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Wireless Century Perspectives

5G/Internet of Things (IoT) and a Vision for 6G/IoE (Internet of Everything)

"*It is dangerous to put limits on wireless.*" Guglielmo Marconi (1932)

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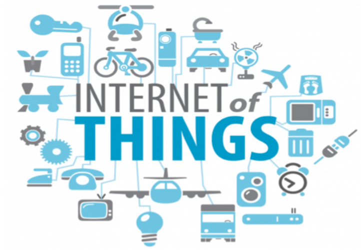


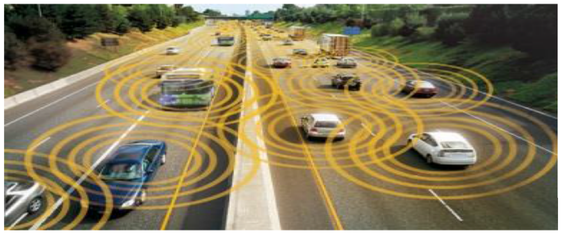
=> ***The Wireless Century***

- Mobile Communications: Decades of "Big Leaps" between generations
- 5G Drivers, Vision, and Revolution
- Application Scenarios and Requirements
- Standards and Spectrum Availability
- 5G Revolutionary Technology and Research Issues
  - Network Architecture and Protocols,
  - Radio Access Virtualization
  - Software-based Networking
  - Fog Computing/Edge Networking
- Impact of Machine Learning
- 6G Vision
  - IoE (Internet of Everything)
  - A New Wireless Frontier: *In Vivo* Communications and Networking
- Concluding Remarks

The 5G Revolution

- The **5G/IoT r**evolution is being driven by technologies that can communicate immense amounts of data at unprecedented speeds that will:
  - Fuel new services: autonomous vehicles, precision robotic control, telemedicine, future factory ..
  - Shrink perceptions of distance with exponentially faster communication and imperceptible delay,
- **5G high-impact technologies to meet the demands include**
  - HetNets, Edge Computing, Massive MIMO, mmWave, SDN/NFV, SON, network slicing, NOMA, …
  - Machine Learning (ML) will impact most of these technologies.
- **Potential impact of 5G is striking**
  - **Consumers**: immersive experiences (VR/AR), higher mobile data rates and Internet of Things (IoT) connectivity will revolutionize interactions with the world around them.
  - **Enterprises**: new, reliable wirelessly enabled IoT applications, drive industries towards the Fourth Industrial Revolution, and create new opportunities to improve efficiency.
  - For **service providers**:
    - New service architecture, resilient, and self organizing networks
    - New markets (above)
    - **End of cellular paradigm**?

Mobile Broadband



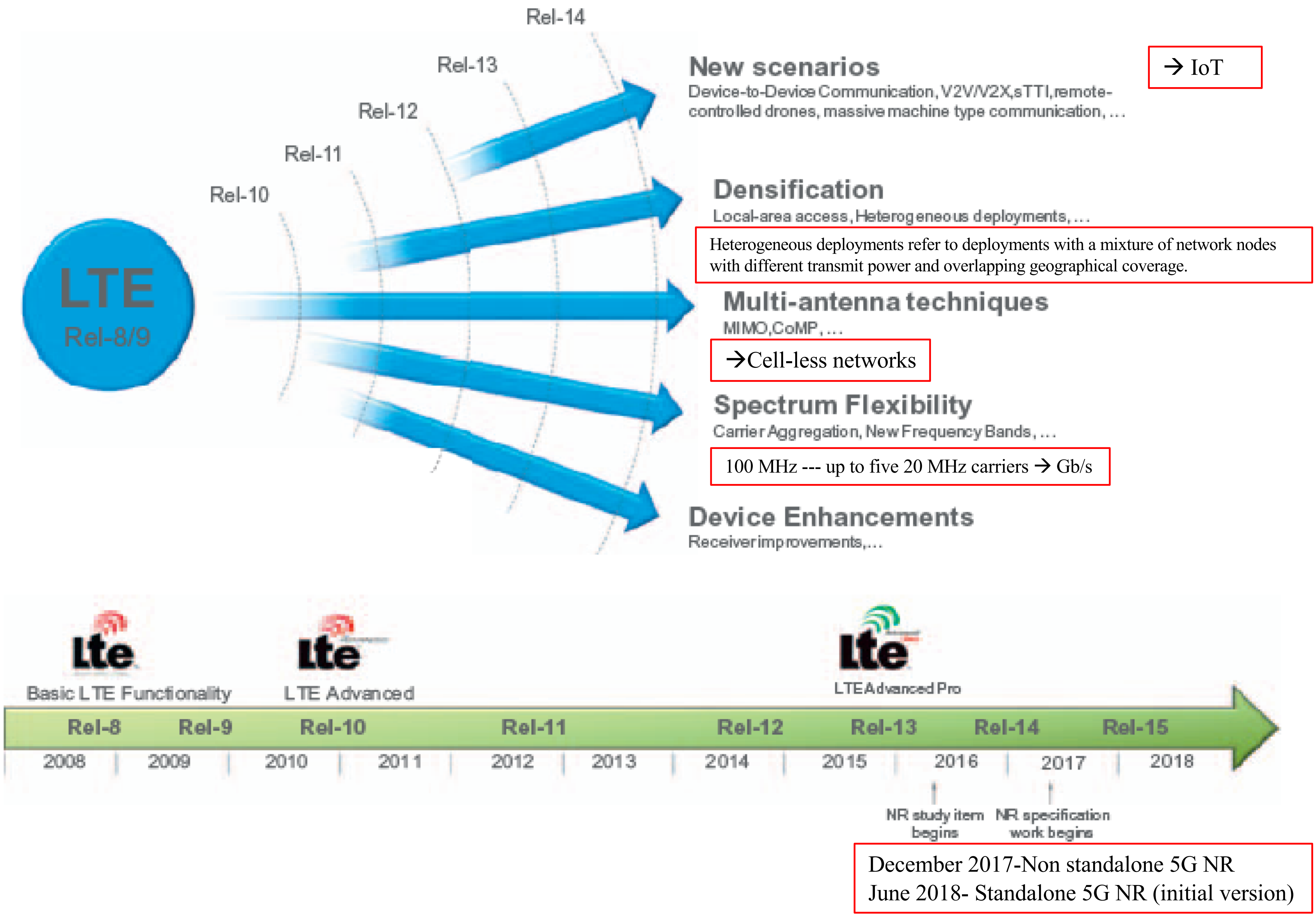
Low Latency
(Autonomous Vehicular Networks, Tactile Internet)

Internet of Things
(Machine to Machine Communications)

Cloud Services
SDN =Software Defined Network
NFV = Network Function Virtualization

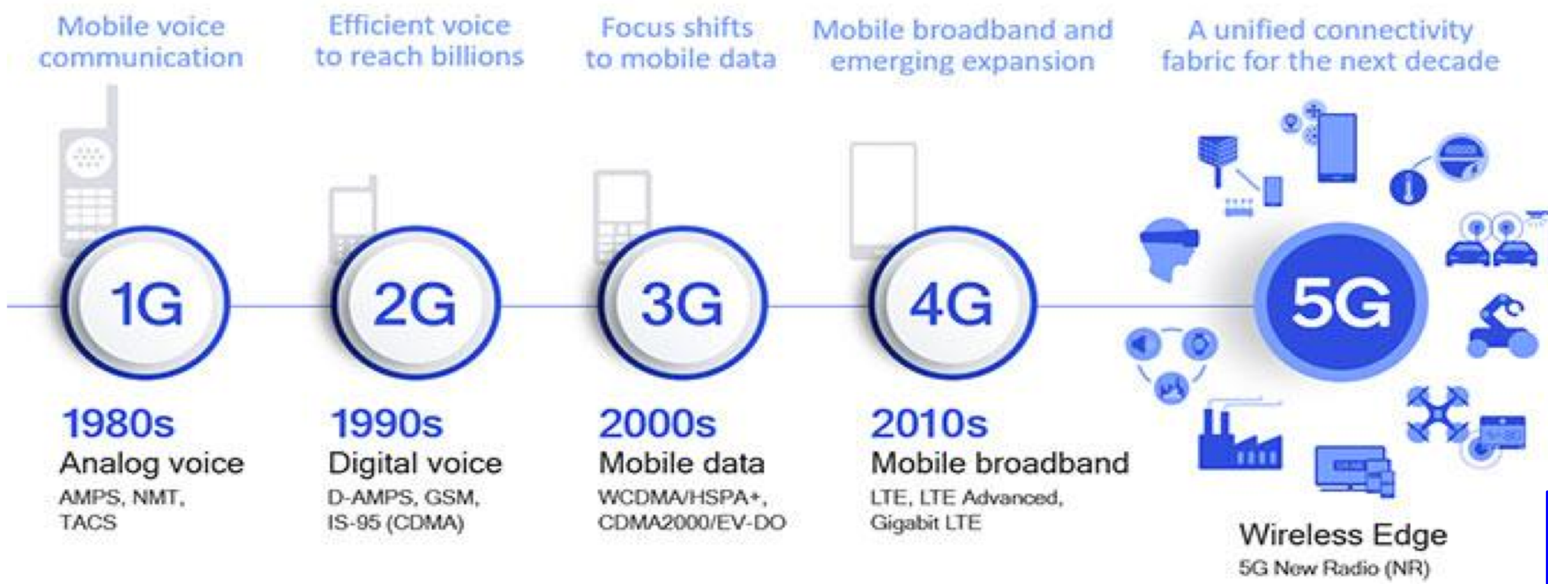
5G Initial Applications

LTE Evolution over a Decade



Mobile Communications Has Made a Big Leap ~Every 10 Years

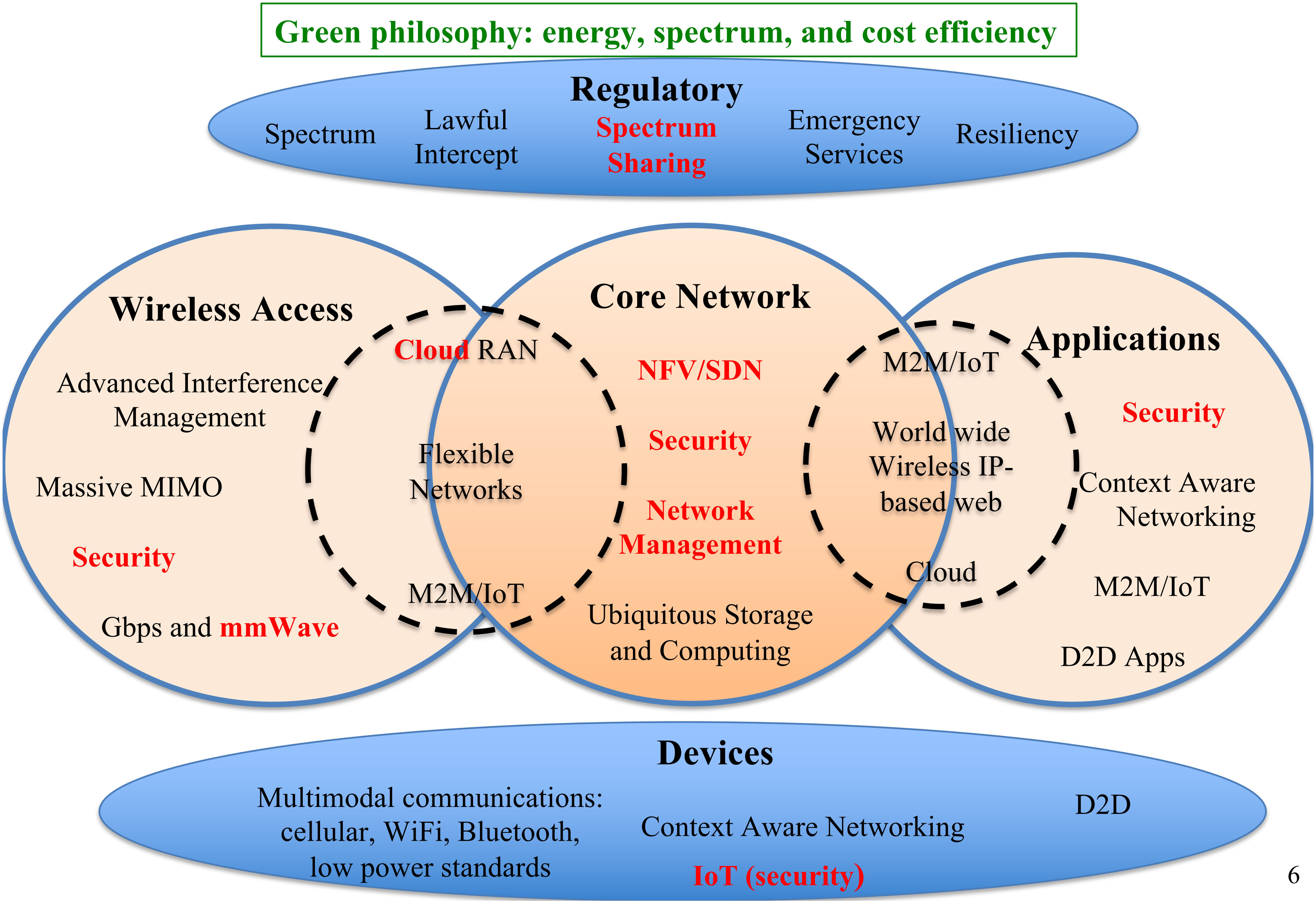
5G NR (New Radio) --> 5G Next Revolution



Courtesy: Qualcomm

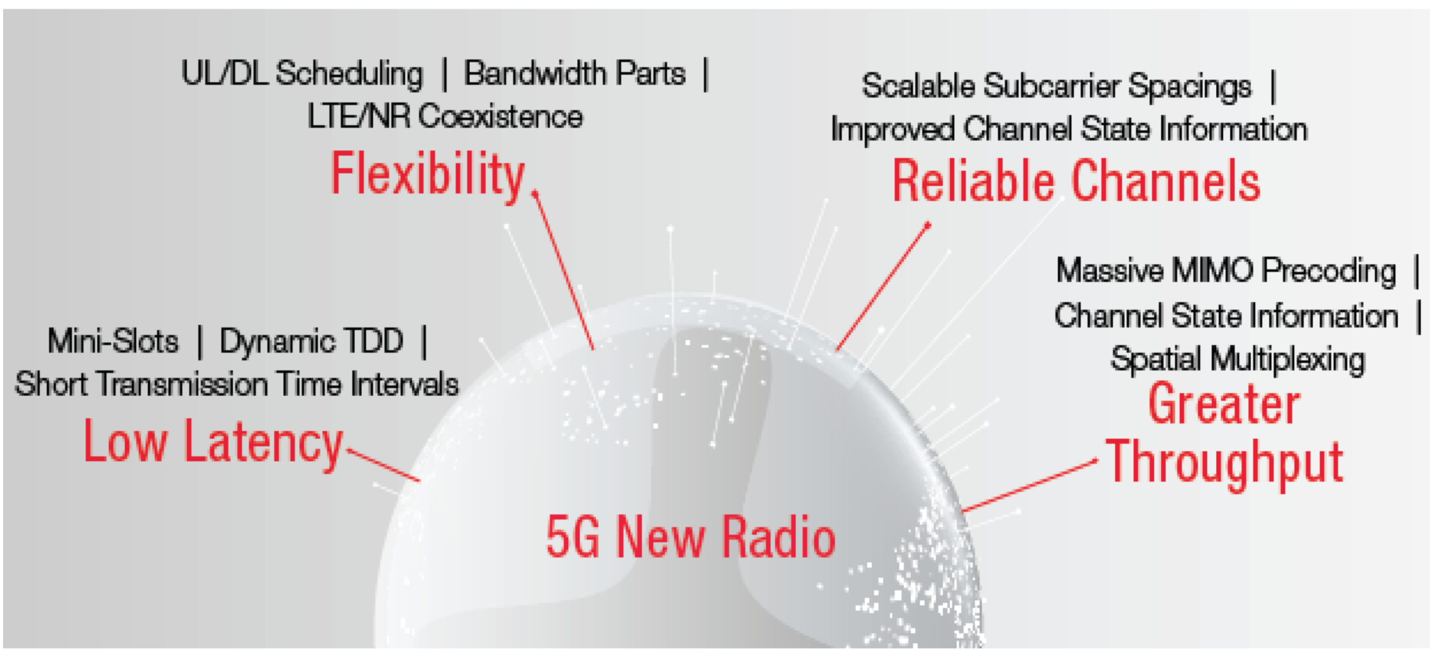
- LTE was an Evolution
- 5G has **revolutionary** architecture, throughput, latency, spectral efficiency, virtualization, …
- 5G NR devices and networks being launched at a rapid rate — significantly faster and more globally than during the first year of LTE.
- In 2019 focus on 5G NR enhanced mobile broadband (eMBB) — and fixed wireless access.
- 5G expectations for 2020
  - Devices: Proliferation to more smartphone tiers and reaching more consumers, expanding to new global markets and device classes such as the always-connected PC.
  - Networks: Coverage in both sub-6 GHz and mmWave will grow and Dynamic Spectrum Sharing (DSS) between licensed and unlicensed users and support for direct migration from today's non-standalone (NSA) networks to standalone (SA) networks will facilitate growth.

Functional View of the 5G Ecosystem

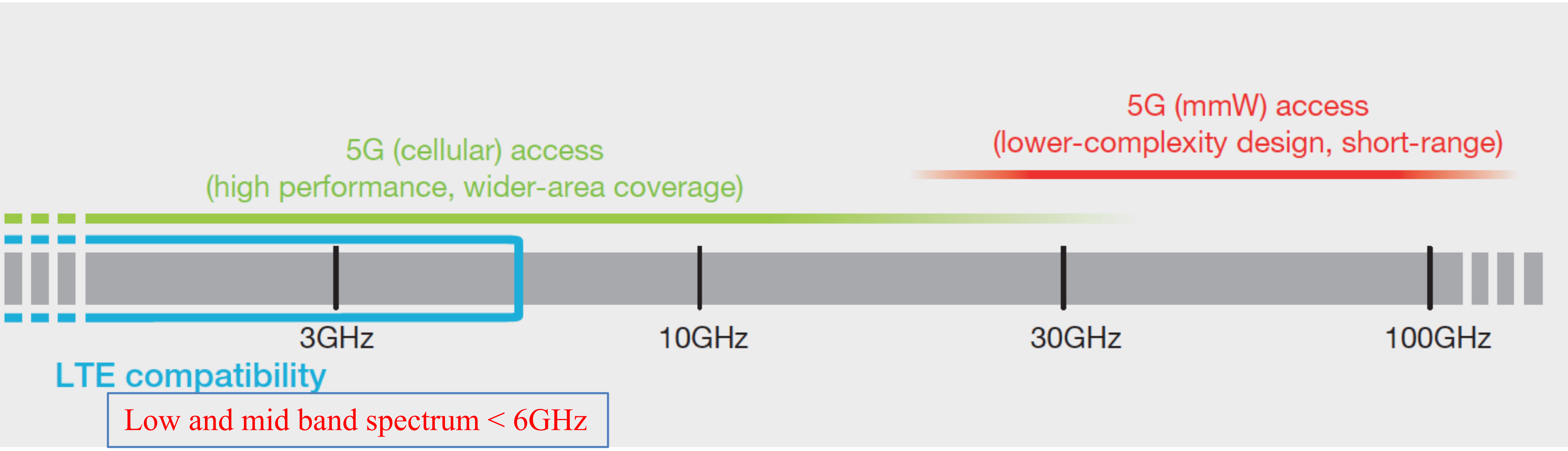


5G New Radio (5G NR)-December 2017

- Rel 15 focus on enhanced mobile broadband (eMBB) and ultra-reliable, low-latency communications (URLLC) to achieve very fast data rates and provide very low latency.
- 5G NR is expected to work alongside 4G and even utilize the 4G core network for both data and control planes in non-standalone mode (NSA). DSS will enable 5G, 4G, and Wi-Fi to coexist on the same carriers and utilize unlicensed bands to increase capacity below 6 GHz.
- Technology components of 5G NR – the figure below maps how different specifications will contribute to delivering a flexible and scalable physical layer
  - Flexible time and frequency intervals enable low latency (OFDM scalable *numerology*).
  - Massive MIMO and mmWave beam steering enable higher throughput and capacity gains, but also introduce new challenges in beam management.
  - mmWave spectrum up to 52.6 GHz: carrier bandwidth of 400 MHz and up to 16 component carriers that can be aggregated up to 800 MHz



5G Spectrum



- In order to offer a broadband 5G experience, network operators are combining the use of low-band (< 1 GHz), mid-band (1- 6 GHz), and high-band (mmWave) spectrum assets for 5G deployments.
- US spectral bands:

  Low-band: 600 MHz, 700 MHz, 800 MHz, 900 MHz
  Mid-band: 2.5 GHz, 3.5 GHz, 3.7-4.2 GHz
  Millimeter wave (high-band): 24 GHz, 28 GHz, 37 GHz, 39 GHz, 47 GHz

- Mid-band and high-band systems are TDD.
- Propagation characteristics, implementation, and compatibility issues imply that the 5G wireless-access solution will most likely consist of multiple radio interfaces. **See 3GPP 38.901 Channel Model.**
- OFDM-based transmission technologies are the baseline, although the details will probably need to be adjusted for frequencies above 10 GHz.
- For higher frequency bands – a few tens of GHz and above – propagation characteristics and implementation aspects will likely dictate a more simplified radio-interface structure targeting short-range communication for ultra-dense deployments.

