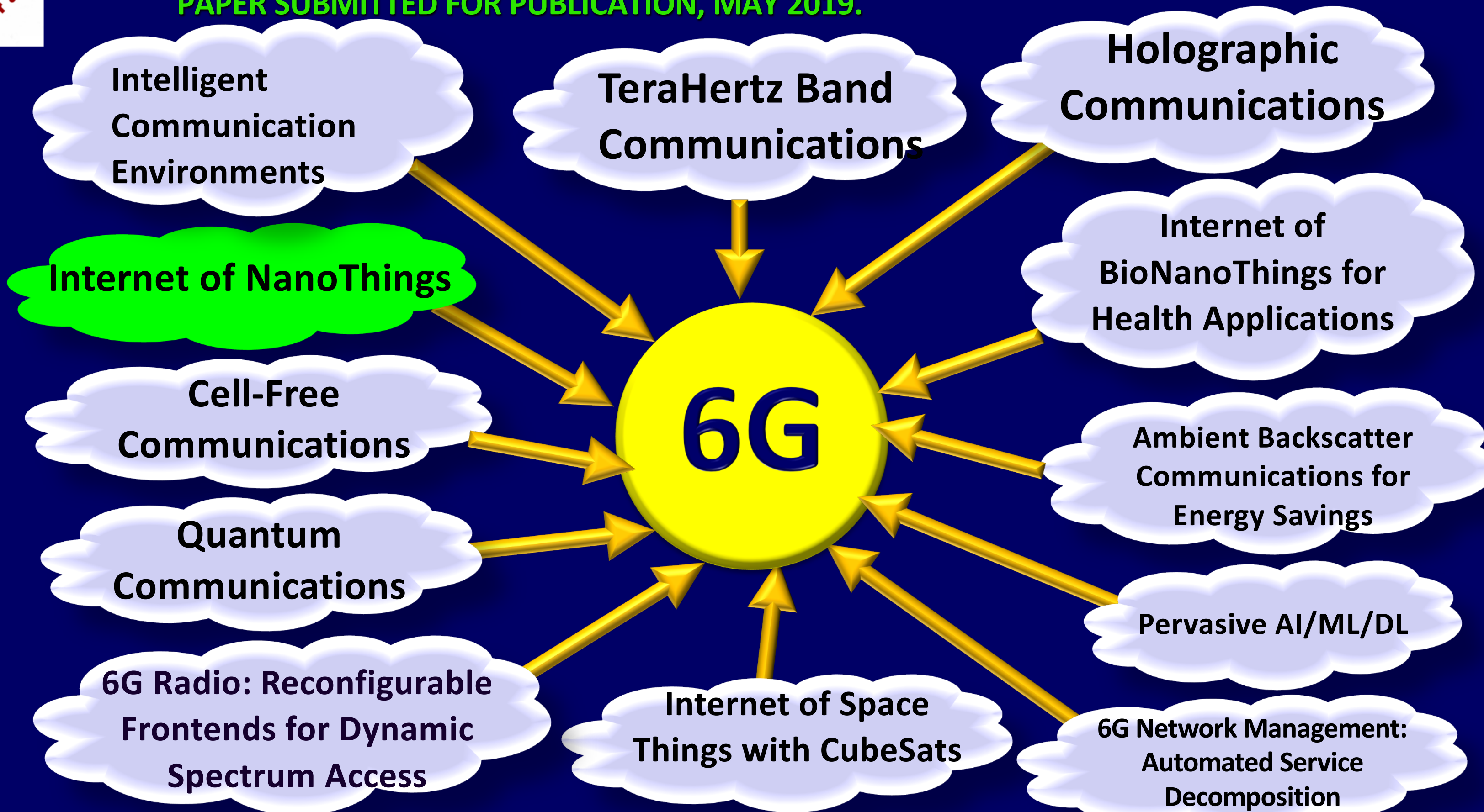


FURTHER RESEARCH DIRECTIONS

- Deployment strategies for indoor and outdoor scenarios
- Efficient user beam discovery and beam routing algorithms
- AI/ML/DL Algorithms
- Fabrication and experimental testing