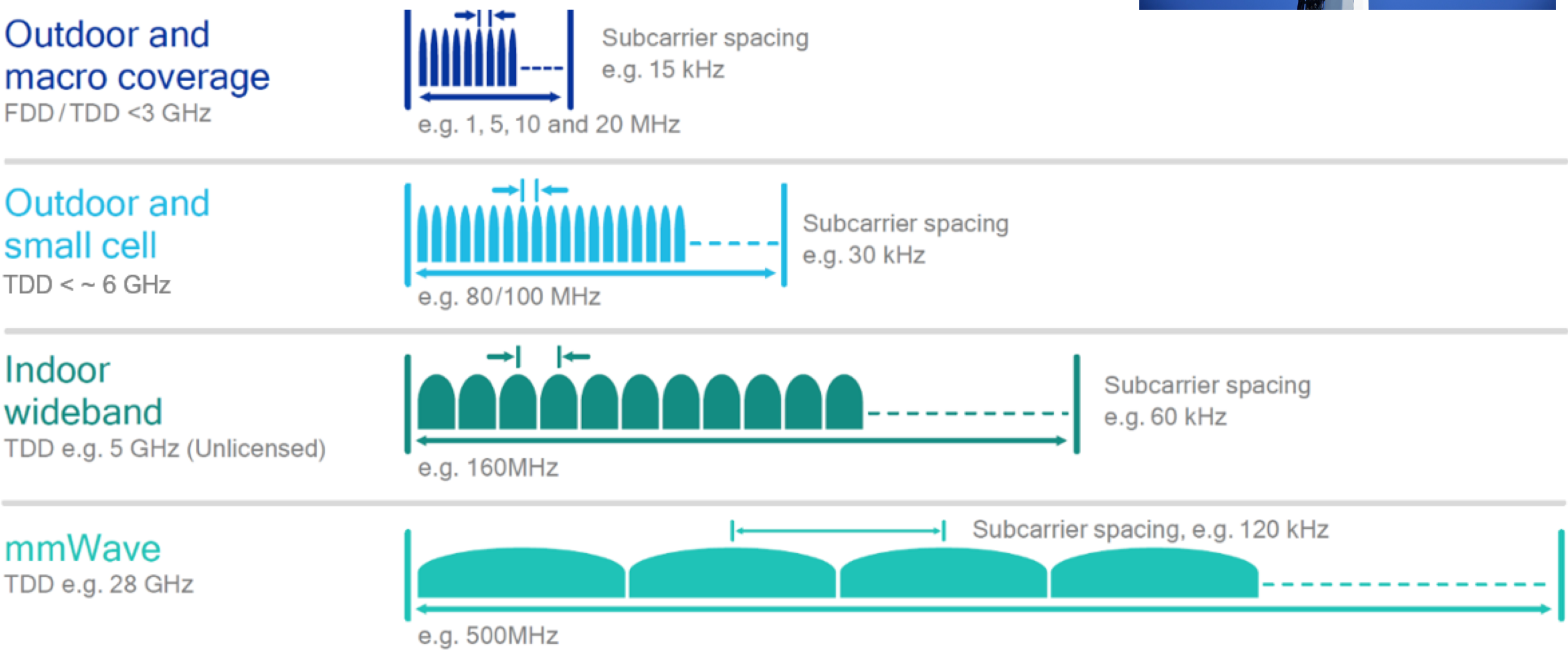
5G NR Release 15 Frequency and Waveform Specifications

Frequency FR= Frequency Range	FR1: 450 MHz - 6 GHz FR2: 24.25–52.6 GHz
Maximum Carrier Bandwidth	FR1: Up to 100 GHz FR 2: Up to 400 MHz
Sub Carrier Spacing Scalable OFDM numerology	Sub-6 GHz: 15 kHz, 30 kHz, 60 kHz >6 GHz: 60 kHz, 120 kHz, 240 kHz
Maximum number of Subcarriers	3300 (up to 4096 FFTs)
Carrier Aggregation	Up to 16 carriers, maximum of 800 MHz BW
Waveform & Modulation	CP-OFDM (UL/DL): QPSK, 16QAM, 64QAM and 256QAM DFT-s-OFDM (UL): π/2-BPSK, 16QAM, 64QAM and 256QAM
MIMO	8x8 MIMO Up to 8 layers in downlink, up to 4 layers in the uplink

- CP-OFDM (cyclic prefix OFDM) is the modulation format in the downlink (DL) and uplink (UL). SC-FDMA is optional in the uplink. Note 256-QAM.
- NR scalable OFDM numerology (μ) where the subcarrier spacing not fixed to 15 kHz.
    - Subcarrier spacing is governed by 2^{μ} x 15 kHz subcarrier spacing.
    - 15, 30, and 60 kHz subcarrier spacings are used for the lower frequency bands, and 60, 120, and 240 kHz subcarrier spacing is used for the higher frequency bands.
    - LTE has standard slot boundaries, which are not optimized for minimal latency. Scalable numerology enables scalable slot duration to optimize for different service levels in throughput, latency, or reliability.
    - In 5G NR a standard slot has 14 OFDM symbols and as the subcarrier spacing increases, the slot duration decreases. A mini-slot is shorter in duration (2, 4, or 7 OFDM symbols).
    - The cyclic prefix length also scales with the carrier bandwidth.

5G Air Interface: Scaling from Low, Mid, and to mm-Wave Bands

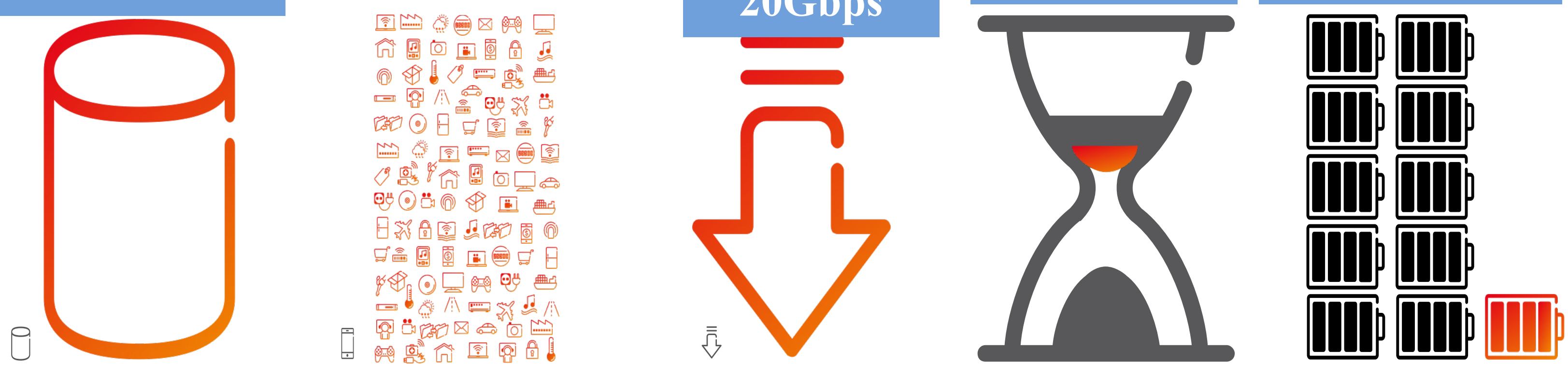
Scalable OFDM numerology: number of subcarriers, frequency band, subcarrier bandwidth, and slot duration



5G Drivers

Revolutionary Technology Is Required to Meet These Requirements

1000x data volume	50/500 B devices	Up to 10-20Gbps	Few ms E2E	10 years



1000x higher mobile data volumes	10-100x higher number of connected devices	10-100x typical end-user data rates	5x lower latency (1ms target)	10x longer battery life for low-power devices

IoT = Internet of Things

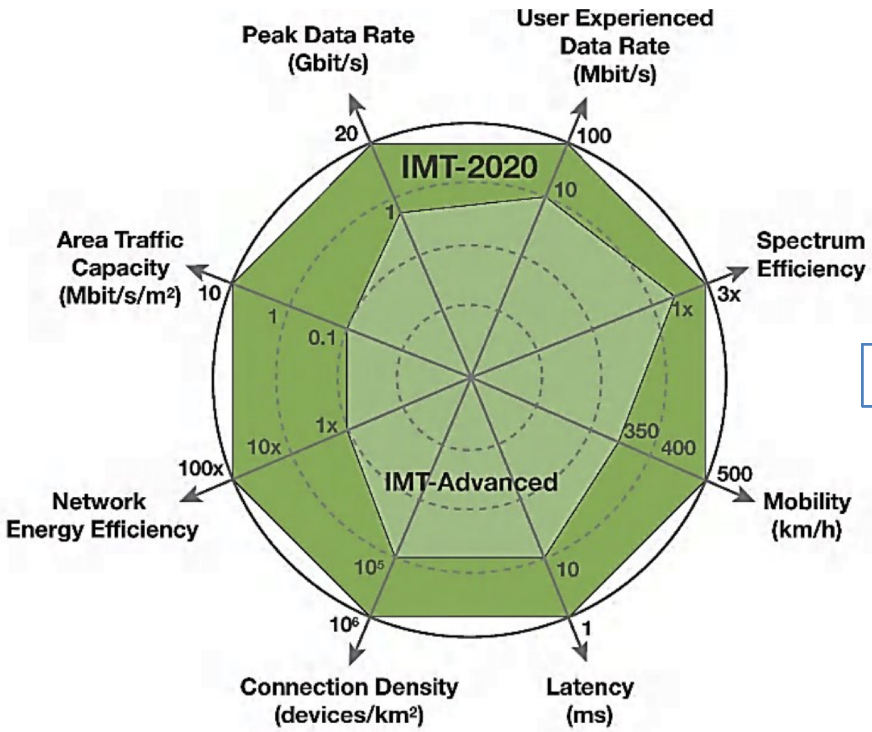
Plus: Security, Network Management, IoT integration, …

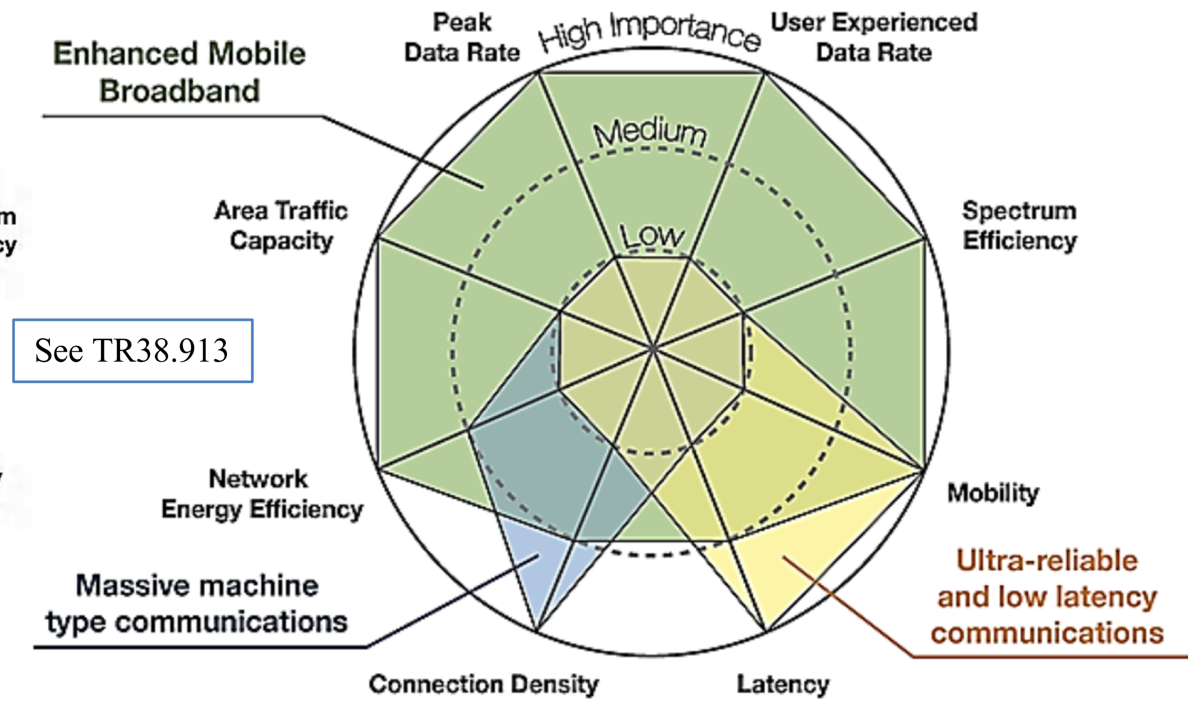
5G + IoT = A Century of Wireless Connectivity, Applications, and Opportunity

- Meeting 5G expectations will impact the way we live, work, play,…
- The impact will be transformational and will be central to everything we do, and forever alter how people access and use information, and will ultimately create...

The Wireless Century

5G *Revolutionary* Requirements and Research Directions-IMT 2020





Enhancement of key capabilities from IMT-Advanced to IMT-2020

<1ms air interface latency
5ms end-to-end latency

The importance of key capabilities in different usage scenarios

Research Directions to Meet Requirements: Many innovations driven by Machine Learning (ML)

- **Architecture:** Multi-tier (high/low power access points), dynamic, dense, high capacity and low latency, cooperating/cell-less, and heterogeneous (IoT/M2M/WiFi). A paradigm shift to a device/user-centric network
- **Software-driven networking**: SDN/NFV, network slicing, and SONs that enable adaptive and customizable networking and effective network management..
- **Higher capacity/low latency**: mmWave systems, Massive MIMO, cell densification, cognitive and non-orthogonal multiple access (NOMA), FDX systems.
- **Network Management**: The mix of high and low power base stations, WiFi hotspots, and peer-to-peer [D2D and M2M] and IoT connections, network management becomes a greater challenge.
- **Security and Authentication** for Device-to-Device, IoT, and networked systems with new models of trust and service delivery in an evolved threat landscape.

5G Revolutionary Networking Technologies

Technology	Description
Software-Defined Networking [SDN]	SDN is an approach to networking in which routing control is decoupled from the physical infrastructure enabling a networking fabric across multi-vendor equipment.
Network Function Virtualization [NFV]	NFV moves network services out of dedicated hardware devices into software. Functions that in the past required specialized hardware devices can now be performed on standard servers.
SDN/NFV Orchestration	The new network operating system. Supports lifecycle management, global resource management, validation and authorization of new requests, policy management, system analytics, interface management.
Fog Computing / Edge Computing	Extends cloud computing and services to the edge of the network and into devices. Similar to cloud, fog provides network, compute, storage (caching) and services to end users. **Fog networking reduces latency** and improves QoS resulting in a superior user experience.
Contextual Networking [CN]	5G may not deliver "infinite" bandwidth but it may well deliver a reasonable perception thereof. CN includes all categories of analytics (behavioral, predictive, etc.) and cross layer techniques applied to enable the more efficient and "just in time" use network capacity.
Information Centric Networking [ICN]	ICN directly routes and delivers content at the packet level of the network, enabling automatic and application-neutral caching in memory wherever it's located in the network. Improved mobility, security, privacy, resiliency, multicast support, etc.

- **PHY Innovations**: mmWave/beamforming, massive MIMO, NOMA, cell densification, cell-less nets
- **Machine Learning (ML):** Significant impact at all layers

5G Internet of Vehicles Scenario with C-V2X* Technology

Source: Qualcomm

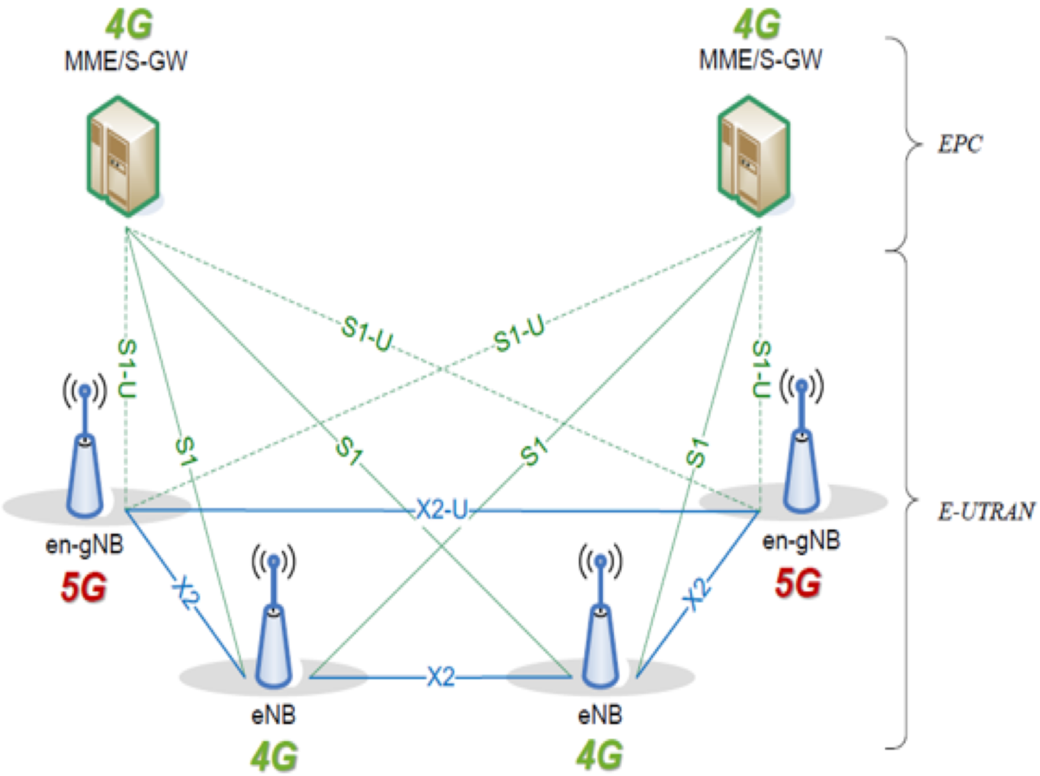
- State-of-the-art cellular technology designed to extend (autonomous) vehicle's ability to see, hear and communicate further down the road, even at blind intersections.
  - Unified connectivity: vehicle to vehicle, vehicle to pedestrian, vehicle to infrastructure, vehicle to network within 1ms
  - 3D mapping and precise positioning of <<1m (satellite based GNSS)
  - On-board intelligence
- 5G's low latency URLLC will be essential when the vehicles can not operate in the autonomous mode and need near-instant command and control assistance.