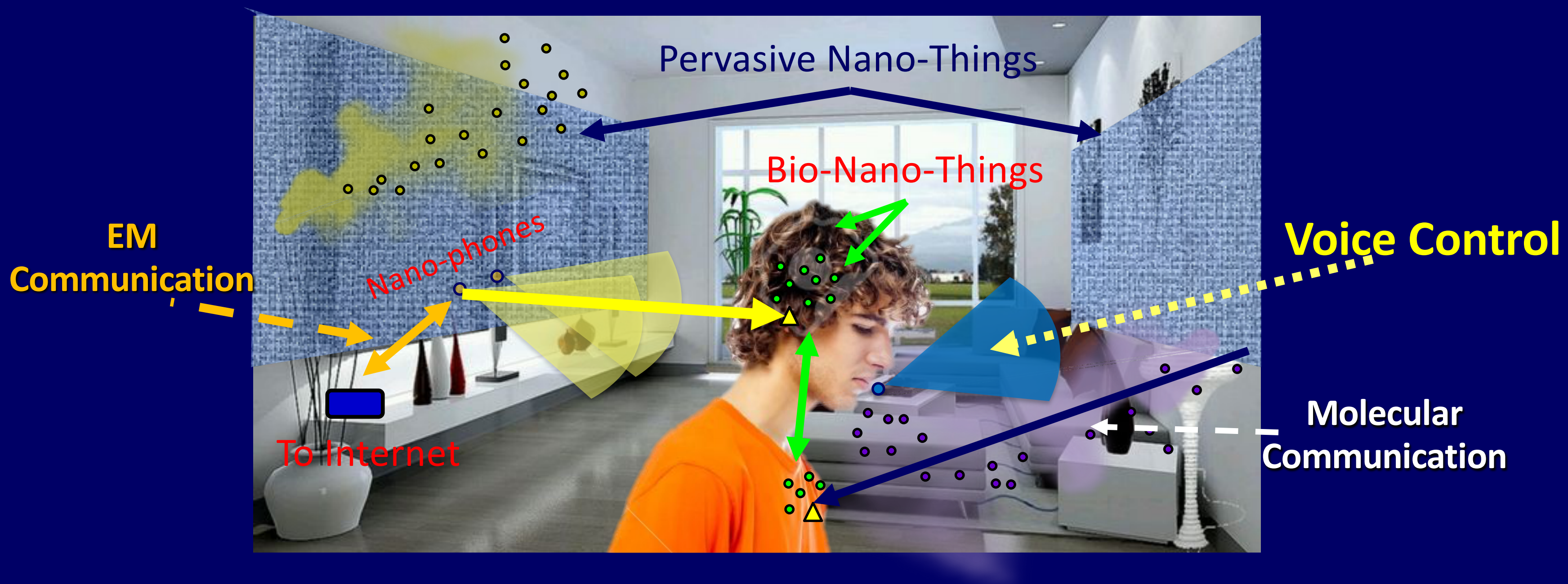
KEY TECHNOLOGIES FOR 6G

I. F. AKYILDIZ AND S. NIE,
"6G: NEXT FRONTIER IN WIRELESS COMMUNICATIONS"
PAPER SUBMITTED FOR PUBLICATION, MAY 2019.



INTERNET OF NANO-THINGS

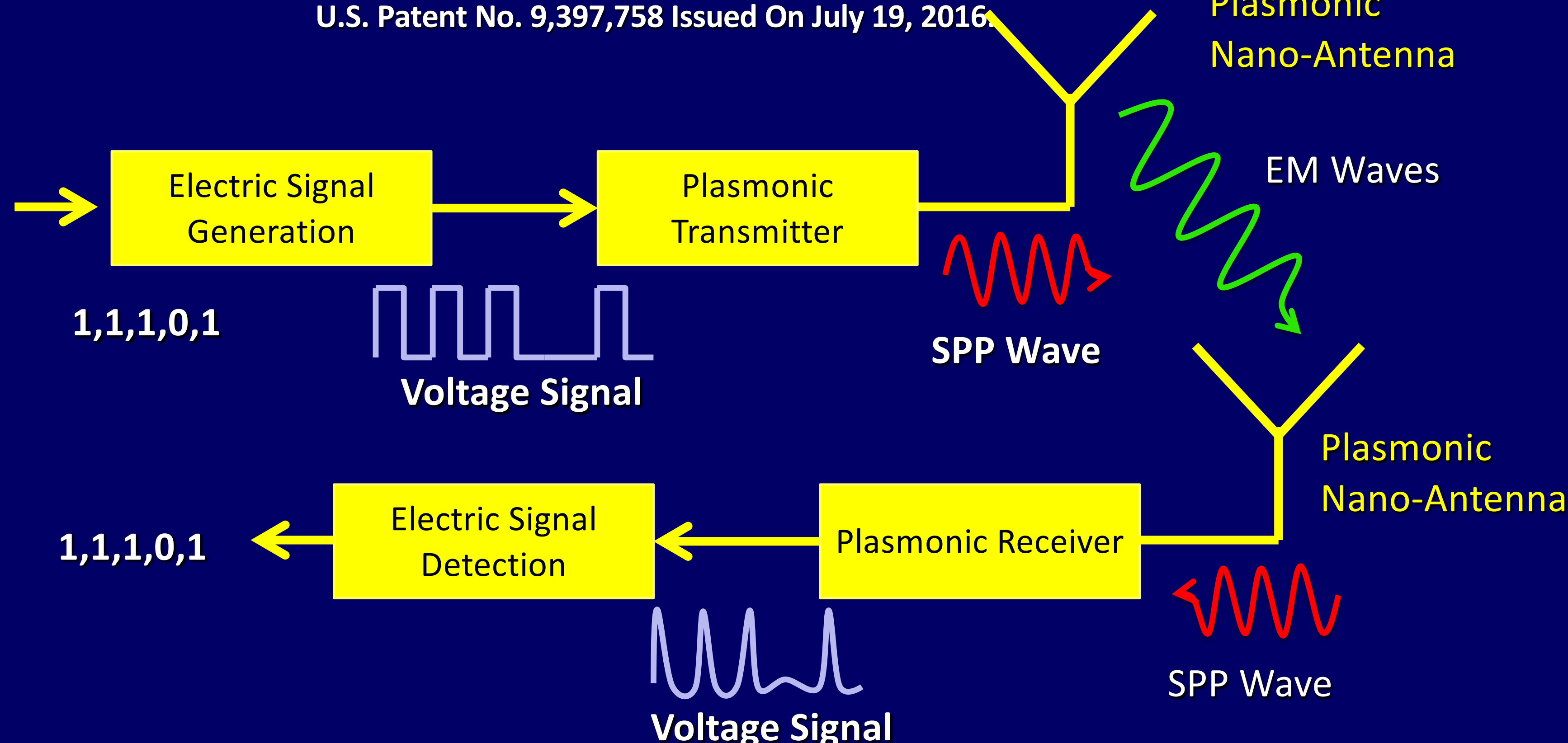
I.F. Akyildiz and J.M. Jornet,
"Internet of Nano-Things",
IEEE Wireless Communications Magazine, Dec. 2010.



GRAPHENE-BASED PLASMONIC NANO-TRANSCEIVERS

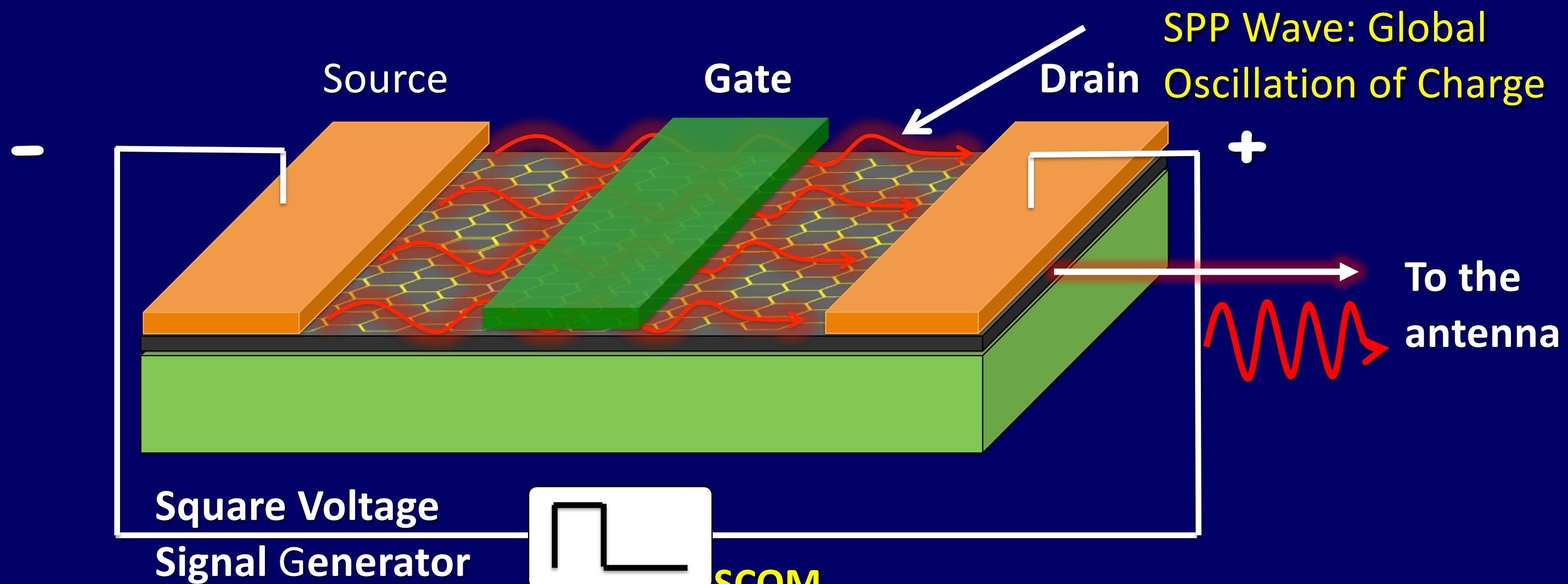
(INJECT PLASMONS INTO PLASMONIC NANOANTENNA)

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.



WORKING PRINCIPLE IN TRANSMISSION

- **Based on a High Electron Mobility Transistor (HEMT):**
  - * Voltage at the Drain > Voltage at the Source
  - * When a sufficiently large voltage is applied to the Gate, the transistor is ON and electrons can move from the Source to the Drain.. This generates a Surface Plasmon Polariton (SPP) waves
  - * When there is no voltage at the gate, the transistor is OFF and electrons cannot move