*C-V2X = Cellular Vehicle to Everything--- R16 5G NR support for advanced safety applications--- builds on Rel 14-15.

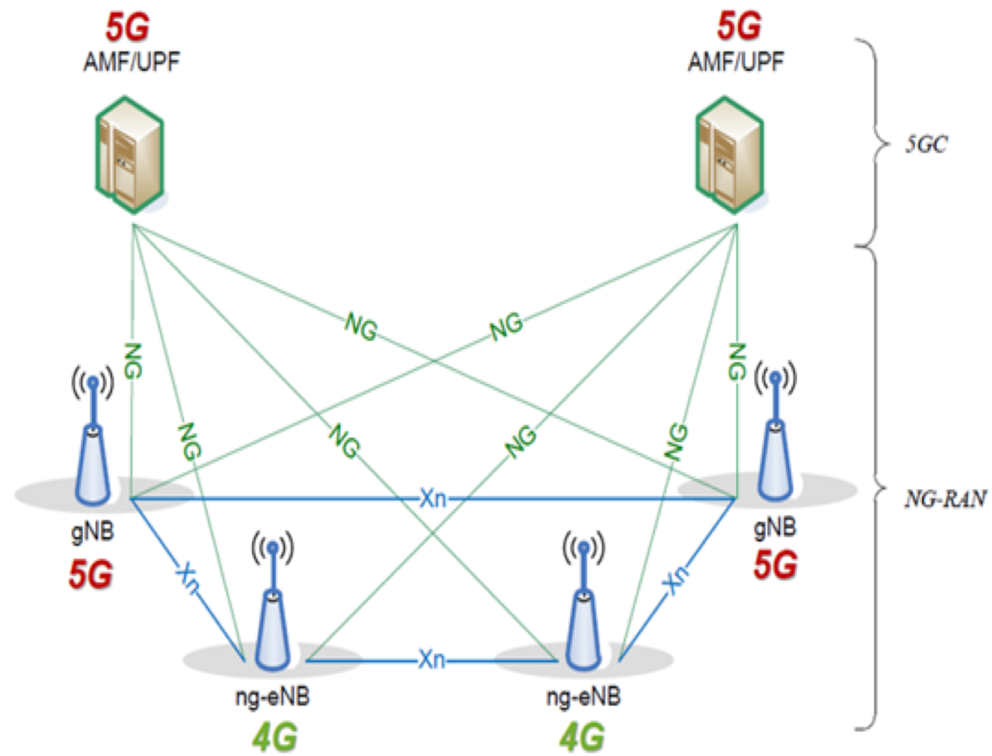
5G RAN Architecture

EN-DC = E-UTRA (Evolved Universal Terrestrial Radio Access) - NR (New Radio) Dual Connectivity (DC)

UPF = User Plane Function
AMF = Access and Mobility Management Function (Control Plane)



Non-standalone (NSA) 5G: LTE (E-UTRAN)-NR DC architecture

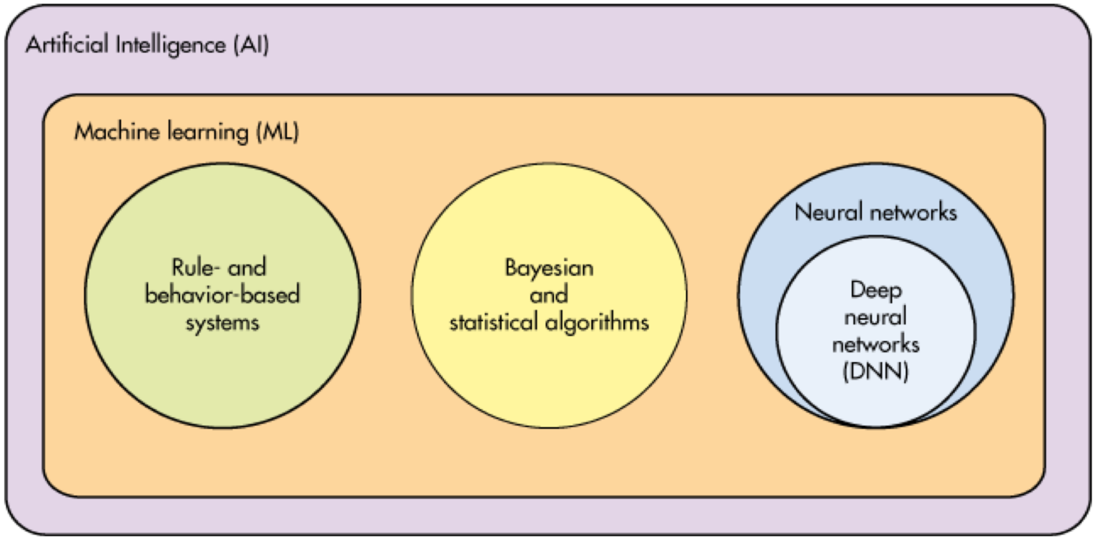


Standalone (SA) 5G: NG-RAN architecture

- The 5G core network builds upon the 4G core with new areas of enhancement: service-based architecture, network slicing, control-plane/user-plane split, and CN/RAN split to enable independent evolution of core and access network.
- Current 5G deployments are based on NSA architecture enabling tight interworking with 4G as it allows network operators to build 5G on top of their existing E-UTRAN and EPC 4G networks.
- Once the 5G Core (5GC) is developed, network operators will start following the SA architecture and build NG-RAN.
- 5G Core (5GC) entities include User Plane Function (UPF), Access and Mobility Management Function (AMF), Session Management Function (SMF), Unified Data Management (UDM), Authentication Server Function (AUSF), Policy Control Function (PCF), and Network Slice Selection Function (NSSF).

Source: 3GPP TS 23.501, 3GPP TS 37.340, 3GPP TS 38.300

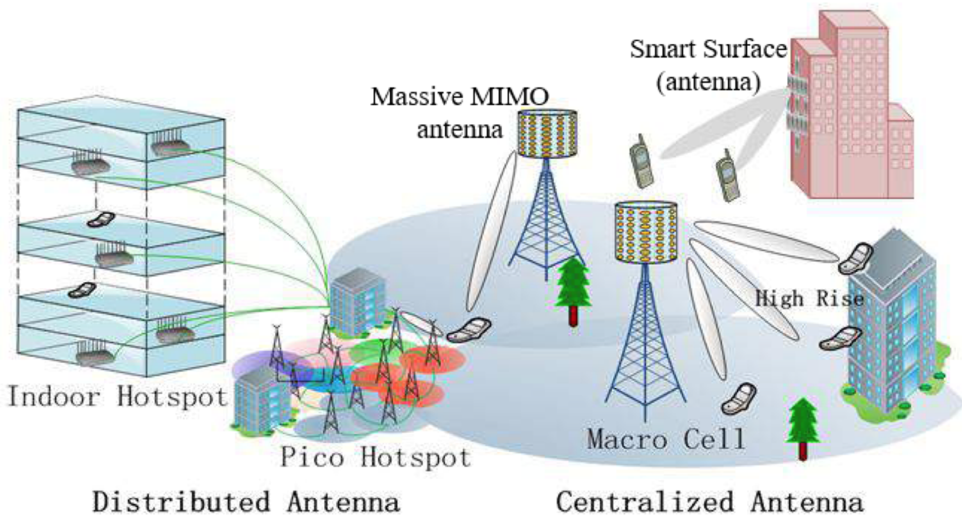
The "Magic" of Machine Learning (ML) (for 5G/6G)

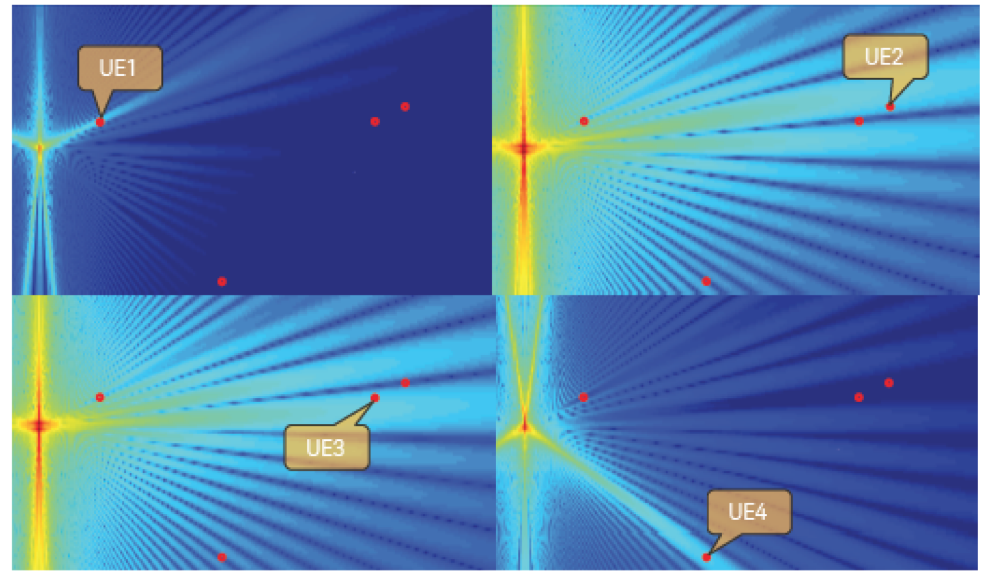


ML results sometimes appear as "magic" ---especially with DNNs

- ML algorithms automatically improve through experience (i.e., processing "data").
  - ML classes include Support Vector, Machines, Decision Tree, Clustering, and Neural Networking
  - Learning (supervised or unsupervised) by examining data to find common patterns and explore nuances..
  - Performs detection, estimation, classification, segmentation, path optimization, anomaly detection, ….
- ML is expected to deeply transform designing and optimizing 5G wireless systems.
  - As opposed to well-established mathematical models, machine learning is a data-driven paradigm shift.
  - ML is being explored in the physical layer, MAC layer and higher software, as well as in many subtasks in 5G network design (e.g., network slicing, self-organizing networks, anomaly detection, scheduling, …)
  - DNNs popularity increased because of open-source solutions, including platforms like TensorFlow and Caffe with hardware and software support from Xilinx, NVIDIA, Google, and Intel.
  - DNNs are not the only types of NNs commercially available: convolutional neural networks (CNNs) and recurrent neural networks (RNNs) are some of the other options available for dynamic wireless systems.
- **ML ideas and tools can be used to solve different problems across a variety of applications and emphasizes thinking outside a single issue and beyond established boundaries**.

5G PHY Technology: Massive MIMO [M-MIMO] and Beamforming
Provides Diversity, Directivity, and Spatial Multiplexing





200-antenna massive MIMO provides great precision in the placement of signals and nulls
Courtesy: Keysight.

- Releases 13/14 improved support for massive antenna arrays (improved channel-state information).
  - The larger degrees of freedom can be used for, for example, beamforming in both elevation and azimuth and **massive multiuser MIMO** where several spatially separated devices are simultaneously served using the same time-frequency resource.
  - These enhancements are sometimes termed full-dimension MIMO and form a step into massive MIMO with a very large number of steerable antenna elements that exceeds the number of users.
- A large number of steerable antenna elements for both transmission and reception is a key feature of 5G NR.
  - At higher-frequency bands, the large number of antenna elements are primarily used for beamforming to extend coverage. An antenna panel with a large number of small antenna elements enables the direction of the transmitter beam (e.g., beamforming) can be adjusted by separately adjusting the phase of the signals applied to each antenna element and improve throughput and reliability
  - At lower-frequency bands they enable full-dimensional MIMO referred to as massive MIMO, and interference avoidance by spatial separation.

Research: Machine Learning Beam Sweeping for 5G mmWave Cellular Systems

Problem

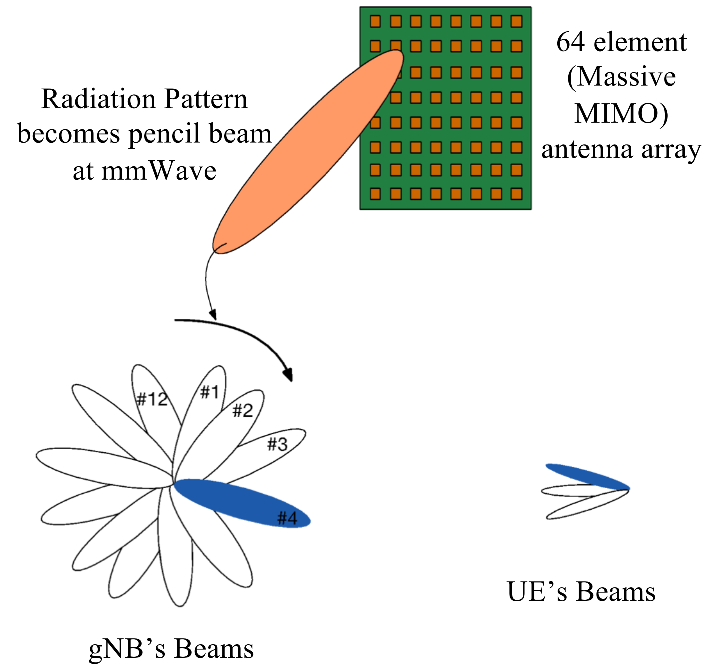
- The reliance on directional beamforming makes cell discovery by a UE challenging since the best aligned beam pair is not known.

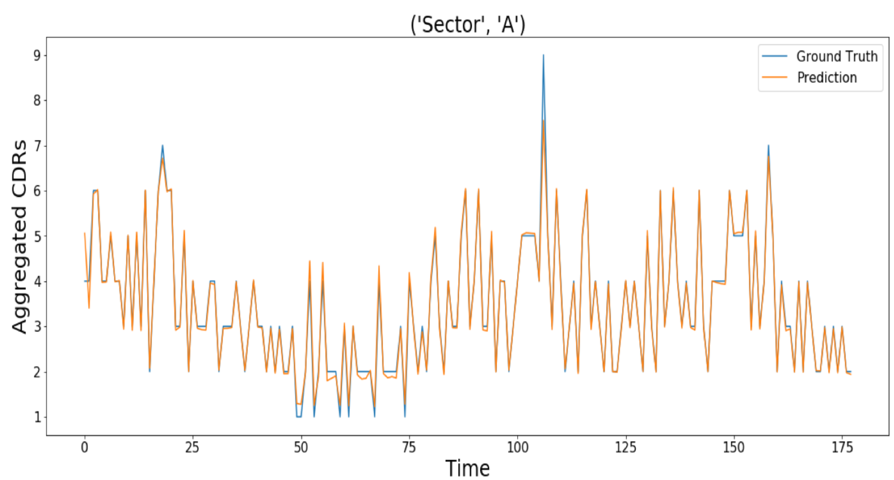
Standard Approach

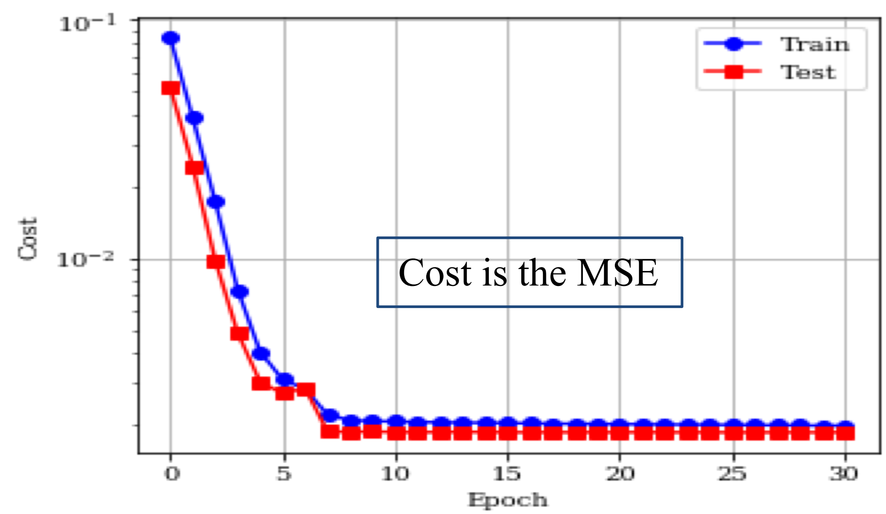
- Sequential beam sweeping is performed to transmit synchronization signals using a Random Starting Point (RSP)

ML-based Approach

- A Gated Recurrent Neural Net (G-RNN), optimizes the **sweeping pattern** of the gNB (5G NR Base Station). Using call detail records (CDRs), the G-RNN predicts the beam hopping pattern.
- G-RNN beam sweeping outperforms the RSP scheme with sparsely distributed UEs, requiring approximately 0.2 scanning cycles on average. RNN and RSP have similar performance with uniform distribution in the CDRs.

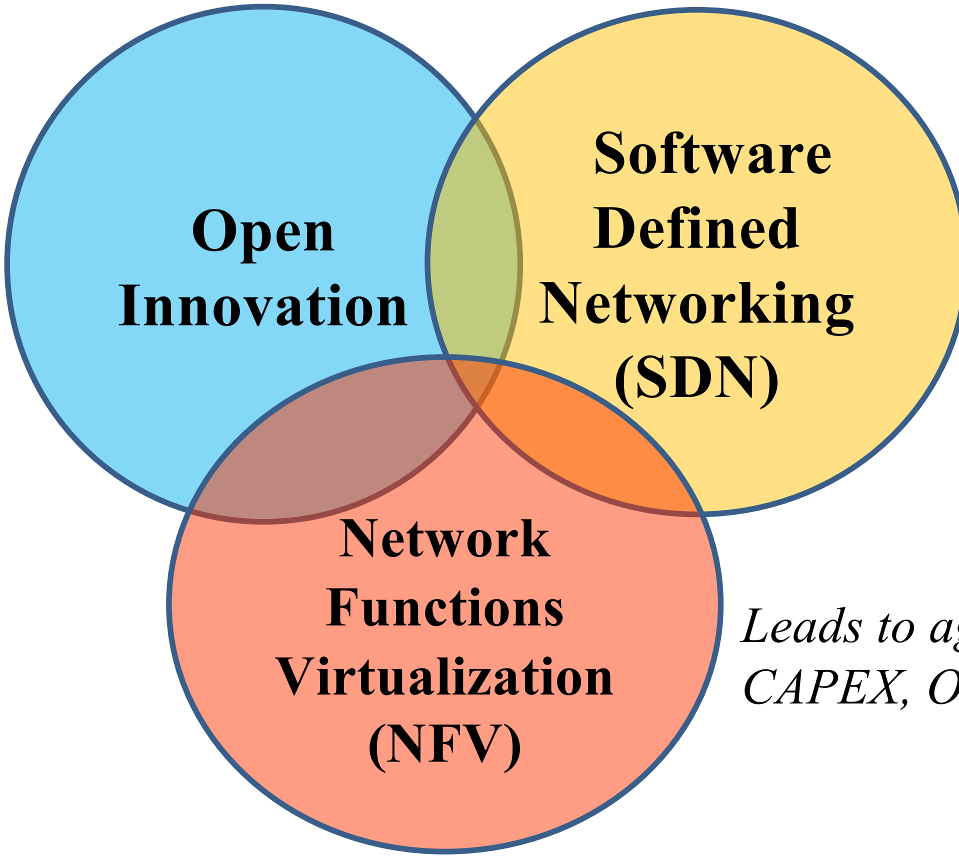






A. Mazin, M. Elkourdi and R.D. Gitlin, "Comparative Performance Analysis of Beam Sweeping Using a Deep Neural Net in mmWave 5G New Radio," UEMCON2018.

5G Strategic Networking Paradigms ---All About Software



Creates competitive supply of innovative applications by third parties generally on commercially off-the-shelf (COTS) platforms.

Creates network abstractions to allow application-aware behaviour, and increased flexibility

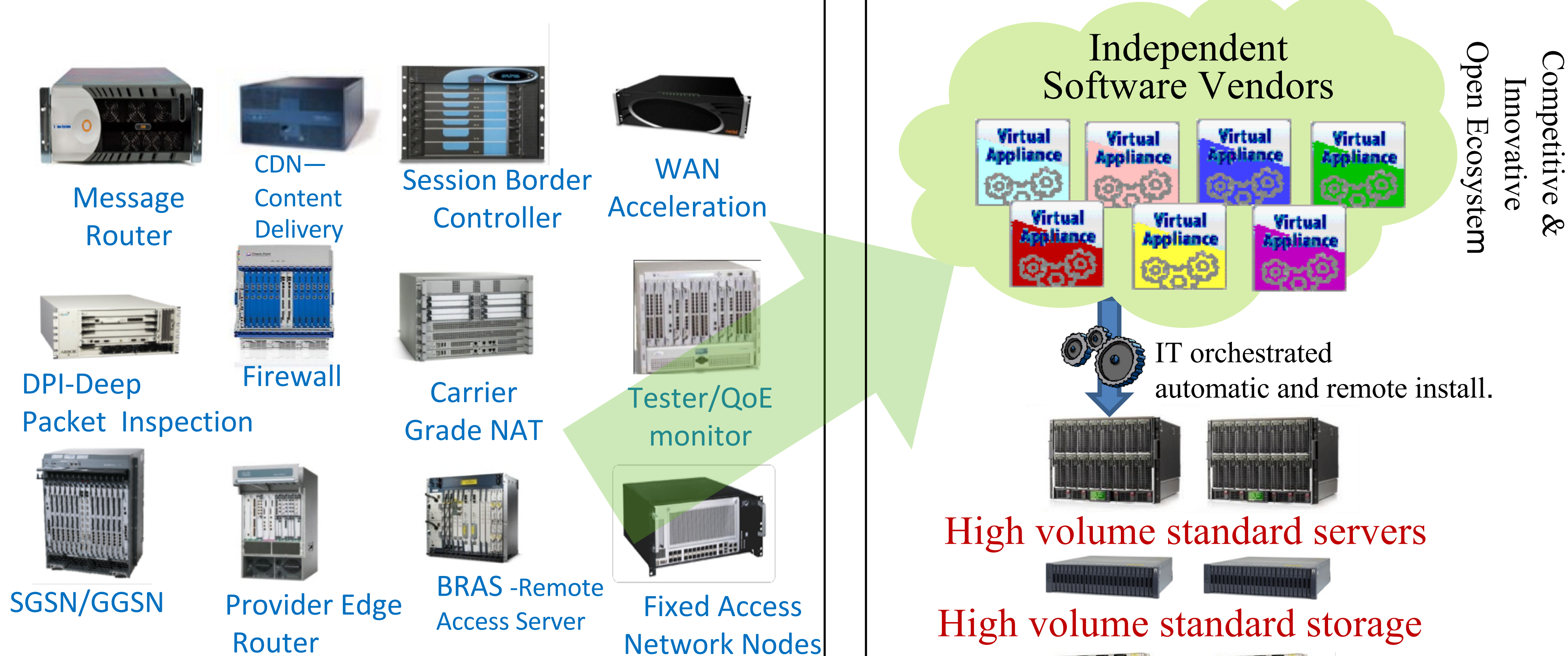
Leads to agility, Reduces CAPEX, OPEX,…

- SDN: Separate CONTROL and DATA plane
- NFV: Separate SERVICE logic from HW Platform
- NFV and SDN are highly complementary. They are mutually beneficial but not dependent on each other (NFV can be deployed without SDN and vice-versa)
- SDN can enhance NFV performance, simplify compatibility, facilitate operations
- NFV aligns closely with SDN objectives to use **software, virtualization and IT management techniques in 5G.**

Network Functions Virtualization [NFV]
Becoming a Software-Based Network

Classical Network Appliance Approach

Network Functions Virtualization Approach

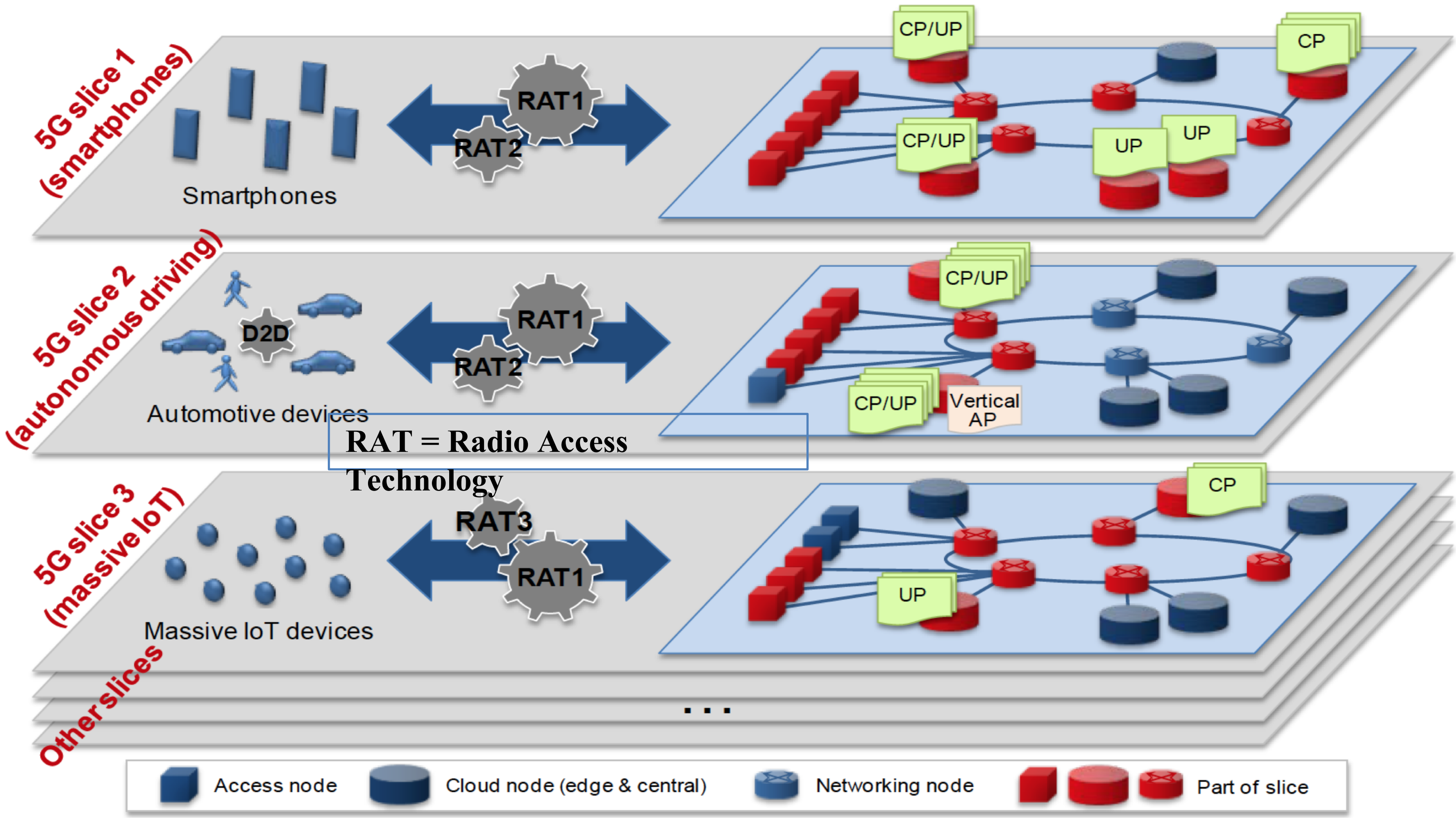


- Fragmented, purpose-built hardware.
- Physical install per appliance per site.
- Hardware development large barrier to entry for new vendors, constraining innovation and competition.

NFV: network functions in SW leverage (high volume) standard servers and virtualization

5G NFV: Network Slicing

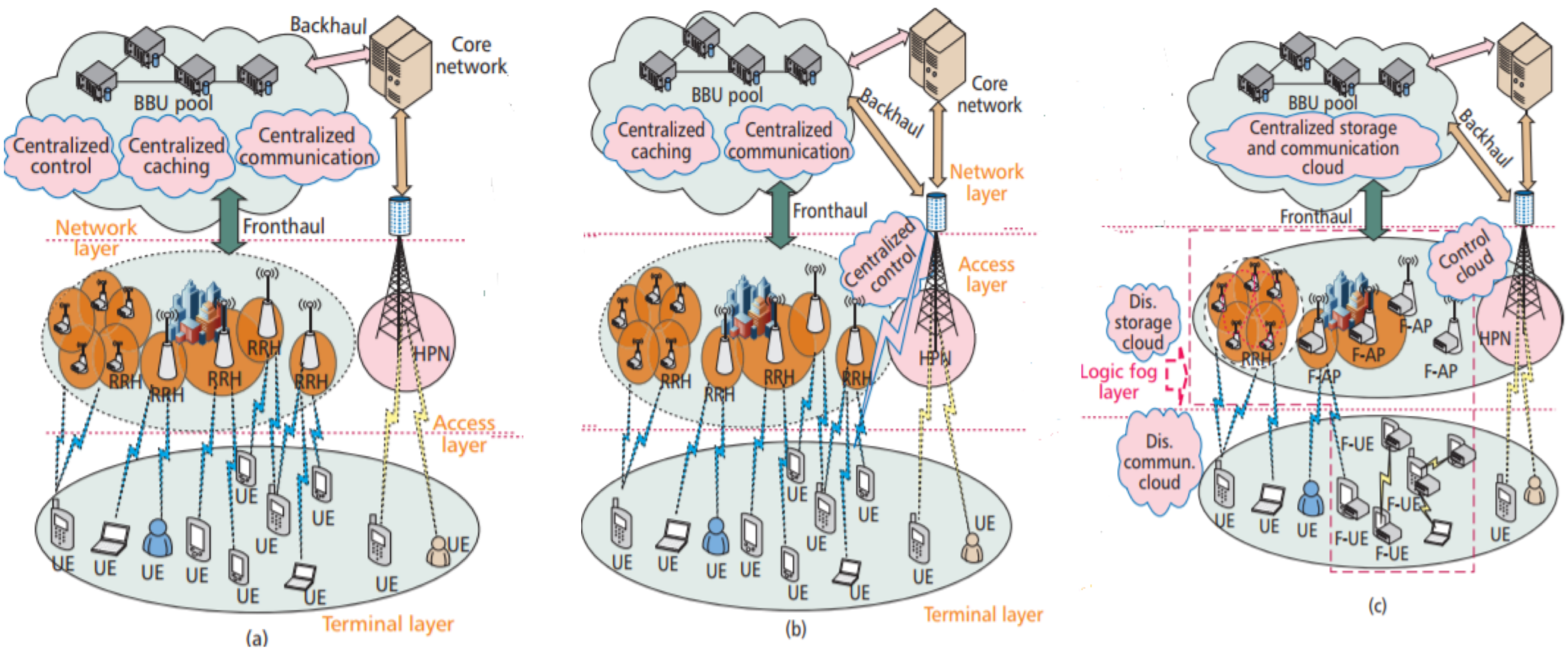
- A network slice is an end-to-end logically isolated network including devices, access, transport and (virtualized) core network functions to support diverse scenarios on a common infrastructure.
- Enables operators to launch a range of highly differentiated network services, each aimed at a distinct vertical market but relying on the same infrastructure.



RAT = Radio Access Technology

5G RAN Architecture: Competing Implementation Approaches

Cloud (Centralized) and Fog Networking (Distributed)

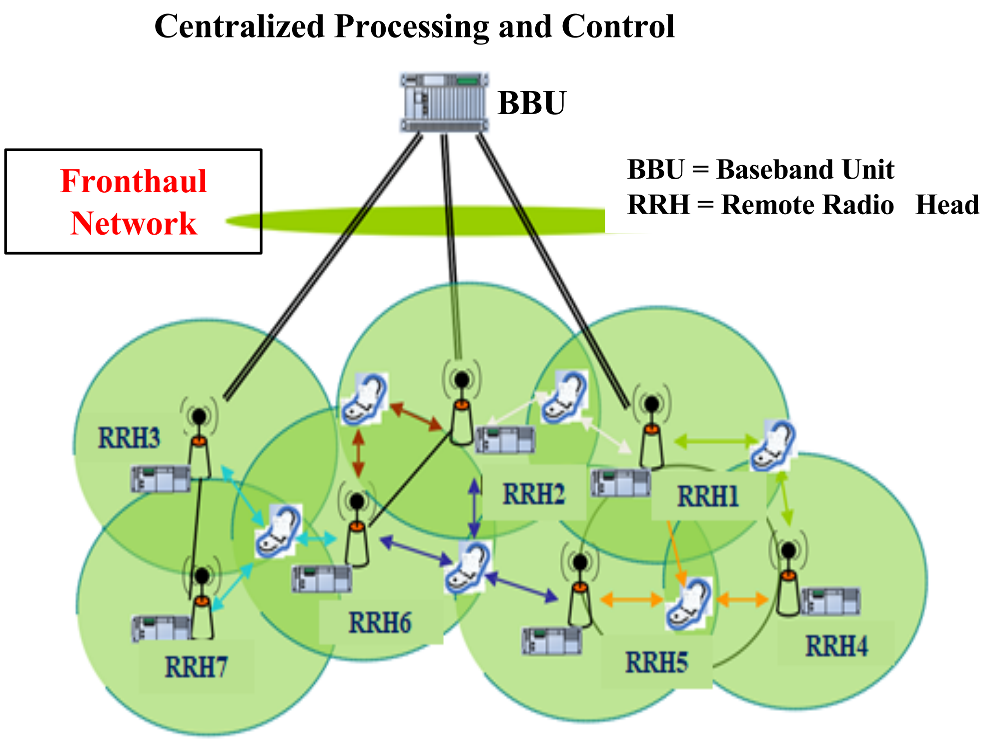


	CRAN [Centralized RAN]	H-CRAN (Hybrid CRAN)	F-RAN (Fog-RAN)
Advantages	• Incorporates cloud computing technology into wireless nets. • Global centralization (efficient coordination and interference mitigation) and distributed radio heads (RRH).	• Centralized control is shifted from the BBU to the High Power Nodes (HPN) BSs. • Global centralization, i.e., efficient coordination, interference mitigation, etc.	• Resources closer to the user. • Low front-haul bandwidth requirement • Interference mitigation • **Low latency (~1ms)**
Disadvantages	• Challenges in realizing a fronthaul network with high bandwidth and low latency.	• Medium fronthaul bandwidth constraint • High latency	• Many research issues • Complexity and cost?

*M. Peng, S. Yan, K. Zhang, C. Wang, "Fog-computing-based radio access networks: Issues and challenges", *IEEE Network.*, July/Aug. 2016.

5G Cloud Radio Access Network: C-RAN

- The C-RAN separates base station functions into two parts:
  - The centralized processing and control functions that are processed in the baseband unit (BBU).
  - The user interface and radio functions are handled by the remote radio heads (RRHs) that are densely distributed and can be arranged in a hierarchical network.
  - Fronthaul networks connect the RRHs to the BBU and can be wired and/or wireless.
  - The backhaul network (not shown) connects the BBUs to the core network.
- C-RANs are expected to minimize operating costs and improve spectral efficiency due to their interference management and powerful processing capabilities.
- **Research problems addressed**: near-instant recovery from link and node failures.

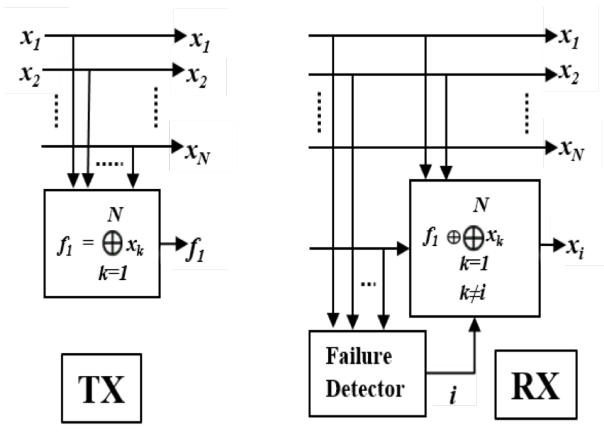


5G Cloud Radio Access Network C-RAN

Research: Ultra Reliable and Low Latency 5G Fronthaul Networks using Combined Diversity and Network Coding (DC-NC)

Diversity Coding (DC)

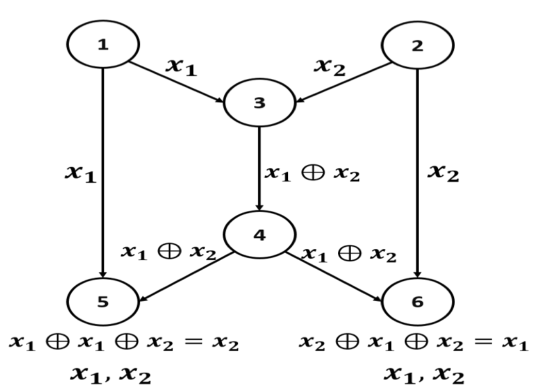
- Diversity Coding enables reliable networking with near-instant recovery from a link failure where a feedforward network design uses forward error control across spatially diverse paths at the expense of redundant transmission facilities.



Diversity Coding

Network Coding (NC)

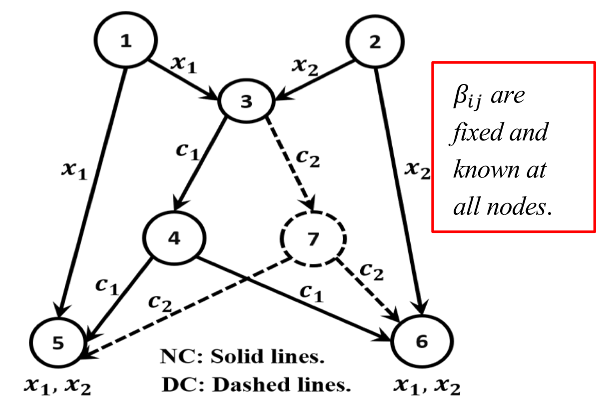
- Network Coding uses coding at a network node to increase network throughput and provide bandwidth for data broadcasting/multicasting applications.
- **In this example network, the throughput is increased by one-third.**
- However, any link failure can strongly impact reliability, and nodes 5 and 6 will not receive the desired data streams.