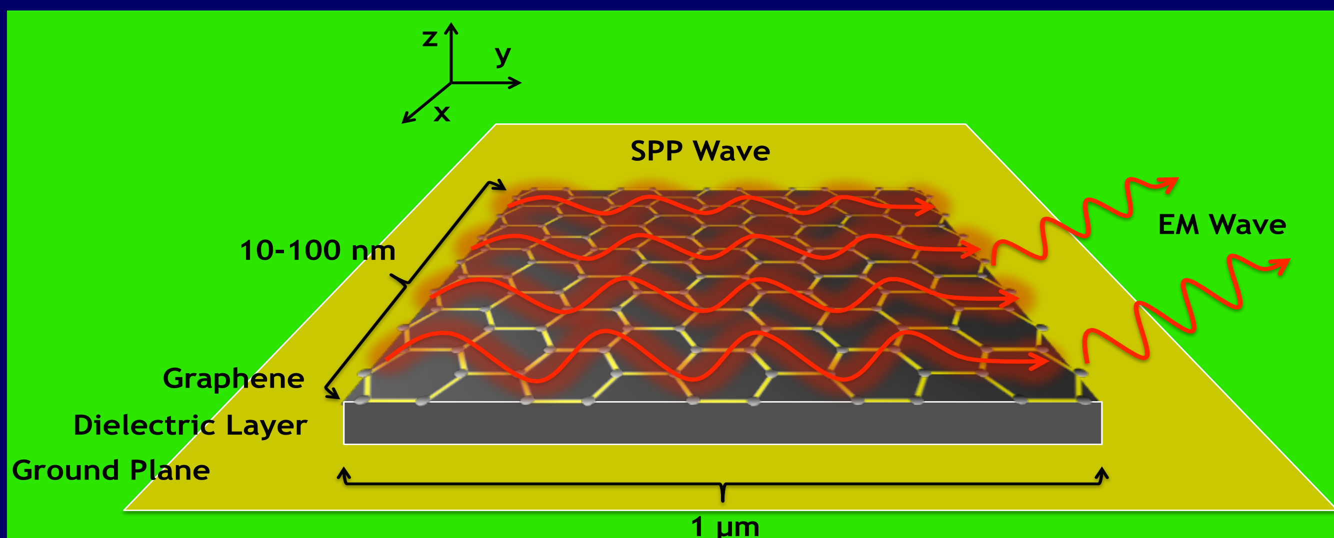


Graphene-based Plasmonic Nano-Antennas

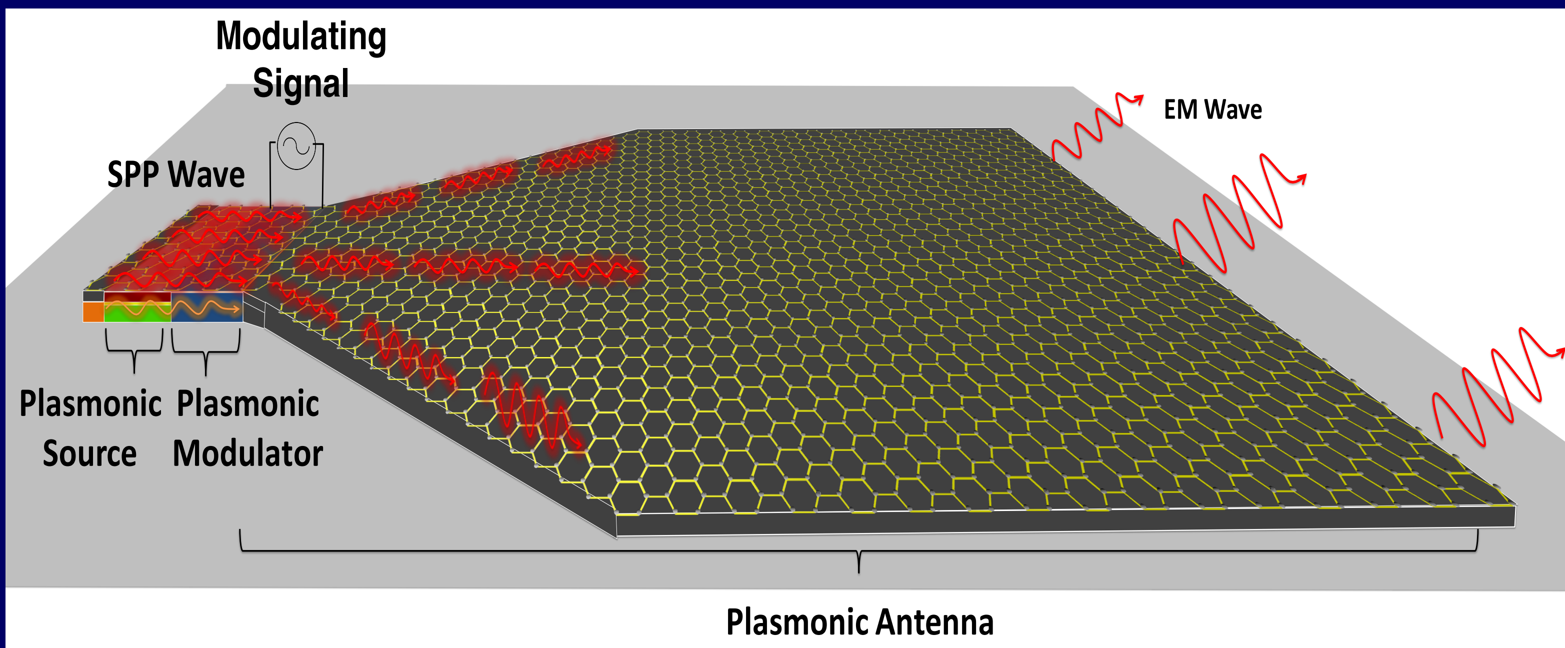
I.F. Akyildiz and J.M. Jornet,
"Graphene-based Plasmonic Nano-antennas for THz Band Communication in Nanonetworks,"
IEEE Journal of Selected Areas in Communications, Vol. 12, pp. 685-694, Dec. 2013.
Prelim. version in Proc. of 4th European Conference on Antennas and Propagation, 2010
U.S. Patent No. 9,643,841, issued on May 9, 2017.

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

→ Can efficiently radiate (convert SPP waves into EM waves) in the THz band at room temperature



GRAPHENE BASED PLASMONIC THZ FRONT-END



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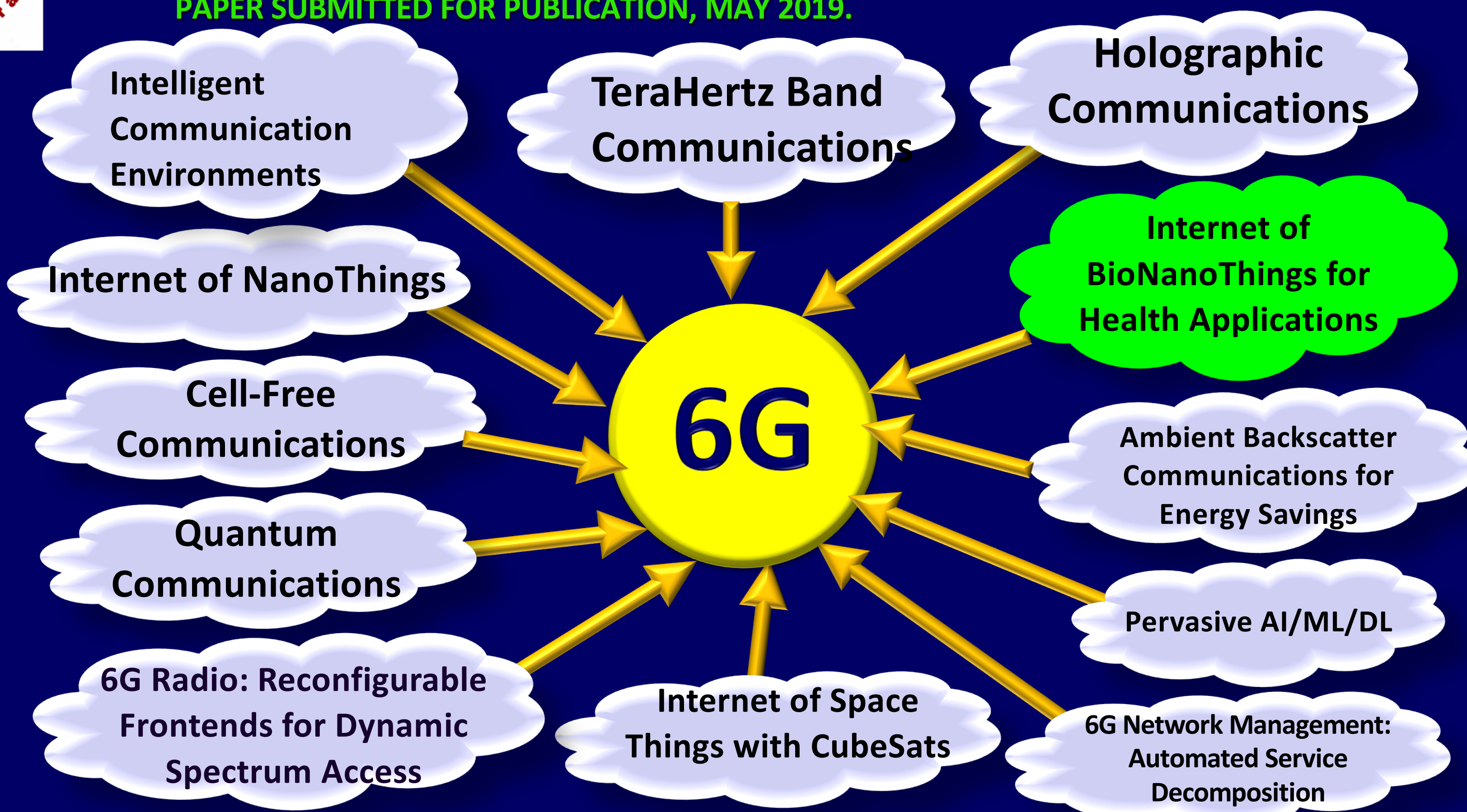
PAPER SUBMITTED FOR PUBLICATION, MAY 2019.