Network Coding

Research*: DC-NC Coding

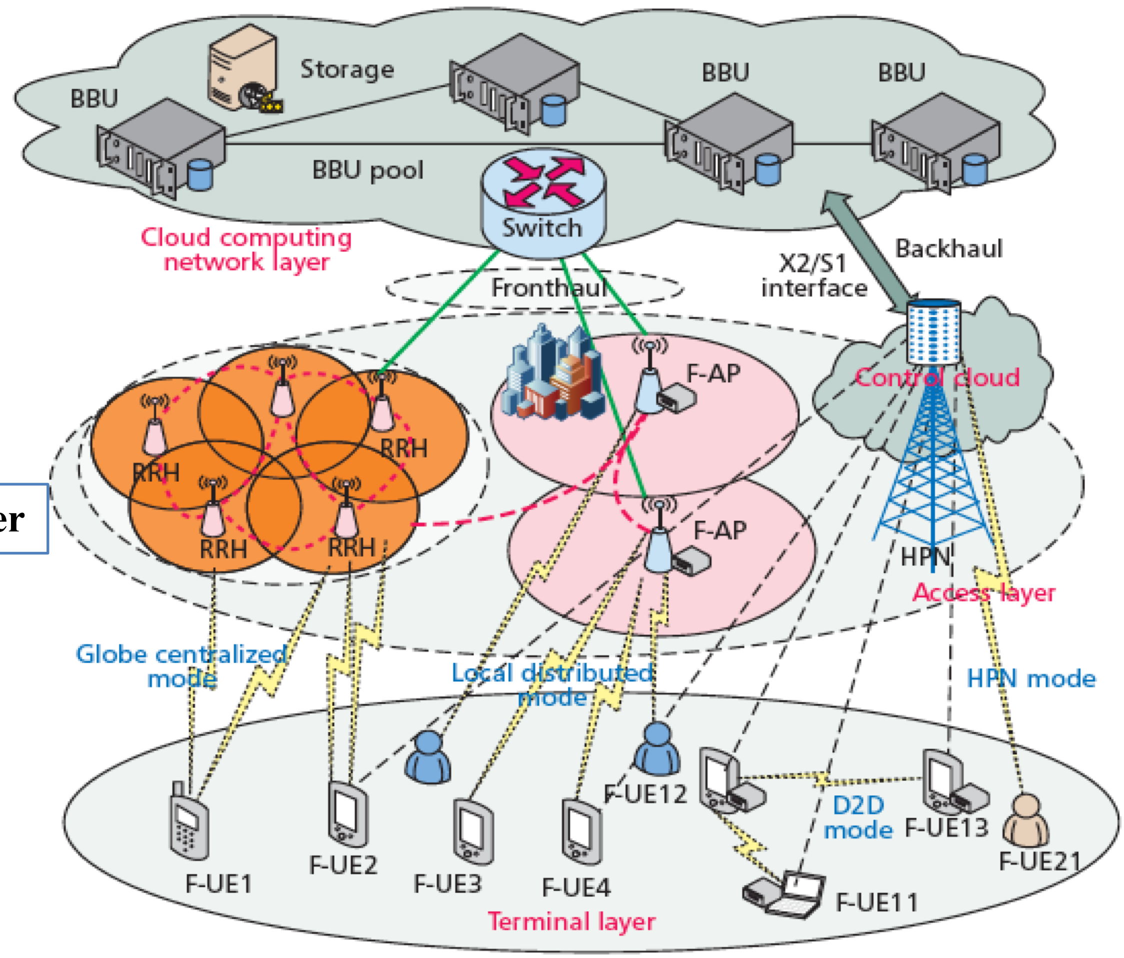
- By combining DC and NC, both reliability and throughput can be increased.
- The figure shows how NC is enhanced with DC. Note the addition of node 7.
- Coded data streams c_1 and c_2 are formed at node 3 as follows:
  - $c_1 = \beta_{11}x_1 + \beta_{21}x_2,$ (1)
  - $c_2 = \beta_{12}x_1 + \beta_{22}x_2,$ (2)
- To improve network reliability, node 7 sends c_2 to nodes 5 and 6. When there are no link failures, nodes 5 and 6 ignore c_2.



DC-NC network

*N. I. Sulieman, E. Balevi, K. Davaslioglu, and R. D. Gitlin, "Diversity and Network Coded 5G Fronthaul Wireless Networks for Ultra Reliable and Low Latency Communications," IEEE International Symposium on Personal, Indoor and Mobile Radio Communications 2017.

F(Fog)-RAN Distributed Architecture:
Striving for 1ms Latency



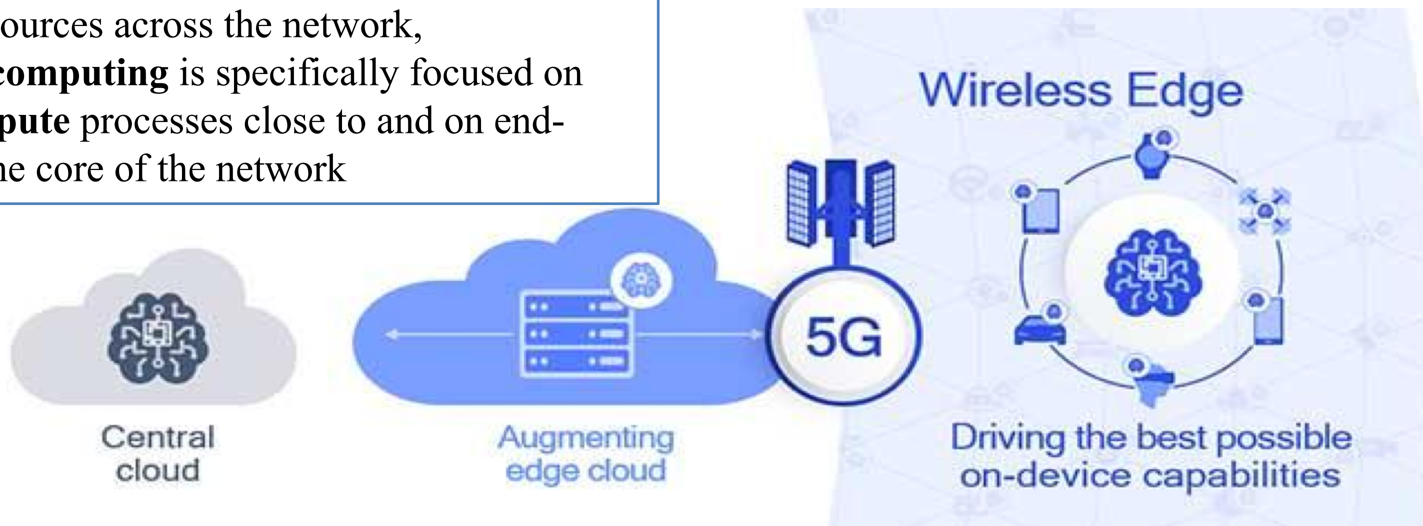
Fog Layer

F-APs [Fog Access Points] cache adjacent RRH data and "smart" UEs (denoted by F-UEs) cache adjacent UE data.

- C-RAN (C= Cloud/Centralized) architecture provides large range of services and virtually unlimited available resources for users, but has large latency.
- Fog and the Mobile Edge Computing networks
  - Have cloud services and resources at the edge of the network closer to the users.
  - The F-APs, which are unique to FRANs, integrate not only the fronthaul radio frequency but also the physical-layer signal processing functionalities and procedures of the upper layers.
  - Run the heavy real-time, low latency applications at the network edge directly using the billions of connected mobile devices
- **F-RAN takes full advantage of the convergence of cloud computing, heterogeneous networking, and fog computing.**

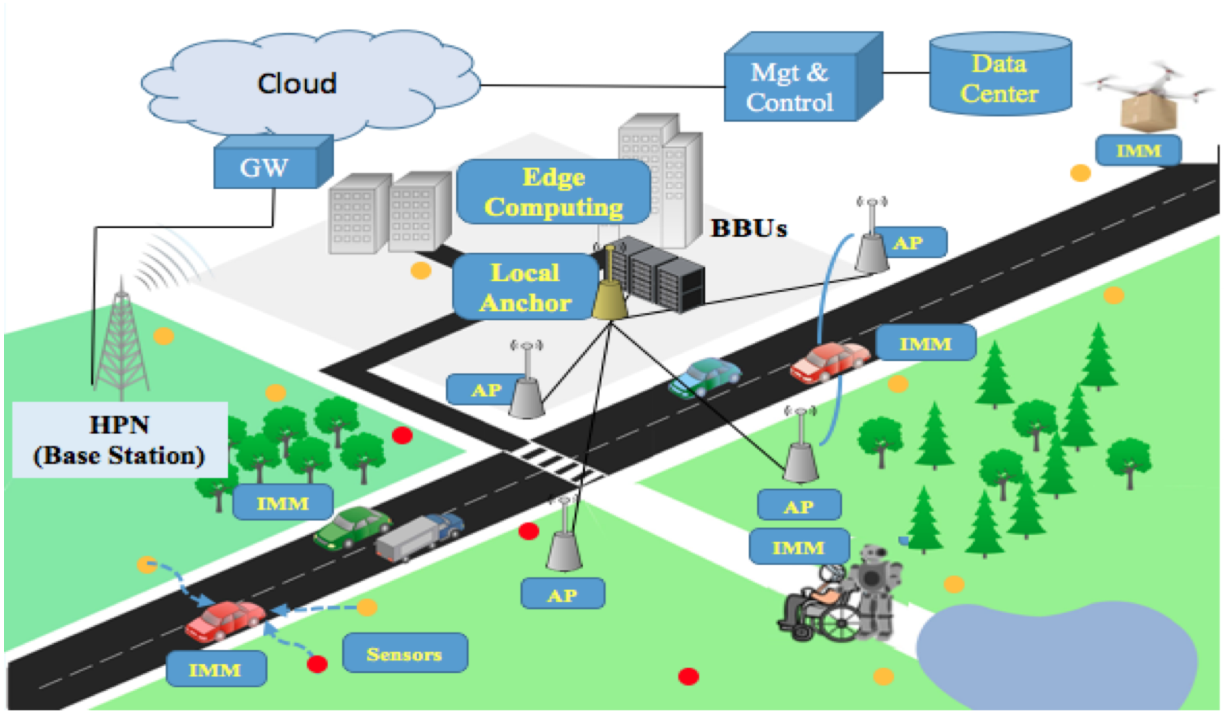
Wireless (Intelligent) Edge: Key to Realizing the Full Potential of 5G

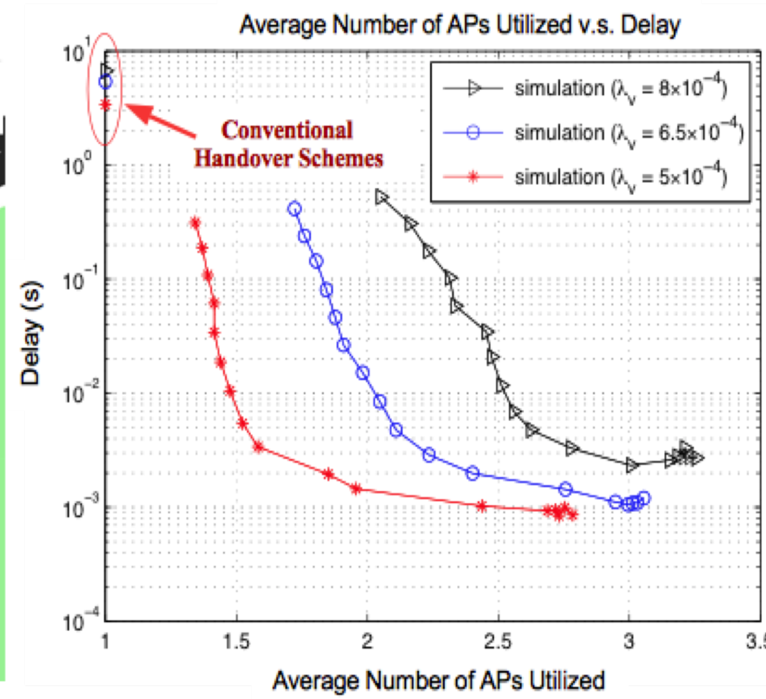
Fog computing is the overall architecture of distributing resources across the network, whereas **edge computing** is specifically focused on executing **compute** processes close to and on end-users outside the core of the network



- To realize 5G's full potential, connectivity alone is not sufficient and new capabilities are needed in the devices.
- To solve this massive scale challenge, as well as address latency, privacy and security concerns, a shift to a decentralized network architecture is likely.
- Intelligence is not just associated with a central cloud, it is distributed to the devices that form the Wireless Edge.
- This will likely require on-device Machine Learning capabilities for smartphones, cars, sensors, and other connected things, so they can perceive, reason, and act on their own, processing low entropy data and transmitting only the *relevant* content back to the cloud.
- The shift to on-device intelligence can bring in broader societal benefits ranging from improved driver safety, more personalized virtual assistants, superior photography, and enhanced security, to cameras with privacy, better connected health care, and more intuitive robotics.
- On-device ML promises the following benefits
  - Privacy — sensitive data that does not leave devices
  - Immediacy — low-latency processing without cloud assistance
  - Personalization — private on-device learning
  - Efficiency — on-device refinement of raw data

Research: F-RAN with ML--- Conceptually Achieving 1ms Latency*



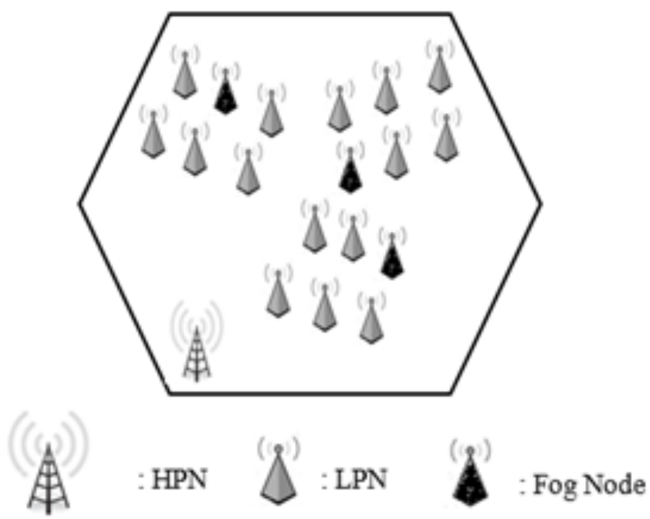


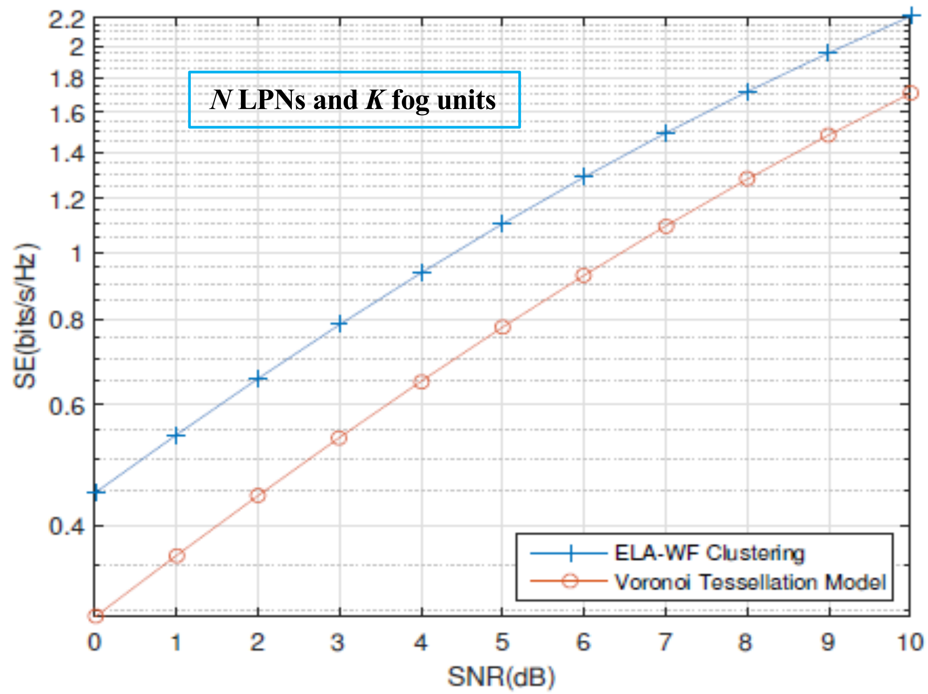
- A two-tier architecture with dense APs (low power) and HPNs (high power) macro-cell nodes is promising for RAN for connectivity to achieve coverage, high-bandwidth and low latency.
- A Fog RAN (F-RAN) with distributed small-cells and ML-based edge computing is appropriate for most real-time, low latency applications.
- **A new paradigm for RAN mobile communication networks is clearly needed to meet the 1ms latency target: computing resources closer to the end user, dense virtual cells, UE autonomy, feed-forward/open loop control, machine-learning based next-cell prediction, …**

* Kwang-Cheng Chen, Tao Zhang, R. D. Gitlin, and Gerhard Fettweis "Ultra-Low Latency Mobile Networking," *IEEE Network March 2019*
* D. S. Wickramasuriya, C. A. Perumalla, K. Davaslioglu, and R. D. Gitlin, "Base Station Prediction and Proactive Mobility Management in Virtual Cells using Recurrent Neural Networks," *IEEE WAMICON,* April 2017.

Research: ML Clustering Algorithm To Maximize Throughput in F-RAN HetNets*

Task: Determine the locations of fog nodes that should be upgraded from low power nodes (LPNs) in order to maximize throughput with a fixed number of fog nodes.

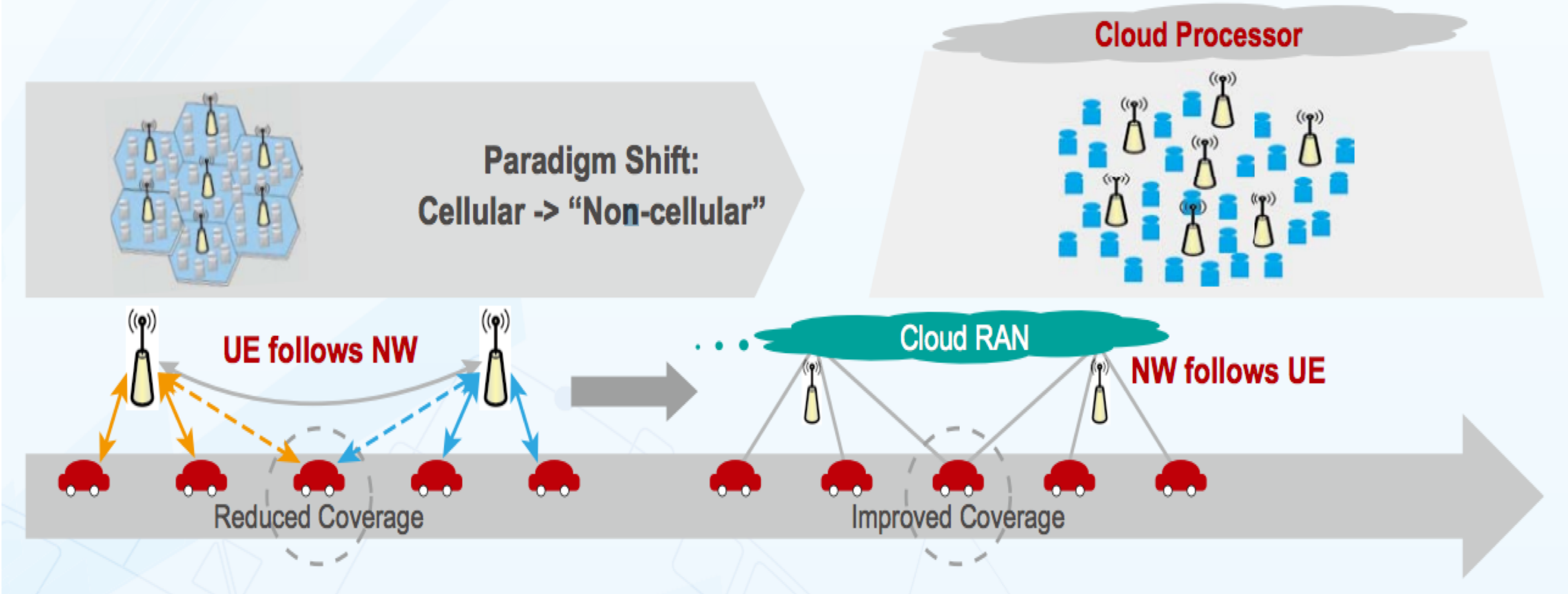




- Two types of clustering considered:
  - Hard clustering *K*-means clustering algorithm based on Voronoi Tessellation mode, where each small cell is connected to **one** fog node at the closest Euclidean distance
  - Soft clustering, edge location assisted soft clustering, water-filling algorithm (ELA-WF) where each small cell can be connected to more than one fog nodes
- ELA-WF has more than a 2 dB advantage in spectral efficiency that translates to an increase of 1 bit/sec/Hz

*Eren Balevi and R. D. Gitlin, "A Clustering Algorithm That Maximizes Throughput in 5G Heterogeneous F-RAN Networks," IEEE (ICC), 2018

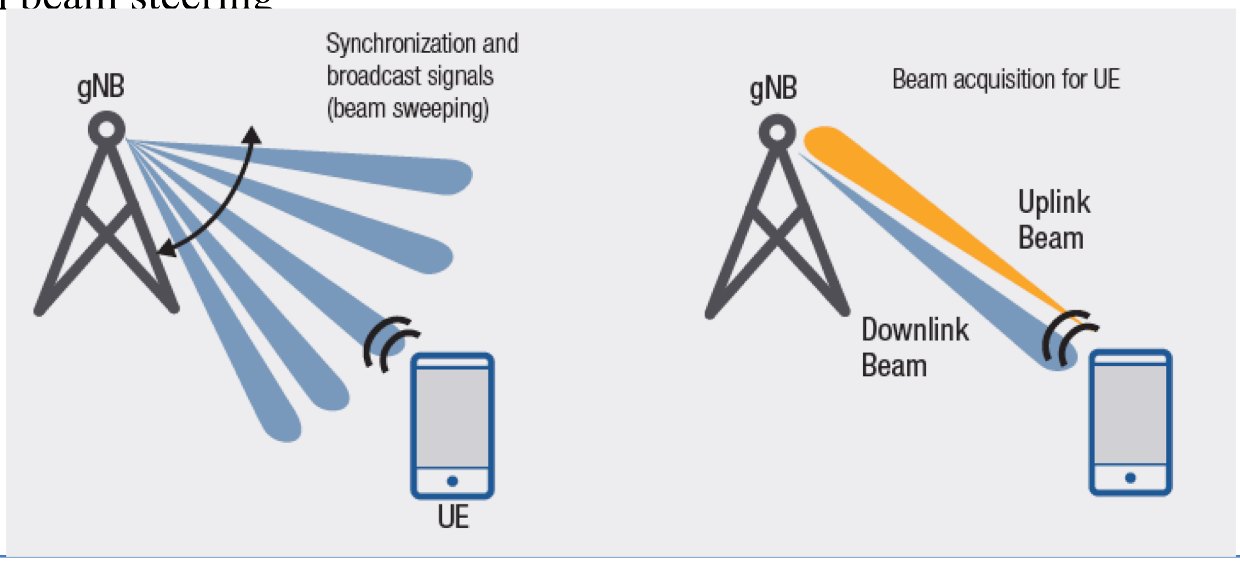
Radio Access Virtualization-Elimination of Cell Boundaries (<u>no more cells)</u>



- Traditionally devices associate with a cell and as a consequence the link performance may degrade as a device moves away from the cell center.
- In a <u>virtualized</u> <u>device-centric network</u>, the network determines which access point(s)/base stations are to be associated with the device.
- Thus the "<u>cell" moves</u> with and the network always surrounds the device in order to provide a cell-center experience throughout the entire network.
- The elimination of the device's view of the cell boundary is illustrated in the above figure.
- LTE standardized Coordinated Multi-Point (<u>CoMP</u>) is an early cell-less system.

Greater Throughput using Massive MIMO and Beam Steering

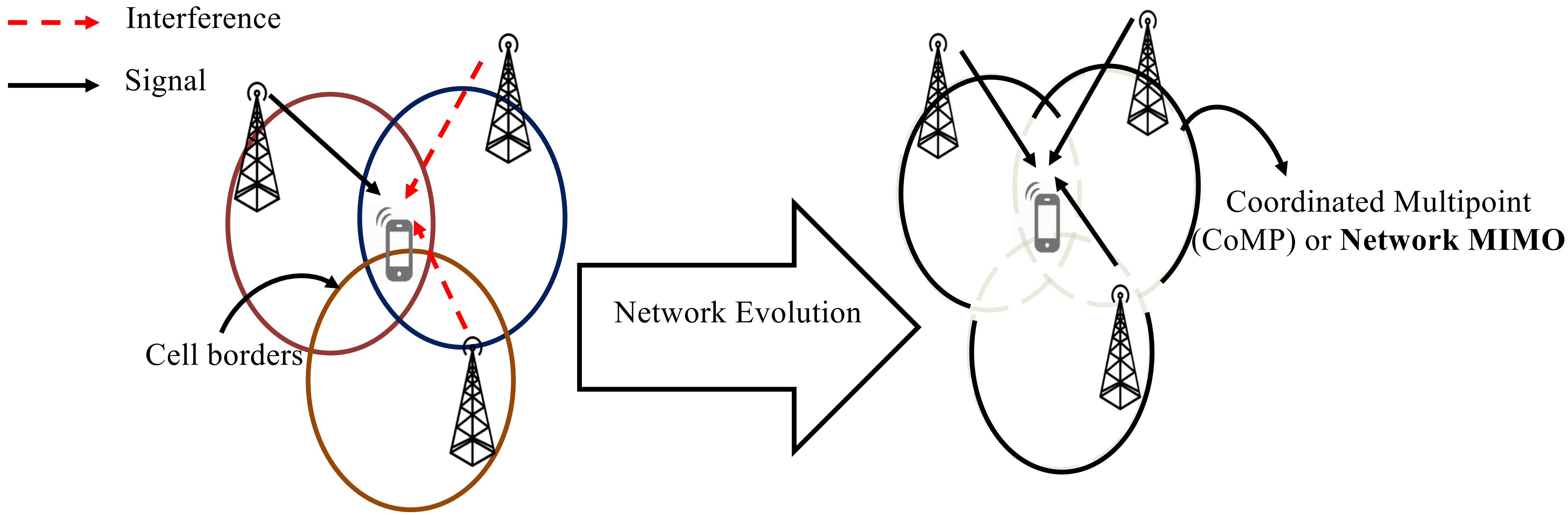
- Increased throughput is achieved in multiple ways in 5G NR (beyond wider channel bandwidths, spatial mux, enhanced channel feedback to optimize the transmitted signal
- In 5G Massive MIMO and beam steering are key technologies to improving throughput
- Operating at mmWave frequencies introduces new challenges in path loss, blockage, and signal propagation.
  - Beam steering will be a key technology used to overcome these issues.
  - NR specifies new initial access procedures to ensure alignment of the directional transmissions used in beam steering



- New initial access techniques where the base station uses beam sweeping to transmit multiple beams, identify the strongest beam, and establish a communication link.
- 5G NR specifies a new beam management framework for CSI (Channel State Information) acquisition so that different beams can be dynamically controlled. CSI uses channel estimation to intelligently change the precoding and adapt the beam to a specific user.

Coordinated Multipoint (CoMP) Networks
Enabling Cell-Less Networks

- Typically, when not in a handover user equipment is associated with one base station (BS).
- Cell-edge users suffer from a throughput degradation due to the Inter-Cell Interference (ICI).
- In CoMP networks, multiple geographically separated base-stations (BSs) coordinate among each other. The Cell-edge users will be served by two or more BSs to improve signal reception/transmission and increase throughput.
- CoMP was first standardized in Long Term Evolution-Advanced (LTE-A), Releases 11 and 12.

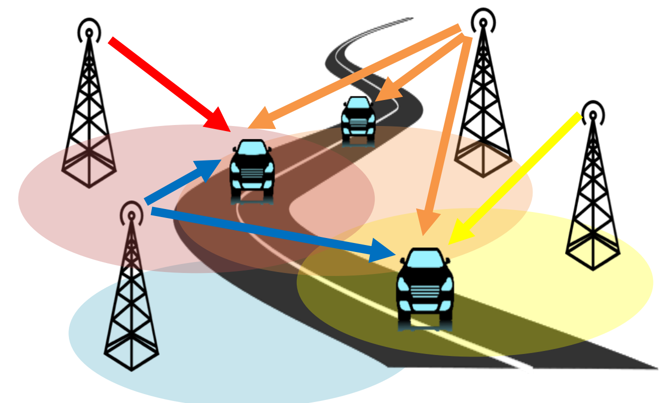


Research: 5G Dynamic CoMP*

Goal: Anticipatory/**proactive** mobility management in 5G Coordinated Multipoint (CoMP) Networks using Machine Learning. Pre-empt the use of conventional handovers.

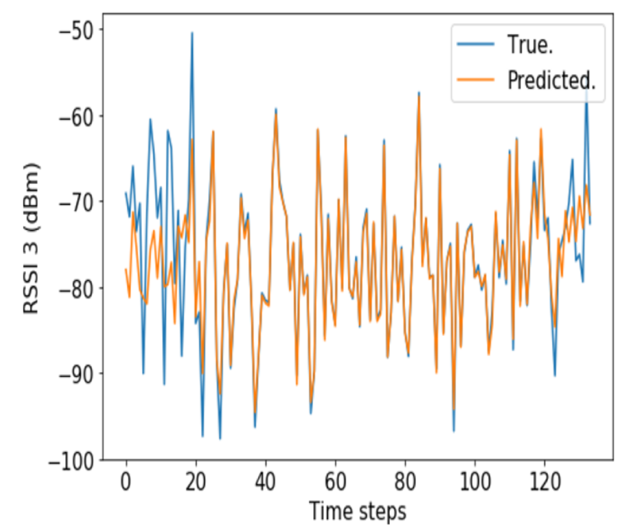
Motivation: Ambitious 5G network goals include:

1) High **data rates** independent of the user location
2) Decreasing end-to-end **latency** to **1 *ms***
3) Providing **seamless mobility** across the network



Methodology: ML Proactive Mobility Management

A Gated Recurrent Neural Network (G-RNN) recognizes how the received signal levels at a mobile node gradually change with motion and identifies patterns within this variation to optimize enabling/disabling the CoMP set.



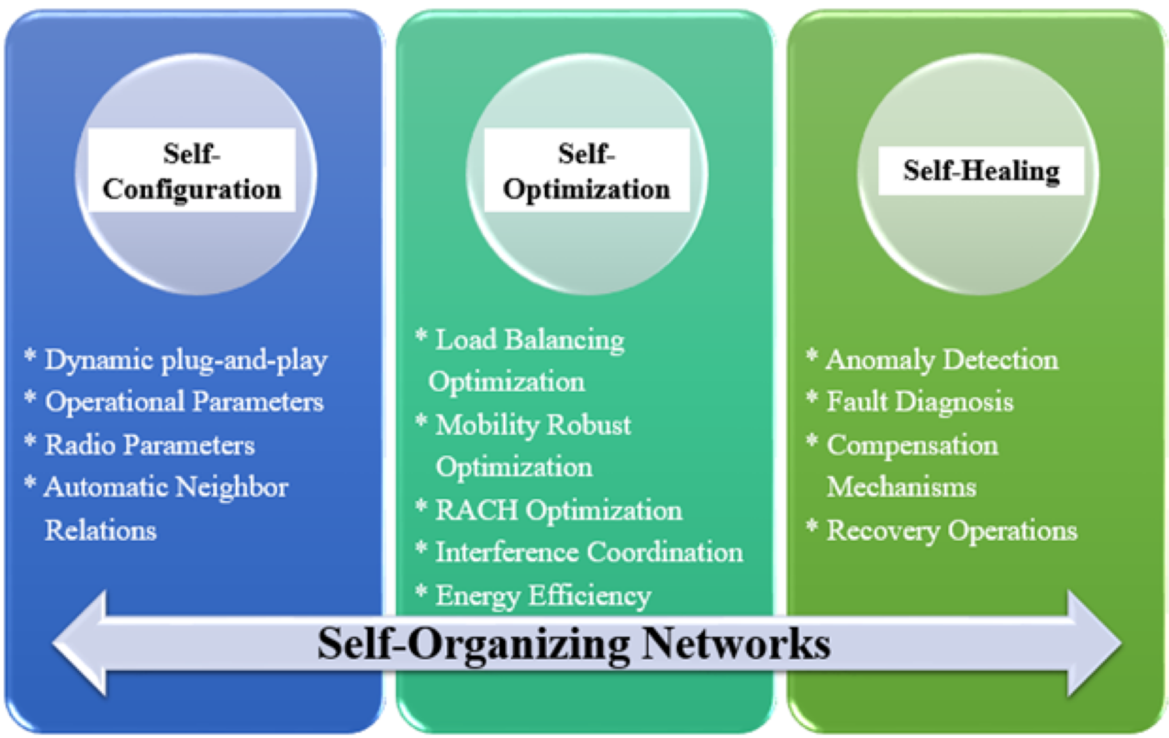
Impact/Benefits

- Pre-empt the use of conventional handovers and save battery power.
- Supportive technology for **cell-less** networks.
- Enabling Dynamic CoMP is important for achieving (1).
- Proactively knowing the BSs that will be joining/ leaving the CoMP set as the user moves across the network (updating the CoMP set) is important for (2) and (3).

* M. Elkourdi, A. Mazin and R. D. Gitlin, "Optimization of 5G Virtual Cell Based Coordinated Multipoint Networks Using Deep Machine Learning," International Journal of Wireless & Mobile Networks (IJWMN) Vol. 10, No. 4, August 2018

Self-Organizing Networks (SON) for 5G

- SON autonomously configures, self optimizes, and self heals its entities thus minimizing OPEX/CAPEX.
- Introduced in 4G (3GPP Rel8-TS 32.500), with limited deployment, currently used to mechanize parallel operations of 4G and 5G, and the rapidly expanding number of network nodes (base stations).
- SON concepts and functionalities continue to be developed in Rel16 (3GPP TR 28.861).
- 5G/6G deployment will benefit from Release 16 3GPP TR 28.861 network automation, and it is expected that integrating ML and user-centric mechanisms with SON will provide an improved end-user experience and seamless network service.



Self-configuration
- Automatic configuration of network nodes and parameters

Self-optimization
- Constant monitoring of network parameters and environment to update system parameters in order to ensure efficient network performance

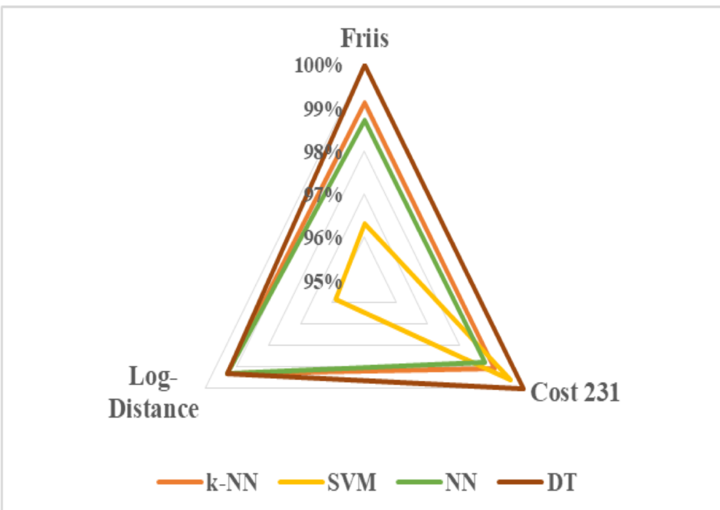
Self-healing
- Automatic detection and remediation of failures in order to ensure a fast and seamless recovery

Research: QoE-driven Anomaly Detection in SONs*

- **Methodology**: A user-centric, resource-efficient approach for anomaly detection to better understand end-user perception of the QoS of the provided service and avoid over engineering.

1. Simulate a cellular network using *ns-3* to test anomaly detection in a SON
2. Collect simulation results to perform data preprocessing and create UC-dependent QoE target values using a parametric QoE model
3. Apply supervised ML algorithms to learn and predict QoE scores (range: 0 to 5 [the best])
4. Evaluate the performance of the ML algorithms for QoE prediction
5. Shortlist network nodes (base stations) that are serving users having poor QoE scores (range: 0 to 1)
6. If the maximum number of users attached to a particular network node have poor QoE scores, the node is declared to be dysfunctional.

- The performance of four supervised ML algorithms was investigated: Support Vector Machine (SVM), k-Nearest Neighbor (k-NN), Neural Network (NN), and Decision Tree (DT).



Note: Regression is used as ML is used for QoE score prediction that ranges from 0 to 5. Classification was also tried but the regression results were superior.

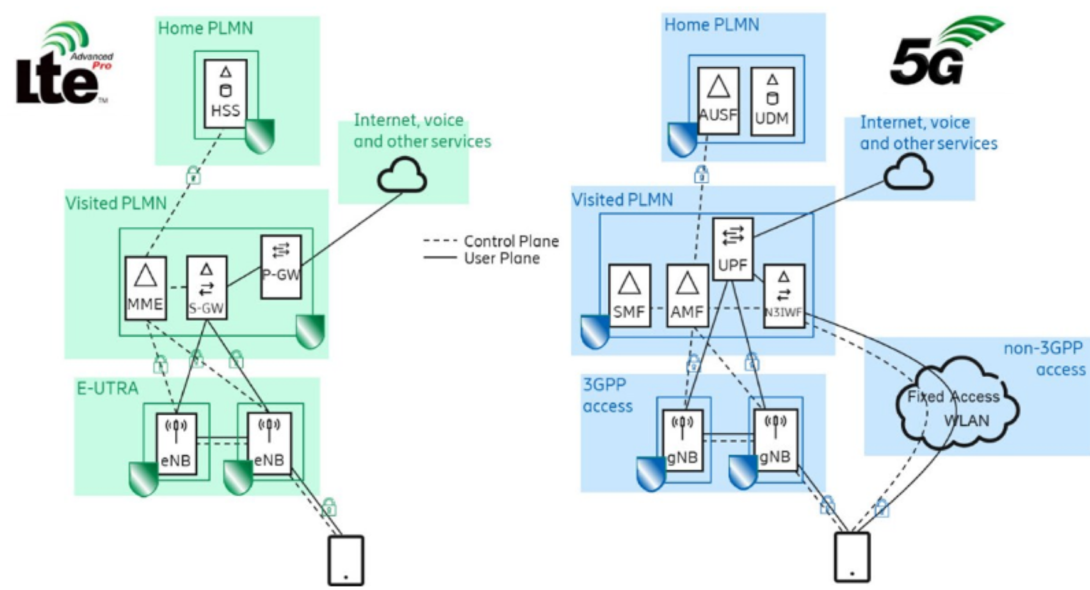
- Each ML method has drawbacks and the algorithm choice depends on the nature of the dataset.
  - SVM complexity is very high and wrong choice of kernel can lead to an increase in error percentage.
  - k-NN is sensitive to localized data (i.e., localized anomalies can affect outcomes significantly).
  - The black box nature of NN makes it difficult to interpret how the results were derived (and troubleshoot).
  - DT has a high probability of overfitting and needs pruning for larger datasets.
- Dysfunctional network nodes were successfully detected based on the QoE scores predicted by each of the ML algorithms.