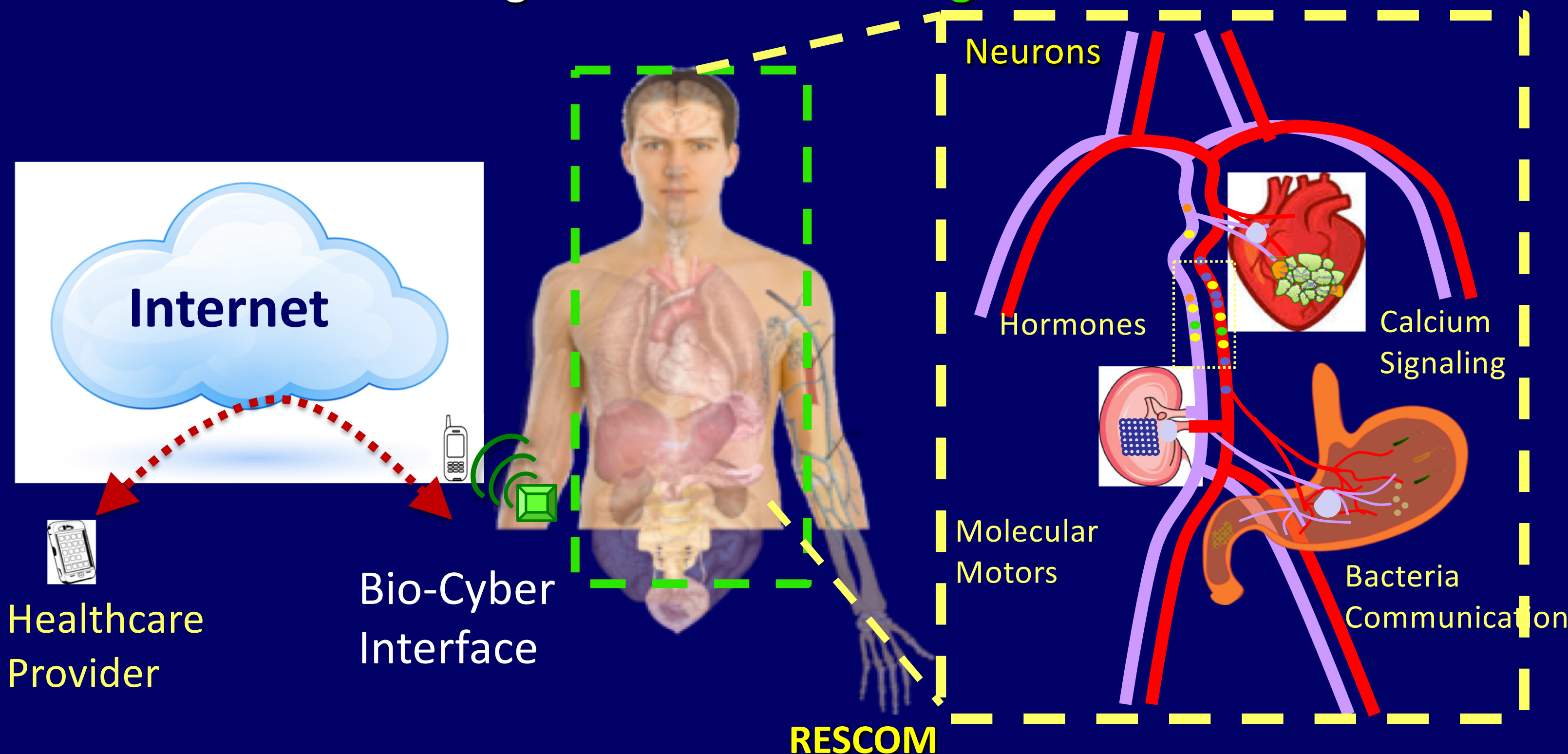


INTERNET OF BIO-NANOTHINGS:

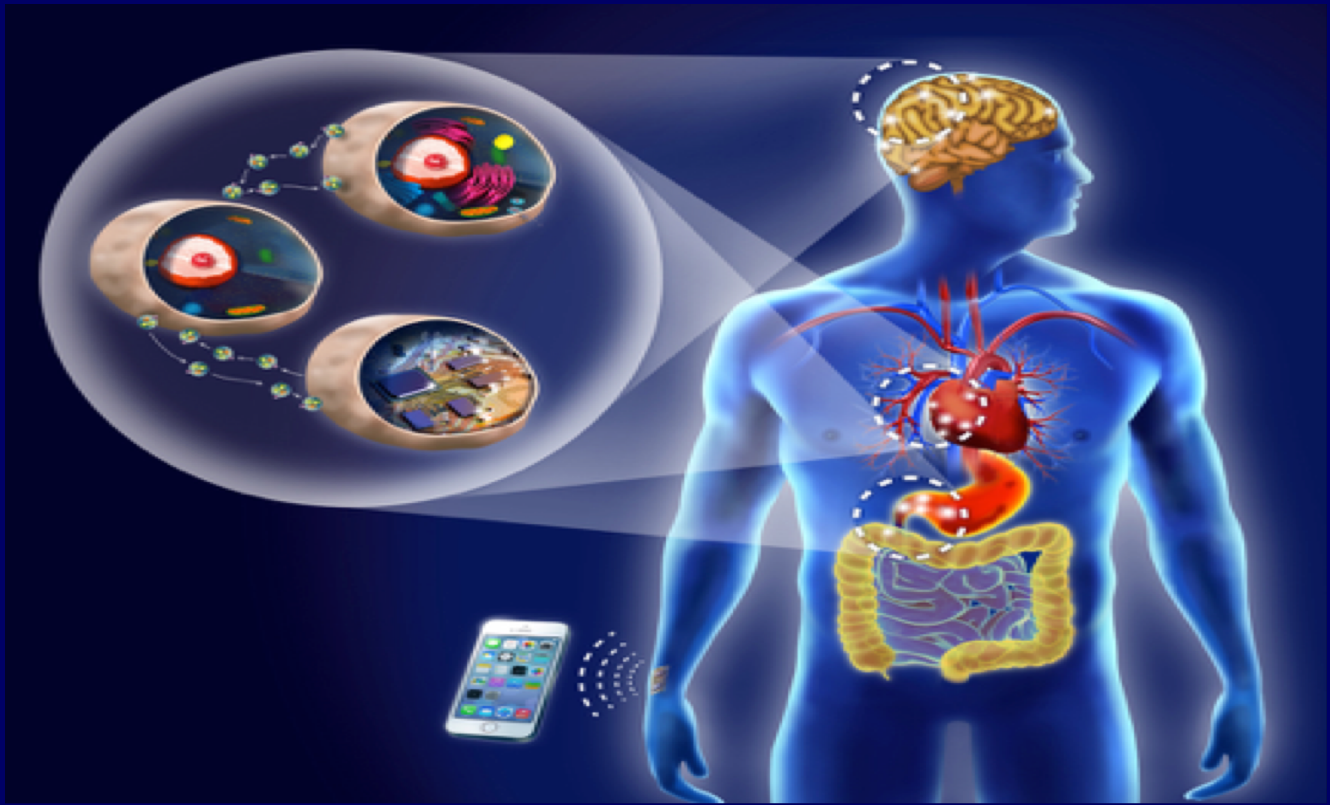
I.F. AKYILDIZ, M. PIEROBON, S. BALASUBRAMANIAM, Y. KOUCHERYAVY,
"THE INTERNET OF BIO-NANOTHINGS",
IEEE COMMUNICATIONS MAGAZINE, VOL. 53, NO. 3, PP. 32-40, MARCH 2015

Objective:

To interconnect the heterogeneous Bio-NanoThing Networks to the Internet



Internet of Bio-NanoThings:
Network Architecture



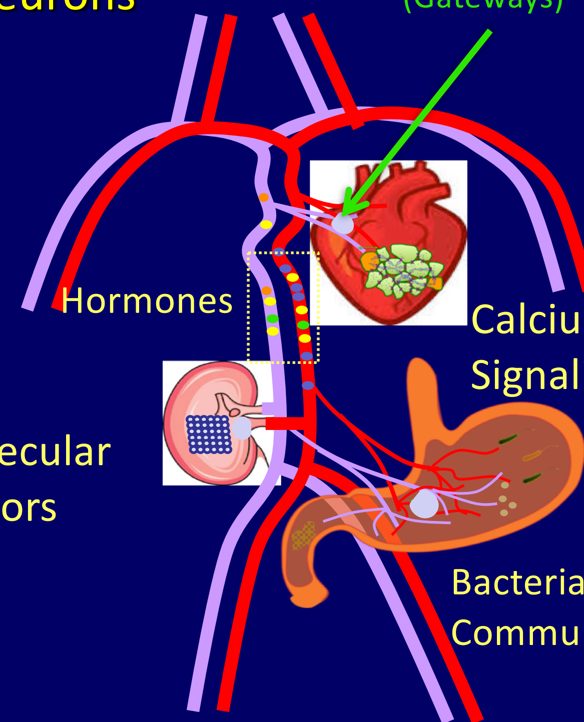
HETEROGENEOUS BIO-NANOTHINGS NETWORK

Challenge

- Translating information between the different Bio-NanoThings networks.