* Chetana V. Murudkar and Richard D. Gitlin, "QoE-driven Anomaly Detection in Self-Organizing Mobile Networks using Machine Learning," *IEEE Wireless Telecommunications Symposium (WTS)*, April 2019.
* Chetana V. Murudkar and Richard D. Gitlin, "Machine Learning for QoE Prediction and Anomaly Detection in Self-Organizing Mobile Networking Systems," *International Journal of Wireless & Mobile Networks (IJWMN)*, April 2019.
* Chetana V. Murudkar and Richard D. Gitlin, "User-Centric Approaches for Next-Generation Self-Organizing Wireless Communication Networks Using Machine Learning," Accepted for *IEEE COMCAS,* November 2019.

Security Enhancement of 5G over 4G Standards

- **5G security challenges are being addressed by 3GPP SA WG3*** [see 3GPP TS 33.501]
  - 5G R15 defined security architectures and standards for eMBB, covering Standalone (SA) and Non-Standalone (NSA) architectures. 5G R16/17 standards will cover security for mMTC and URLLC.
  - New 5G security challenges brought by new services, architectures, and technologies need to be considered, such as authentication for third-party network slicing service providers.
  - Because mMTC devices have limited resources, low transmission data volume, and low transmission rate, 3GPP will consider the security of functions such as identity authentication, confidentiality, and integrity and reduce the overhead of security-related bits.

- **5G Security Enhancements include**
  - Stronger air interface security using mmWave and beamforming
  - User data integrity protection
  - Enhanced user privacy protection
  - Better roaming and inter-operator security
  - Enhanced cryptographic algorithms
  - Adequate security for service based architecture
  - Enhanced authentication



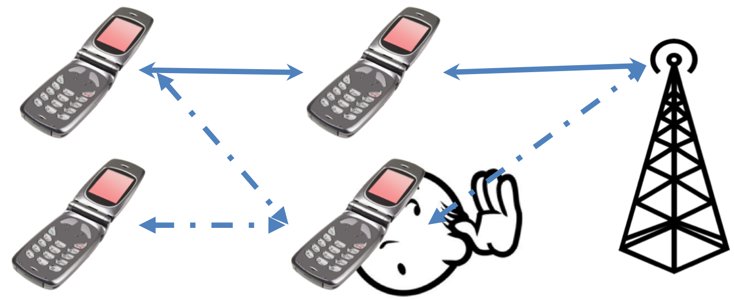
Simplified security architectures of LTE and 5G showing the grouping of network entities that needs to be secured in the Home Network and Visited Network and all the communication links that must be protected.

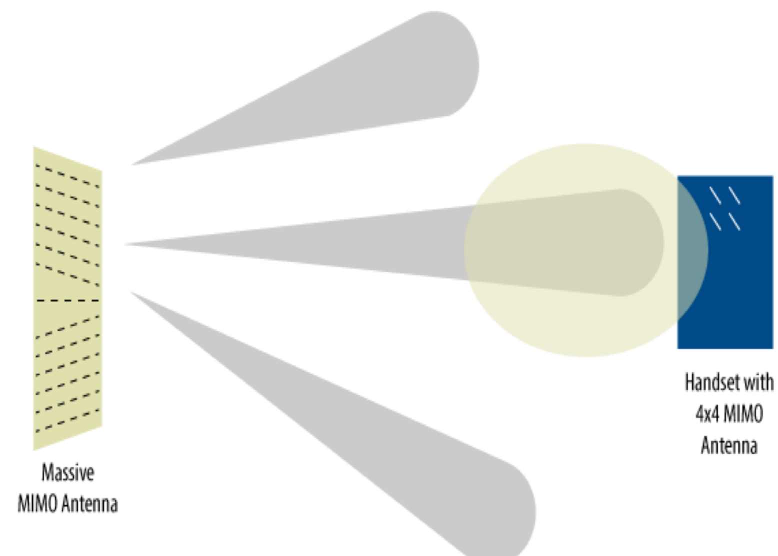
5G Physical Layer Security and Key Management

Problem: Cryptographic key distribution and management is challenging in dynamic and heterogeneous 5G networks.

Advantages of PHY layer security

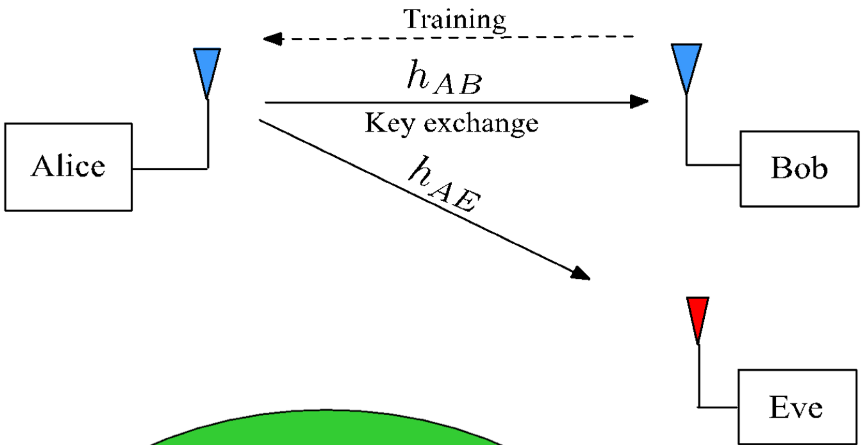
- PHY layer security does not depend on adversary's computational complexity
- PHY-layer security can enable direct secure data communication and/or can facilitate the distribution of cryptographic keys in 5G network.
- **5G Massive MIMO/Beamforming advantages**
  - **More directivity at mmWave frequencies**
  - **Low transmit power:** Decreases eavesdropper's ability to capture signal
  - **Channel State Unknown:** Eavesdropper does not know the CSI to BS.

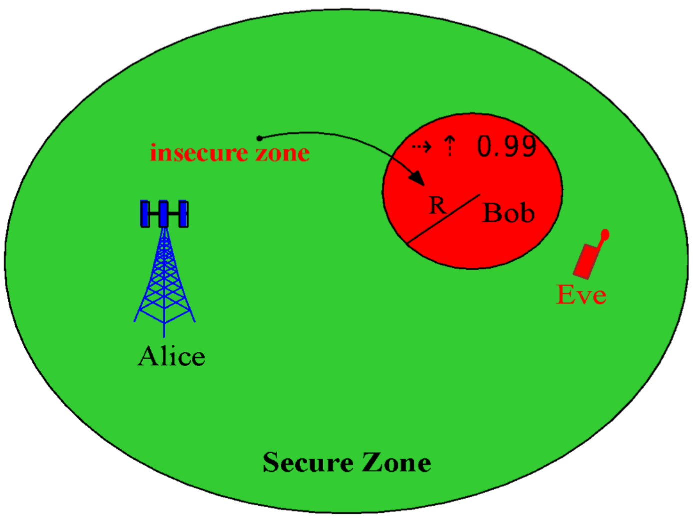


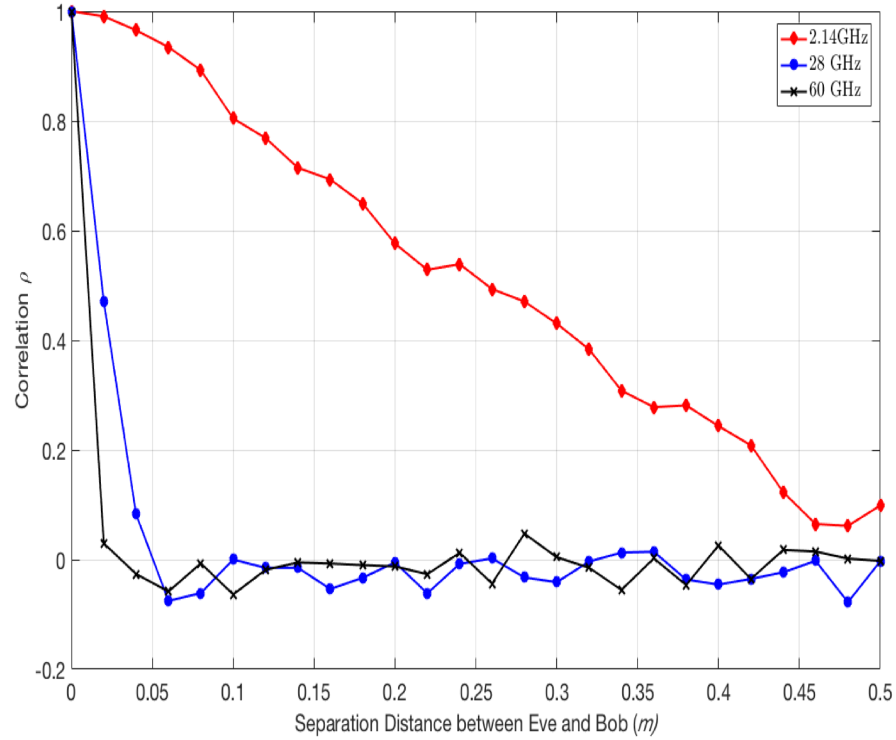


Prior art: Keys derived from Channel CSI or RSS values----limited size keys and consistency of key info at BS and UE.

Research: PHY Layer Key Management Scheme (at mmWave)







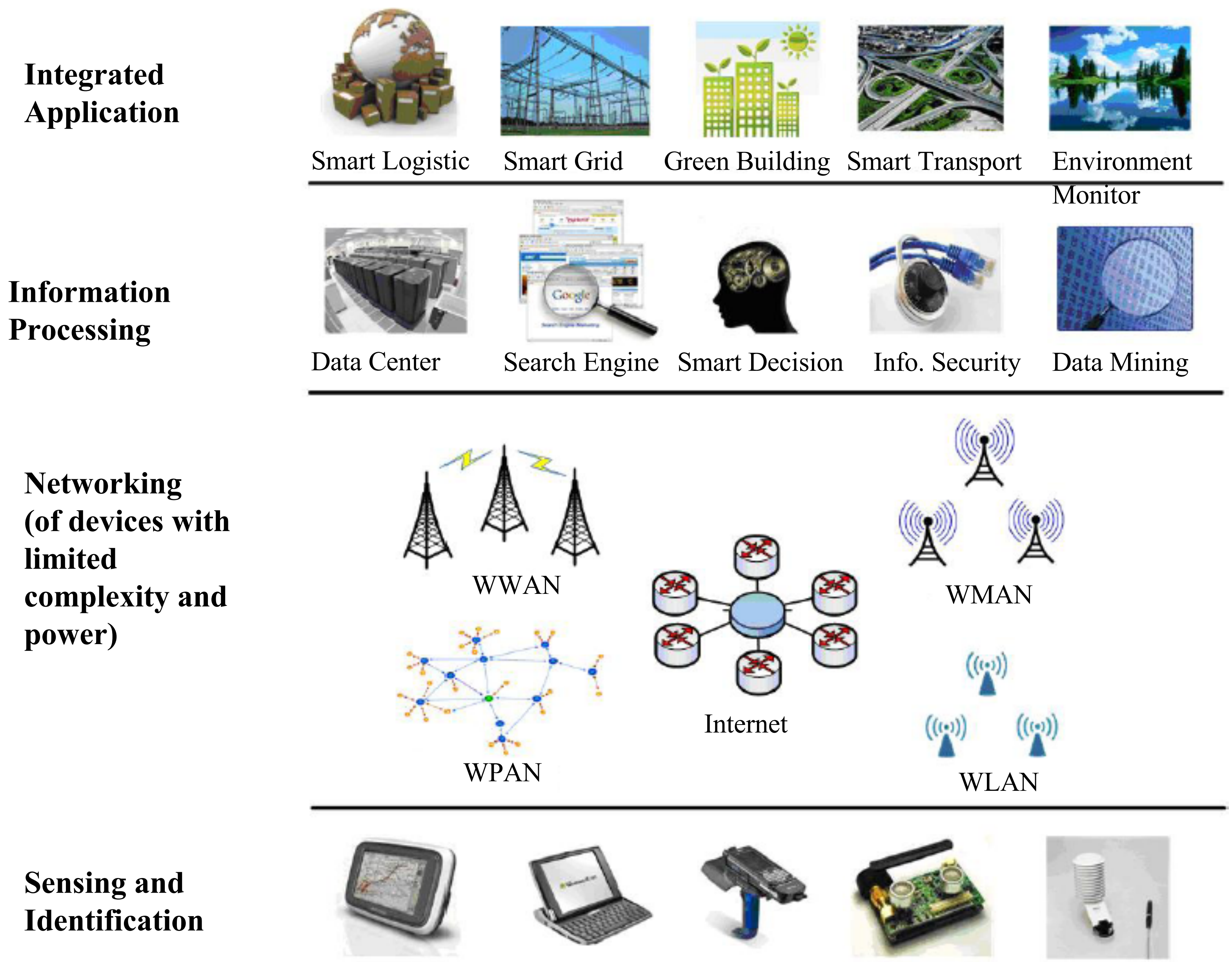
Frequency	Radius (m)
2.14 GHz	0.01 m
28 GHz	0.001 m
60 GHz	< 0.001 m

Insecure zone radius (*R*) for different frequencies

- Bob transmits a training sequence to Alice for channel estimation.
- Alice estimates the channel and determines the channel inverting filter (using TDD).
- Alice sends the session key in the clear to Bob through (channel inverting) transmitter filter.
- Bob receives the pre-equalized, distortion-free signal (containing the session key).
- Question: **Can Eve intercept the session key? Answer: Only when correlation >0.99**

A. Mazin, K. Davaslioglu, and R. D. Gitlin, "Secure Key Management for 5G Physical Layer Security," IEEE WAMICON, April 2017.

A Four-Layer Model for the Internet of Things (IoT)

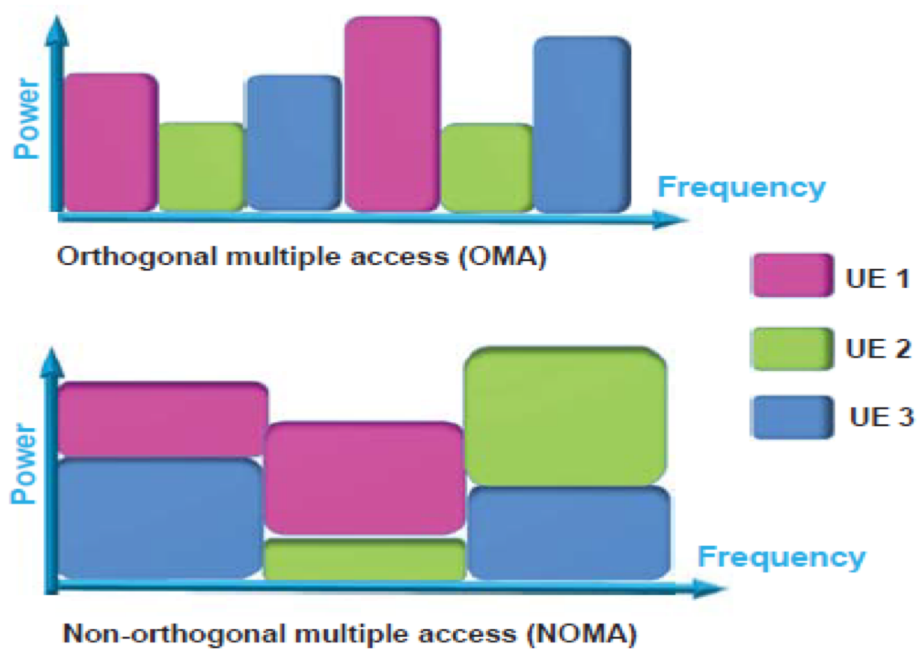


The **Internet of Things** is an ecosystem of physical objects, devices, vehicles, and all kinds of other objects that embed electronics, software, sensors and network connectivity

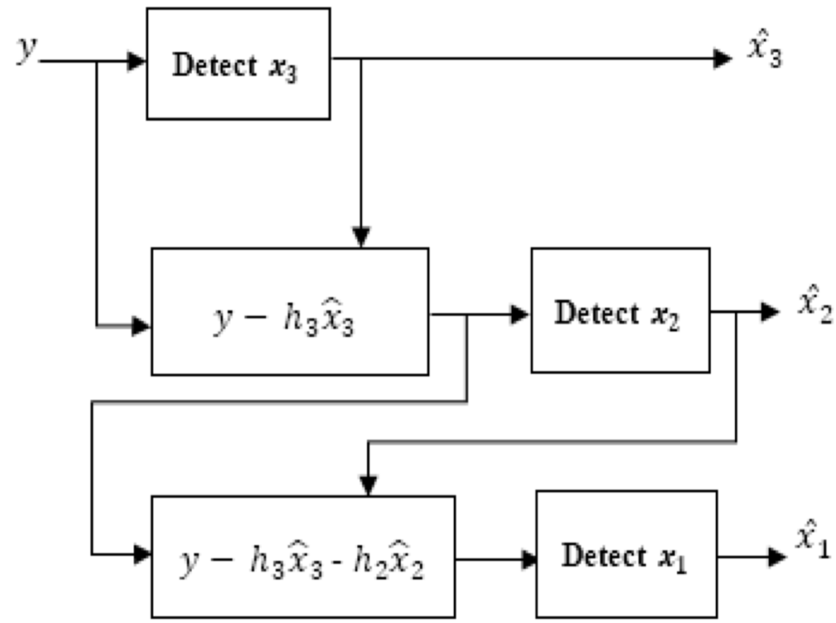
IoT networking requires highly scalable capacity and optimal handling of the differing service needs by **network slices and novel protocols)** (bandwidth, asymmetry, latency, priority) for a broad range of IoT apps.

Non-Orthogonal Multiple Access (NOMA) for IoT Applications

- For rapid access of devices with small payloads, the procedure to assign orthogonal resources to different users may require extensive signaling and lead to additional latency.
- Massive interconnectivity of devices in 5G/IoT requires fundamentally new multiple access technology beyond traditional Orthogonal Multiple Access (OMA).
- Two NOMA approaches power and code domains.
- Power domain NOMA:
  - Different users share the same time, frequency, and code, but multiplexed in the power domain.
  - Successive interference cancellation (SIC) is applied at the receiver to decode each message.
  - The BS first decodes the strongest signal, x_3, where the other signals are treated as noise. The detected signal is subtracted from the composite signal and then x_2 is detected and so on.