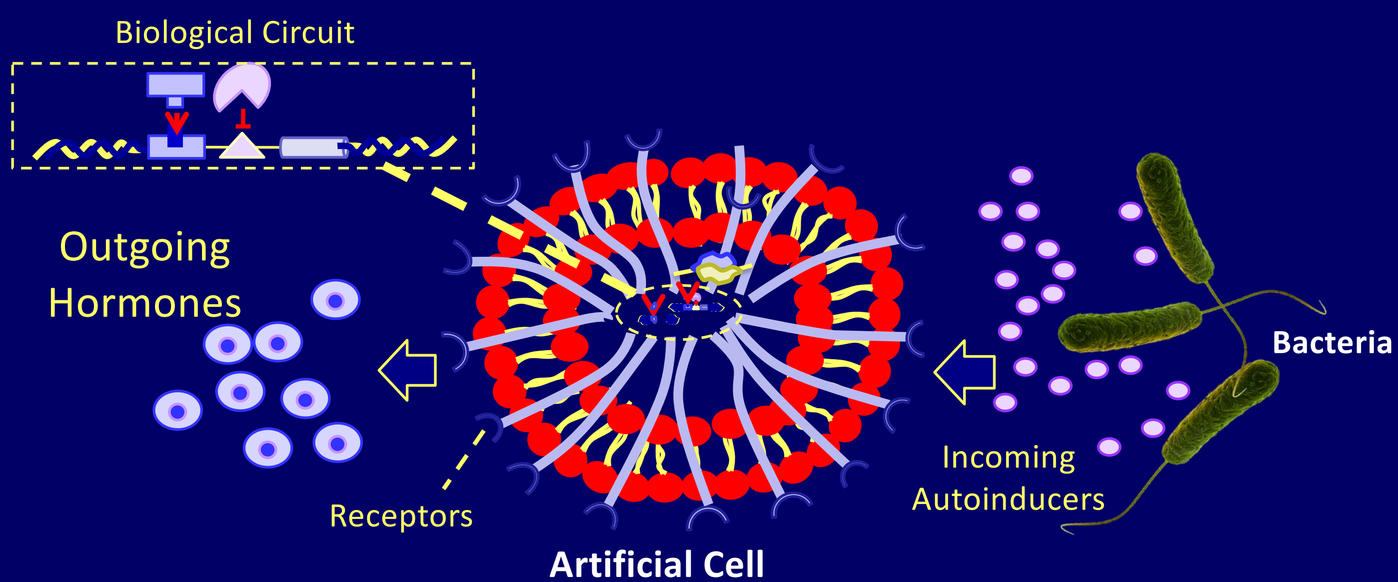
Approach

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



ARTIFICIAL CELLS AS GATEWAYS

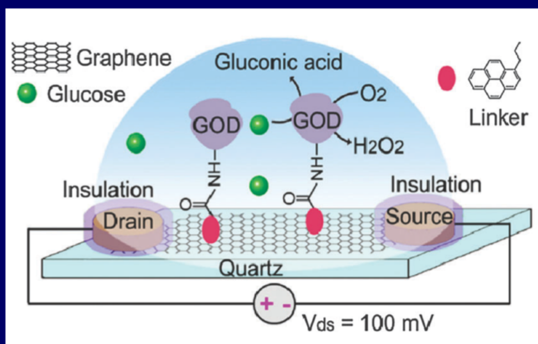
- **Receptors intercept the incoming molecules (e.g.,autoinducers from bacteria).**
- **Activates Biological Circuit to synthesize outgoing molecules (e.g., hormones)**

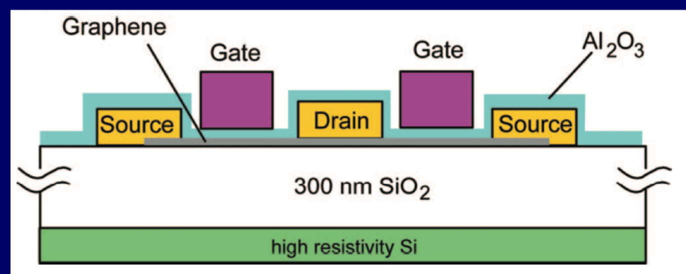


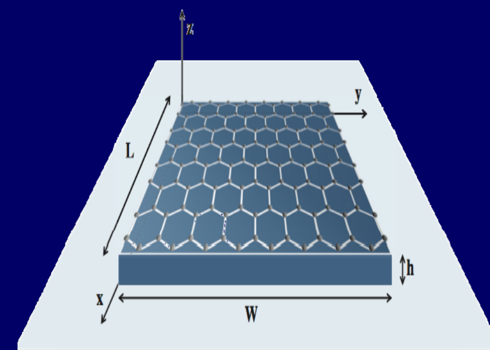
BIO-CYBER INTERFACE:

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







Hormones, Calcium Ions, etc. → MC Receiver → Processing Unit → EM Antenna → EM Waves

Battery

FURTHER CHALLENGES

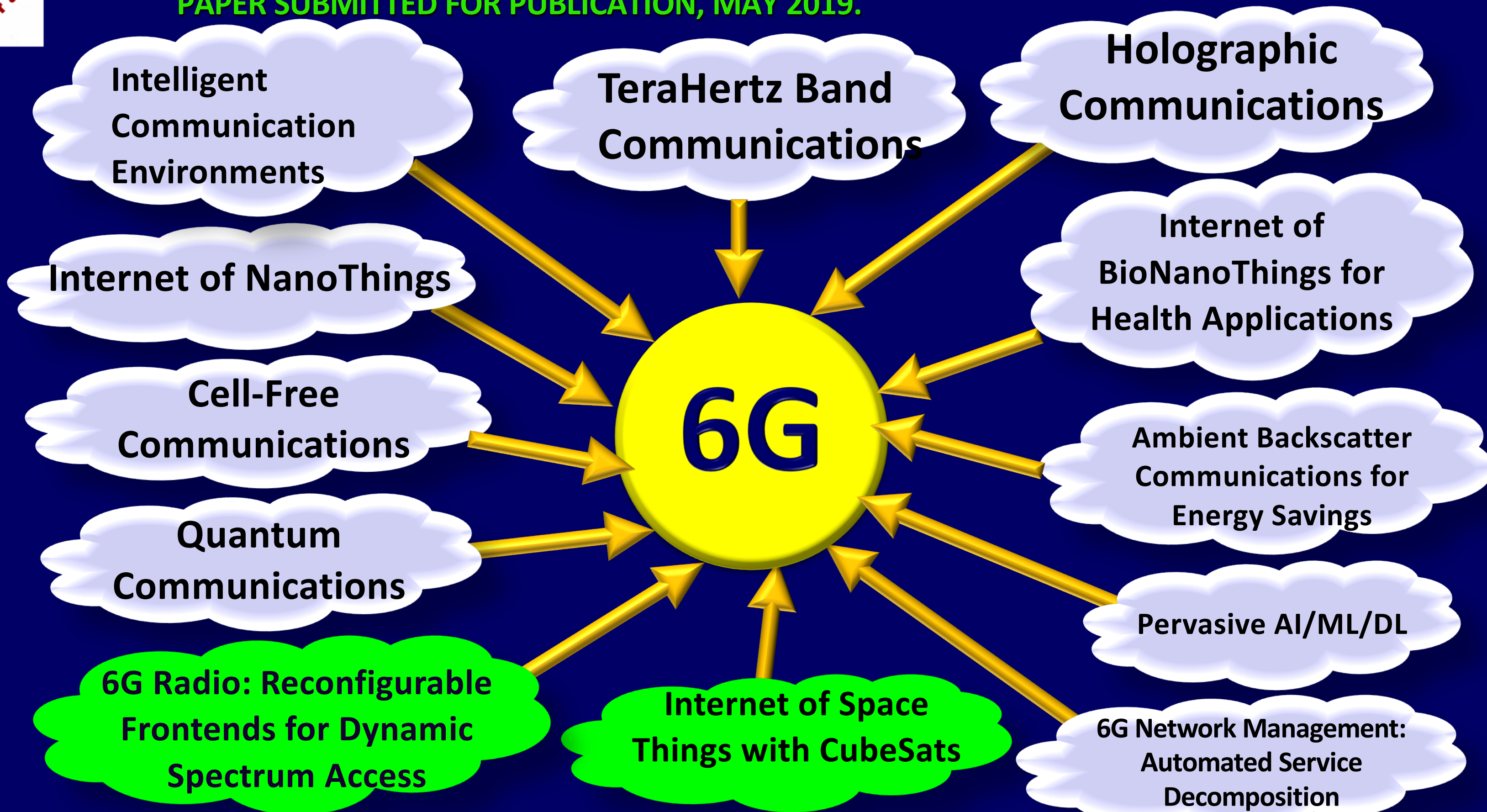
Interconnecting IoBNT to IoNT to IoT

* 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.

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.

KEY TECHNOLOGIES FOR 6G

I. F. AKYILDIZ AND S. NIE,
"6G: NEXT FRONTIER IN WIRELESS COMMUNICATIONS"
PAPER SUBMITTED FOR PUBLICATION, MAY 2019.



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I. F. Akyildiz et.al.
"A New CubeSat Design with Reconfigurable Multi-Band Radios for Satellite Communication in Dynamic Spectrum Frequencies",
Ad Hoc Networks, vol. 86, pp. 166-178, April 2019.
Patent applied, Dec. 2018.

I. F. Akyildiz and A. Kak,
"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.

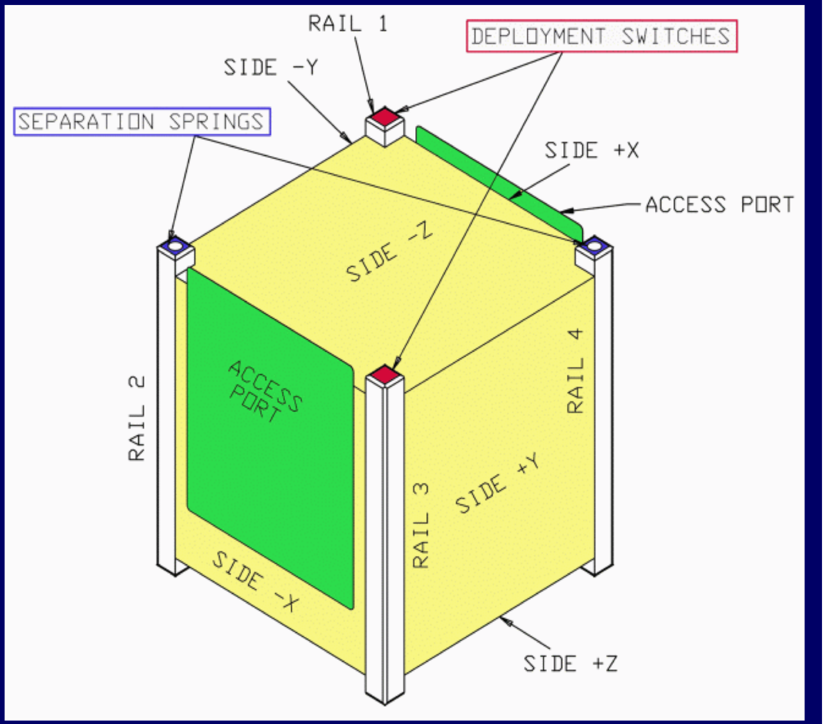
DISADVANTAGES OF CONVENTIONAL SATELLITES

- **Long development and deployment cycles**
  - Typical development and deployment cycle: ~7 years
- **High construction and launch costs**
  - For example, Iridium NEXT cost > $3 billion

e.g., 2016 Hitomi Telescope failure led to loss of ~$300 million, and 10 years of research

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

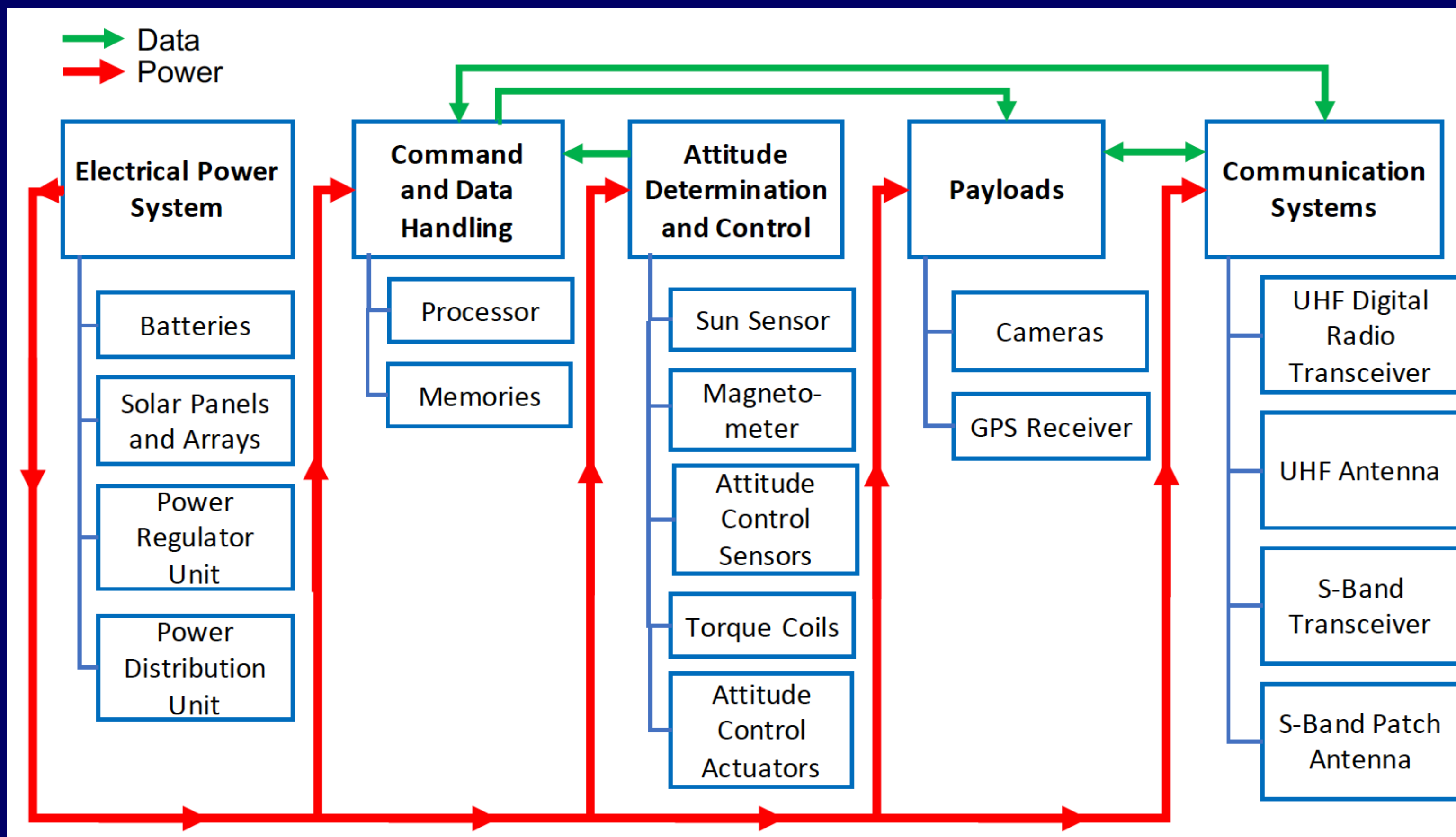


Original CubeSat Specification

ADVANTAGES OF CUBESATs

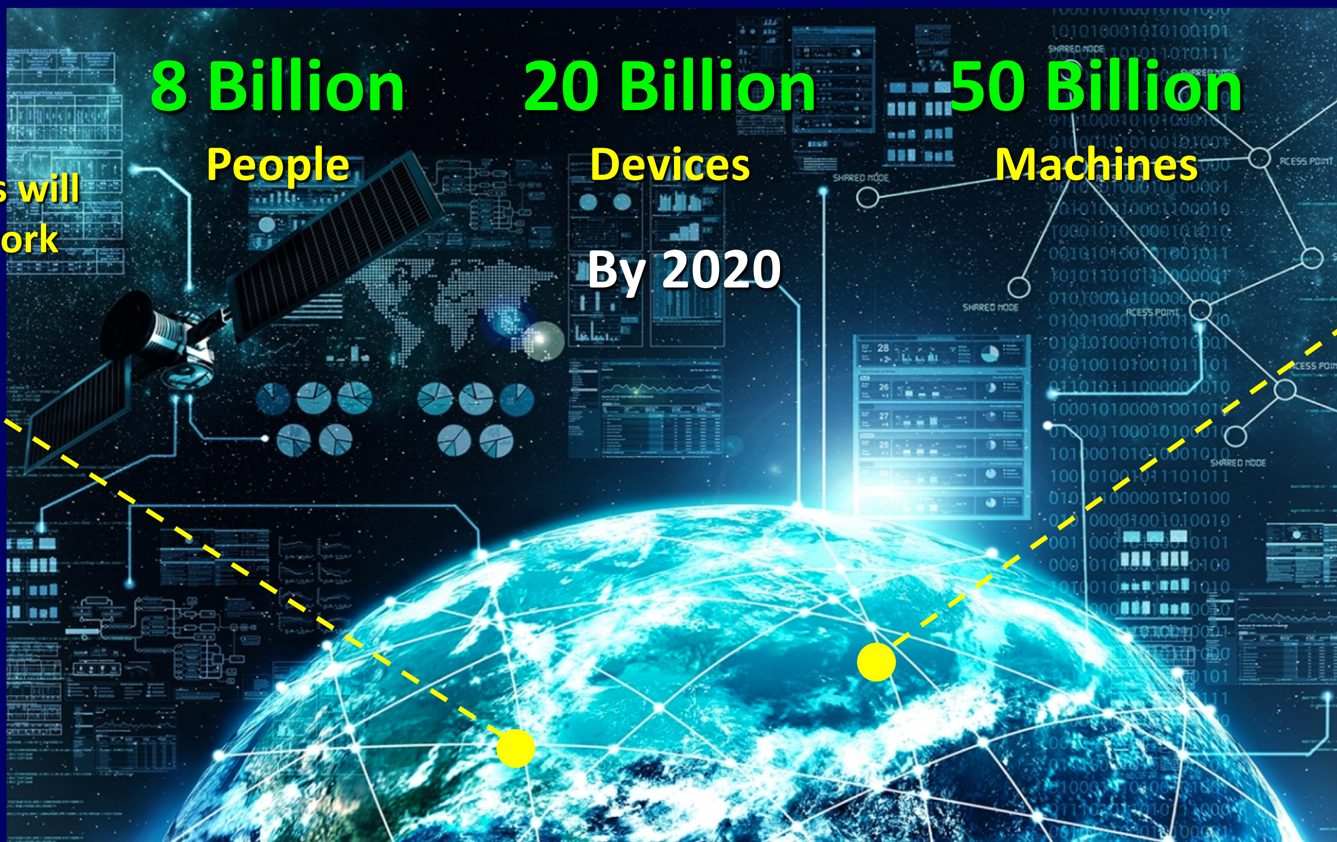
- Scalable
- Flexible
  - Cooperation with Drones, UAVs & Rovers
- Low Cost
- Built with commercial off-the-shelf components
- Short “development to deployment” period

FUNCTIONAL COMPONENTS OF CUBESATS



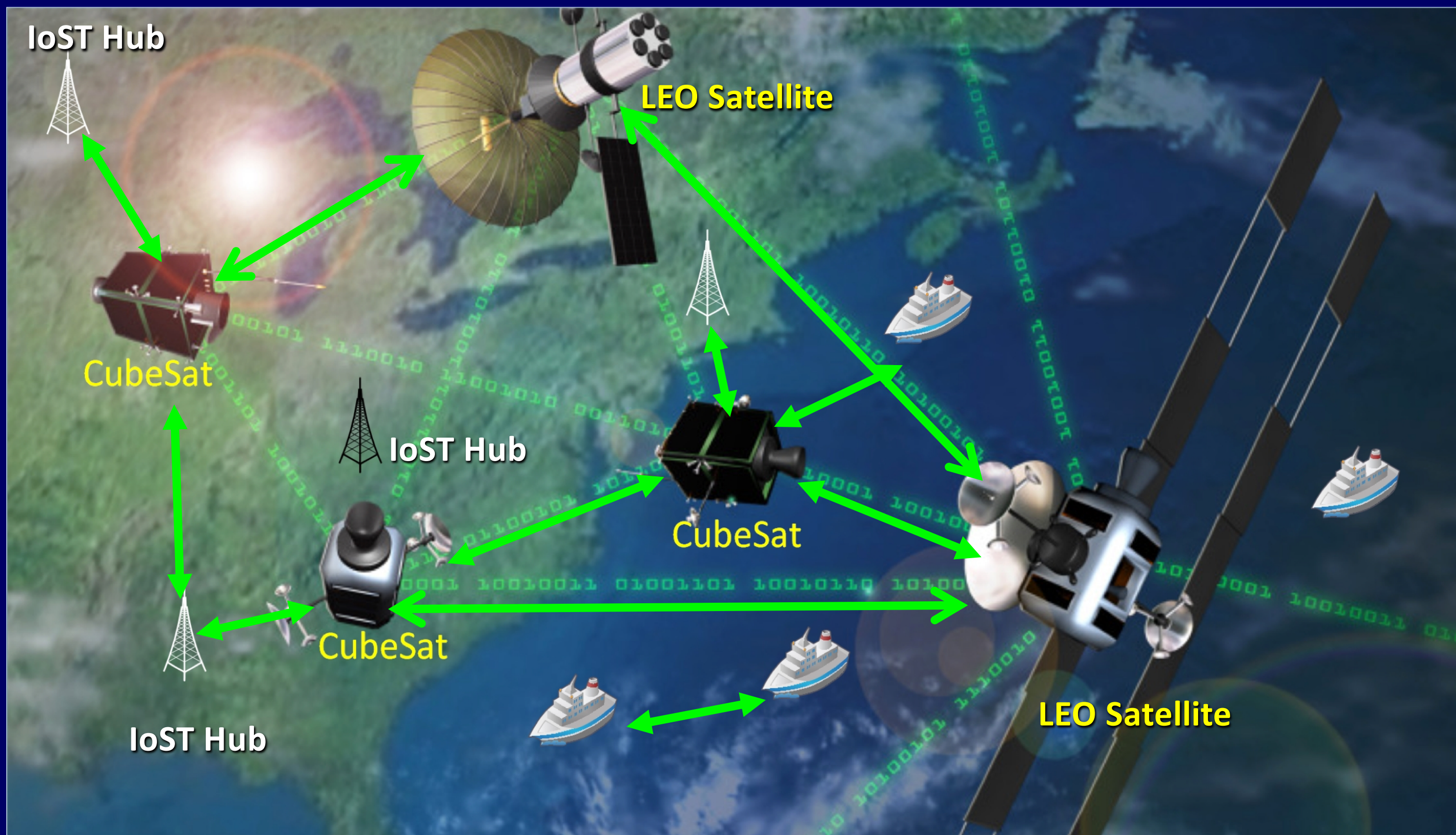
GLOBAL OPPORTUNITY FOR IoT IN SPACE

100% business will require network services



$8.9 Trillion in M2M spending

INTERNET OF SPACE THINGS/CUBESATS



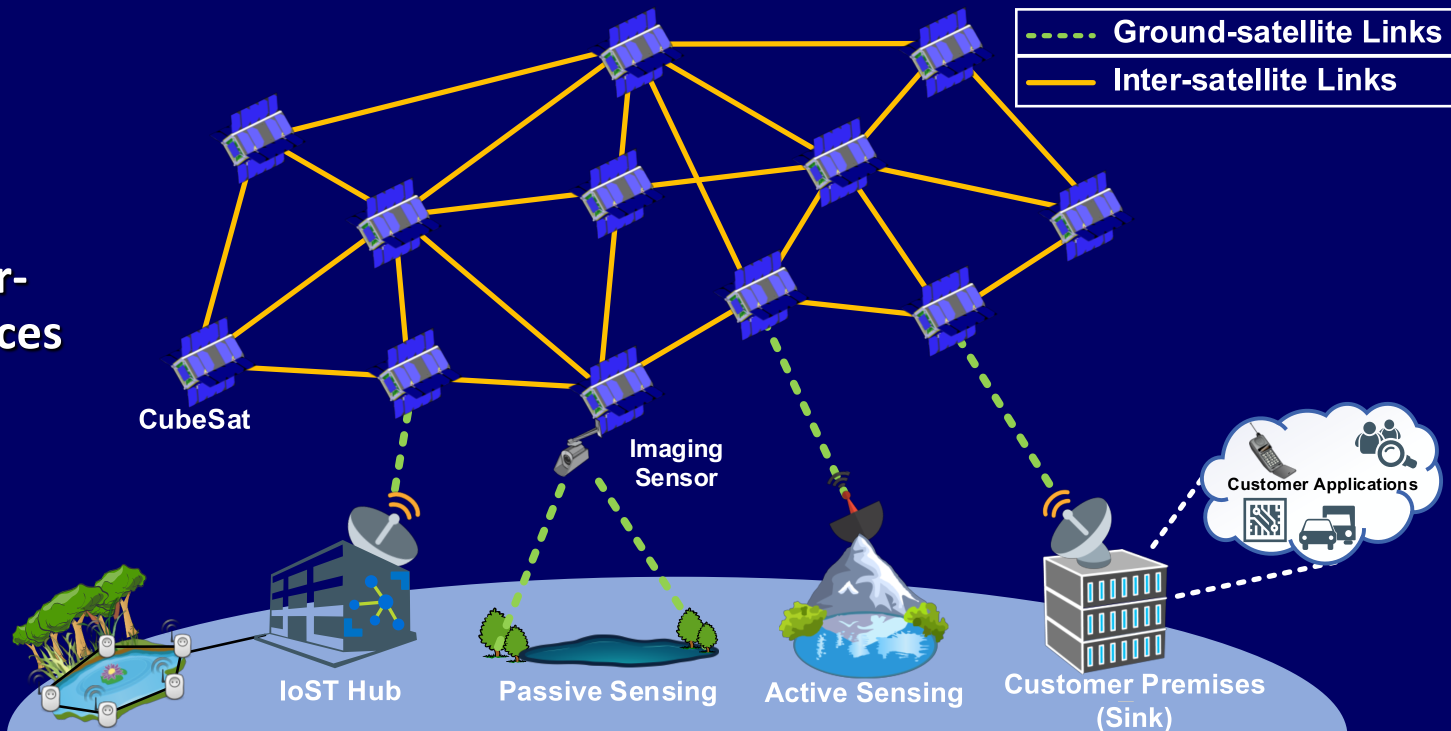
EXISTING SATELLITE-BASED IoT AND BROADBAND NETWORKS

Name	Iridium NEXT SensorPOD	Tintin	Astrocast	Fleet	KIPP	Aistech
Company	Iridium Comm., USA	SpaceX, USA	ELSE, Switzerland	Fleet, Australia	Kepler, Canada	Aistech, Spain
Purpose	Sensing & communications	Broadband network	IoT & M2M	IoT	Satellite backhaul	IoT, M2M & asset tracking
ISL Capability	Only to host satellite	Yes	Yes	N/A	Yes	N/A
Deployment Year	2015	2015 (Trials)	2018	2018	2018	2018
Orbital Altitude	780 km	340, and 1200 km	450–600 km	580 km	500–650 km	N/A
No. of Satellites	66	7518 and 4425	64	100	140	100
Form Factor	4.5U	Not a CubeSat	3U	1.5U, 3U, and 12U	3U	6U
Weight	4-5 kg	100-500 kg	4 kg	N/A	5 kg	N/A
Frequency Band	L and Ka	V, Ka, Ku, > 10 THz	L	N/A	Ka and Ku	N/A
Self-sustained	No (Host dependent)	Yes	Yes	Yes	Yes	Yes

Note: “N/A” means the parameter is not available in published sources.

INTERNET OF SPACE THINGS – ARCHITECTURE

- **Primary Components**
  - IoST Hubs
  - On-Earth, and Near-Earth Sensing Devices
  - CubeSat Network



OUR RESEARCH: *-CUBESAT (2018 – 2022)

Objective: To develop Internet of Space Things, a cyber-physical system that expands across ground, air, and space, to enhance the functionalities of wireless communication networks.

Next Generation CubeSat Hardware Design Operating in Multi-frequency Bands

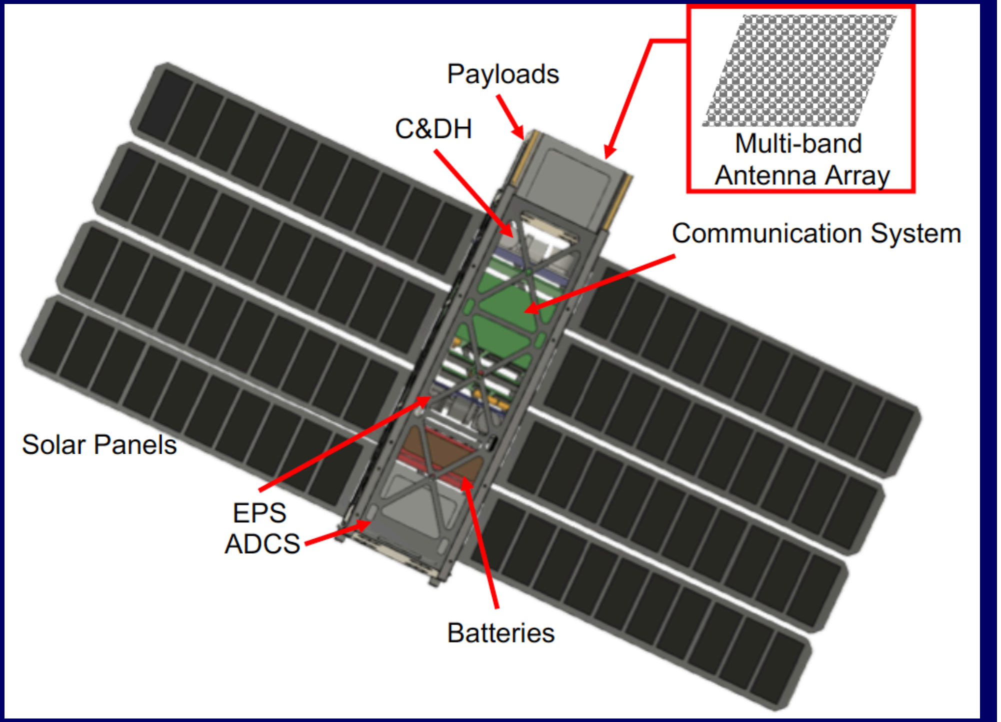
- Multi-frequency transceiver design
- Massive and Ultra-Massive MIMO communications
- Distributed MIMO Communications
- Global Resource Allocation Techniques

Software-defined Networking with Network Function Virtualization

- Dynamic and scalable network configuration
- Satellite-Infrastructure-as-a-Service (SIaaS)
- Generic solution for ubiquitous connectivity
- Security provision

OUR RESEARCH: IoST - CUBESAT (2018 – 2022)

- **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
- **Novelties in communications system design**
  - Multi-frequency transceiver
  - Multi-frequency antenna arrays
  - Global resource allocation strategies

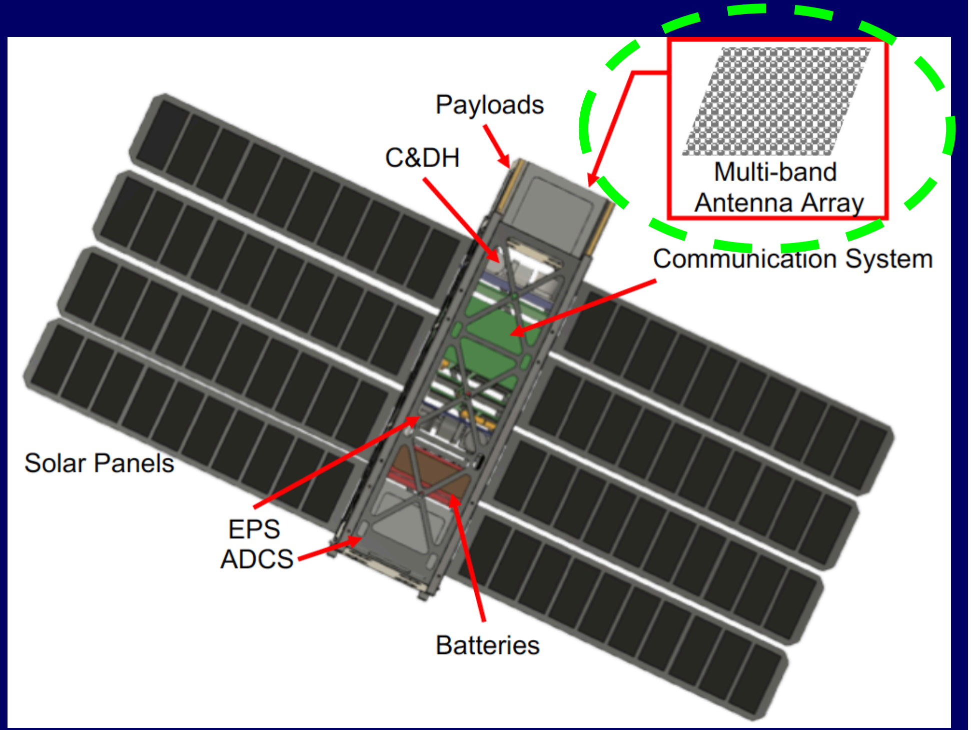


Our IoST CubeSat

IoST CUBESAT MULTI-BAND ANTENNA ARRAYS

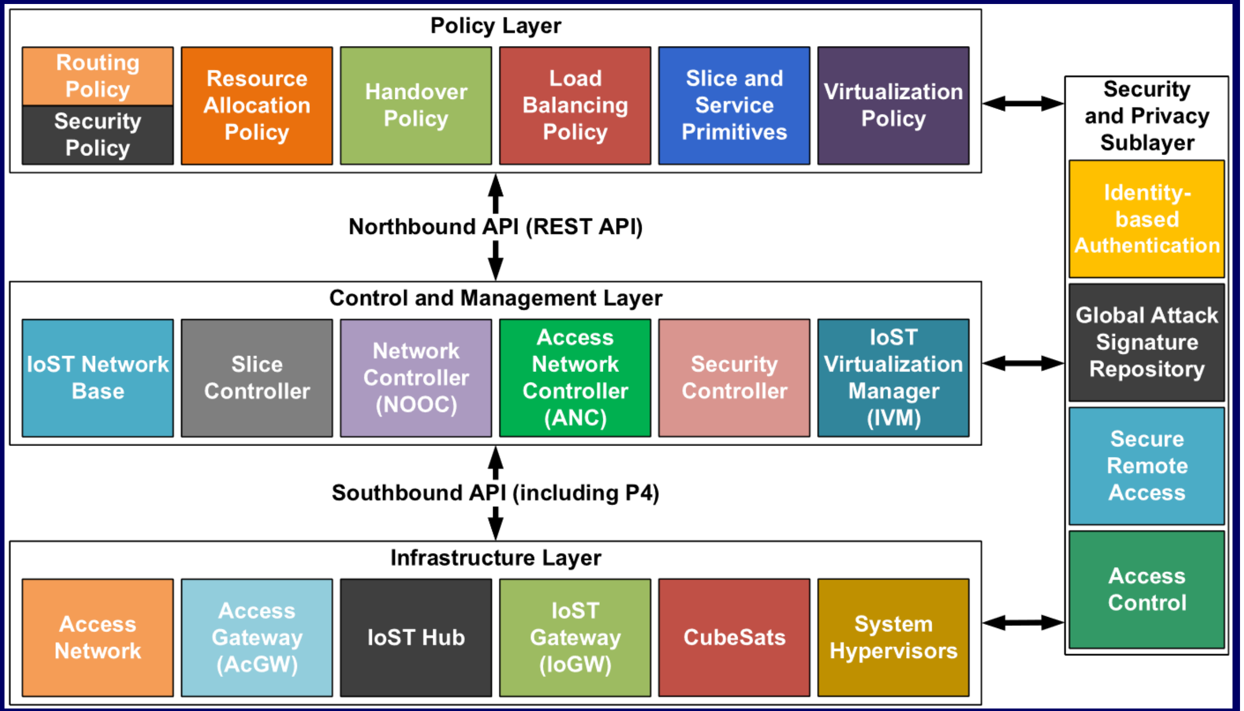
- Multi-band antenna array can operate in frequencies
  - C-band (3.4–6.4 GHz)
  - X-band (8–9 GHz)
  - Ku-band (12–18 GHz)
  - Ka-band (23–27 GHz)
  - Mm-wave (30 – 300 GHz)
  - THz frequency band (0.3 – 10 THz)

Conventional Satellite Comm. Freq.



SDN AND NFV-BASED SYSTEM ARCHITECTURE: LAYERED APPROACH

- Infrastructure Layer
- Management and Control Layer
- Policy and Orchestration Layer
-
- Security and Privacy Sublayer



MANY OPEN RESEARCH CHALLENGES

- IoST expands traditional IoT through
  - Always-available satellite backhaul
  - Real-time information sensing
  - Holistic integration of on-ground data and aerial information

- IoST is enabled by
  - Next generation CubeSat design
    - Multi-frequency front-ends
    - Multi-frequency antenna systems
  - Novel network orchestration and control architecture
    - SDN/NFV-based approach
  - Artificial intelligence for smart resource allocation strategies
    - Deep neural networks

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