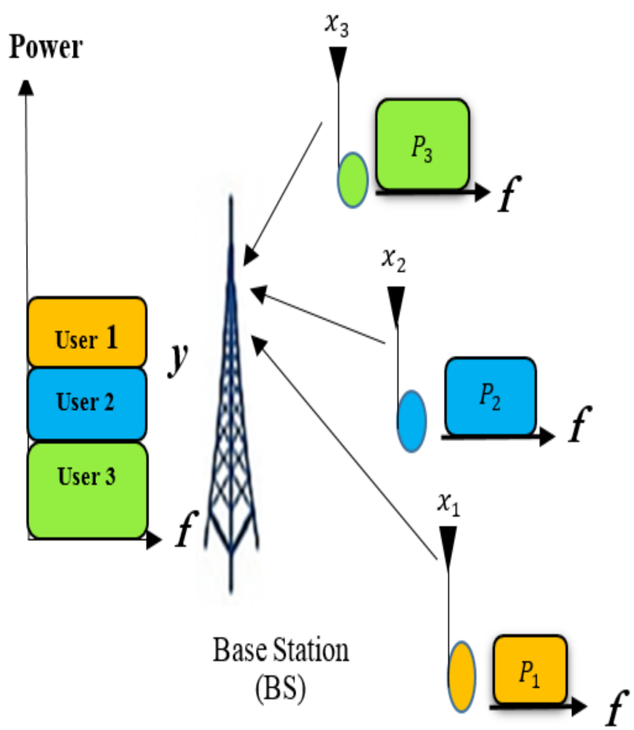


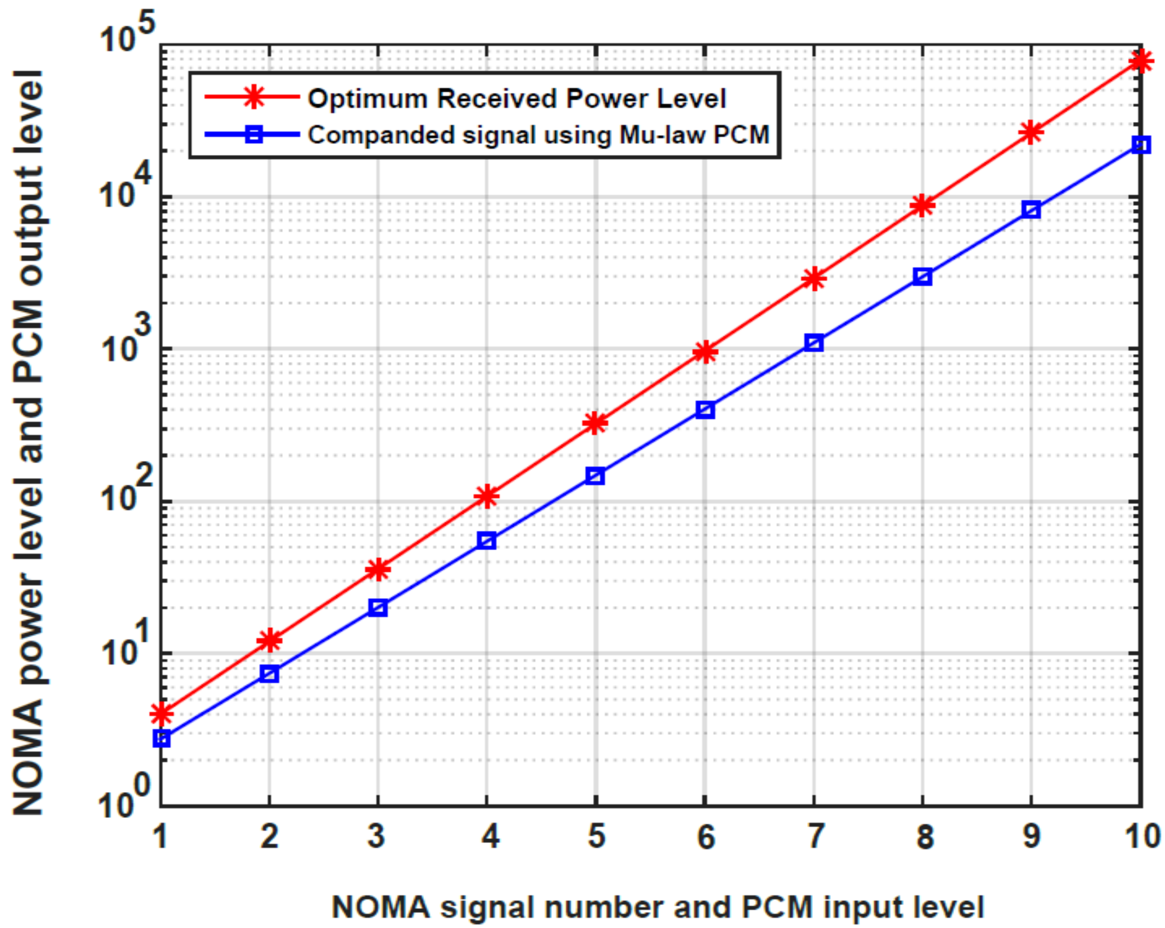
Power-Domain NOMA vs. OMA



Successive interference cancellation (SIC): Three UEs, with x_3 having the largest power.

Research: The Optimum Received Power Levels of Uplink NOMA Signals*



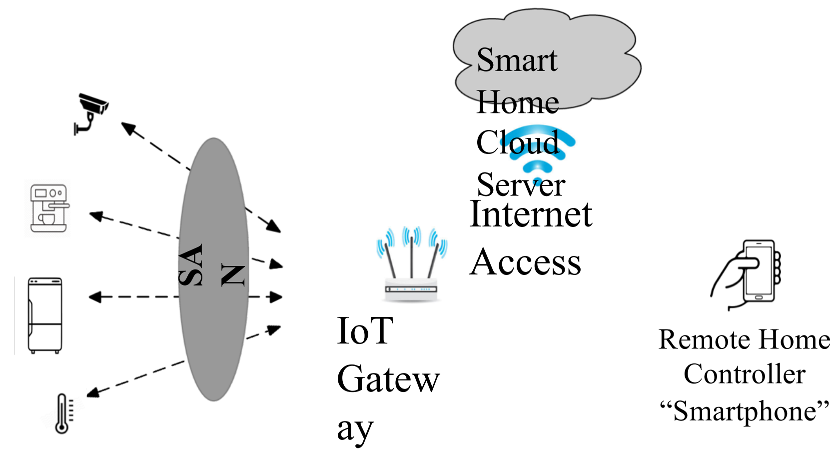


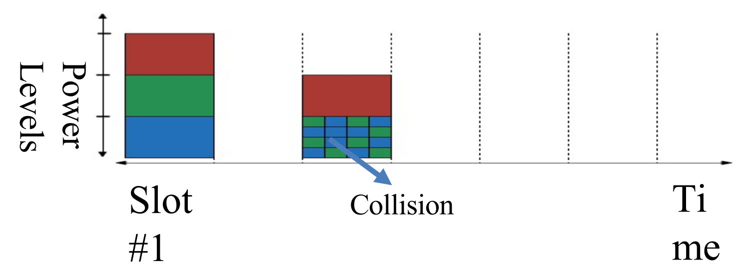
- The optimum received power level is determined for each signal so as to achieve the same bit error rate (BER) for each received signal assuming ideal SIC performance.
- With this criteria of constant SINR per signal, the optimum power levels are very similar to those of μ-law encoders used in pulse code modulation (PCM) speech compandors, where the ratio of signal power to quantization noise is kept constant.

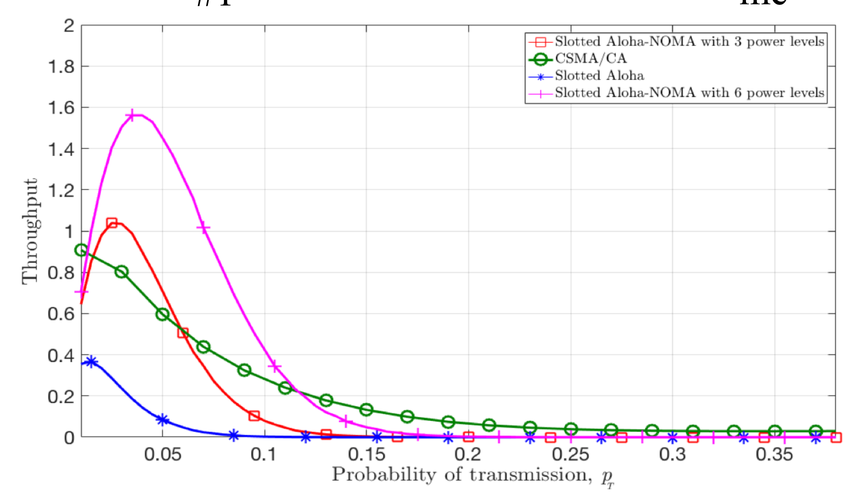
*F. Al Rabee, K. Davaslioglu and R. Gitlin, "The optimum received power levels of uplink non-orthogonal multiple access (NOMA) signals," IEEE WAMICON 2017.

Research: Slotted Aloha-NOMA (SAN) MAC for IoT Applications*

- Slotted Aloha-NOMA MAC protocol is a synergistic combination of low complexity slotted Aloha with high throughput NOMA.
- The IoT gateway transmits a beacon signal to announce its readiness to receive packets.
- The IoT devices with packets ready to transmit send a training sequence to aid the gateway in detecting the number of active IoT devices.
- The IoT gateway <u>detects the number of devices requesting transmission using multiple hypotheses testing</u>.
- If the detected number of active IoT devices is not in the range of the SIC capability, the IoT gateway aborts the transmission and starts the frame again.
- If the detected number of devices is in range, the IoT gateway broadcast the degree of SIC to the transmitters and then each active IoT device <u>randomly picks</u> one of the optimum power levels and starts the transmission.

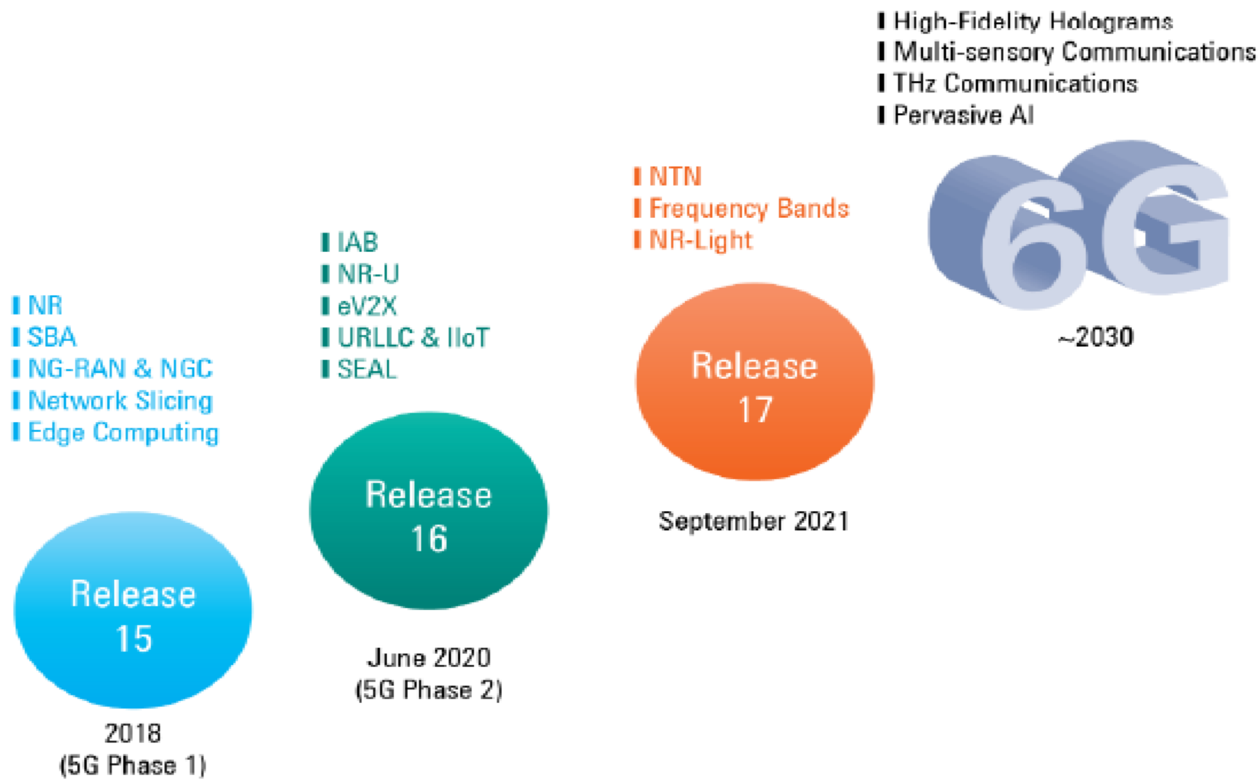






*Asim Mazin, Mohamed Elkourdi and R. D. Gitlin, "SAN- Slotted Aloha-NOMA a MAC Protocol for M2M Communications," Information Theory and Applications (ITA 2019): San Diego, February 11-15, 2019

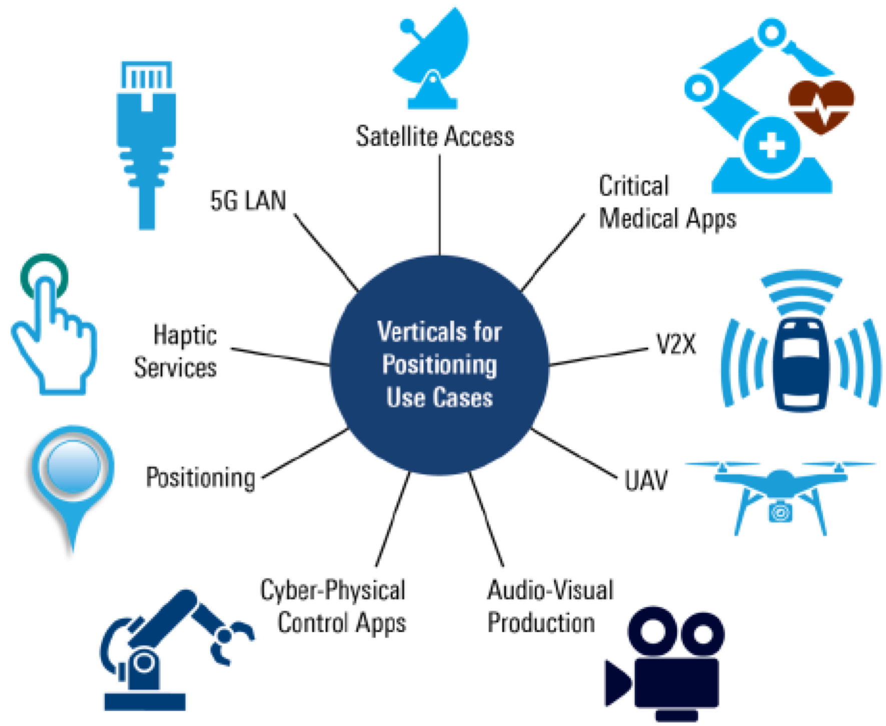
Evolution Path from 5G to 6G



- **5G** is the innovation platform for the next decade, and will continue to push technology boundaries to address new market needs and support future services that are not yet defined
- **Rel 15**: New Radio (NR), Next-Generation Radio Access Network (NG-RAN), 5G Core (5GC), Service Based Architecture (SBA), Network Slicing, and Edge Computing.
- **Rel 16:** (5G Phase 2) Planned features: NR-Unlicensed (NR-U), Integrated Access and Backhaul (IAB), enhanced Vehicle-to-Everything (eV2X), URLLC and Industrial IoT (IIoT) enhancements, and Service Enabler Architecture Layer (SEAL) for verticals.
- **Rel 17:** Potential features include Non Terrestrial Networks (NTNs) (i.e., those using satellites), new frequency bands (e.g., 7-24 GHz and > 53 GHz), and NR-Light.
- **6G:** ~ 2030. 6G could offer high-fidelity holograms, multi-sensory communications (e.g., touch, taste and/or smell!), Tera Hertz (THz) communications, and pervasive Artificial Intelligence (AI).

3GPP: Vision for 5G R16 and Beyond

3GPP is focused on different industries and many of the services shown in the figure are not necessarily distinct from each other.

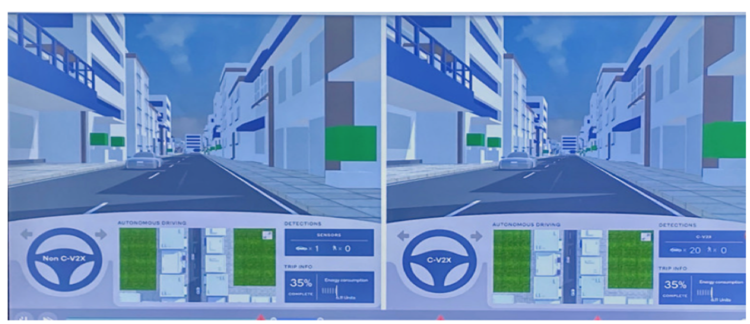


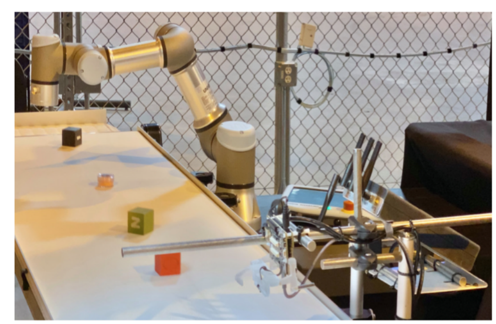
- LAN benefits: superior performance, long-distance access, mobility support, and enhanced security. TR22.821
- Satellite: Use case categories are service ubiquity, service continuity, and service scalability
- Critical Medical benefits: enhancing preventive care, reducing time-to-treatment and reducing overall costs. TR22.826.
- V2X benefits: high data rate, ultralow latency, high reliability and increased positioning accuracy. TR22.886.
- UAV benefits: Delay-sensitive applications can be supported using Multi-access Edge Computing (MEC) and ML.
- Audio-Visual Production benefits: providing flexibility, reducing costs and communications setup times. TR22.827.
- Cyber-Physical Control: Control of interacting networks of physical components and computational components. That can be applied to verticals such as industry/factory automation and energy automation. TR22.104,TR22.832
- Haptic Services: Involve tactile sensing and kinesthetic sensing of movement in the body. TR22.987. 5G could be used to deliver haptic feedback related to vibrations, temperature, texture or electronic stimulus.

Expected 5G Deployment Over the Next 5 Years

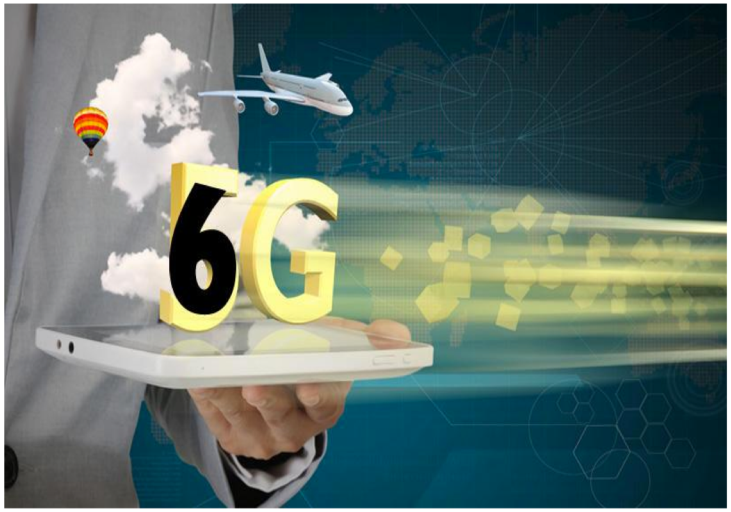
- Continued improvements in smartphone speeds and reliability with additional spectrum
  - 4G/5G handovers, non line-of-sight mmWave communications, massive MIMO grids of beamforming antennas
  - sub-6 and 52.6-114.25GHz
- High bandwidth video: 8K videos, video conferencing, and low-latency games
  - Video: 30fps→120fps, 8K videos, and 10-bit color and Gaming: <16ms lag for 4K streaming at 60fps.
- 5G-powered wearables and sensors
- 5G-NR "Light" optimization for low-power devices.
  - 5G-aided or -powered AR/XR headsets

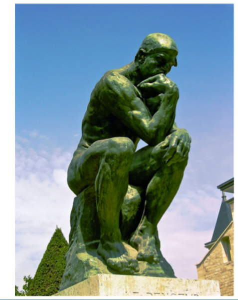
- Improved 5G location services, down to centimeter accuracy (5G NR Rel 17+)
  - Not primarily for location, but for superior cellular quality.
  - C-V2X (Cellular to vehicle-to-everything): aware of multiple vehicle and human positions.
- Expanded use space
  - 5G-based private/enterprise networks: 5G in PCs → tetherless mobile office functionality, paired with WiFi
  - Ultra-reliable, low-latency 5G factories
  - Manufacturing:5G small cells using AI/ML assisted identification of parts on a conveyor belt, …
- Fully integrated, end-to-end 5G solutions: antenna to baseband.





6G Vision





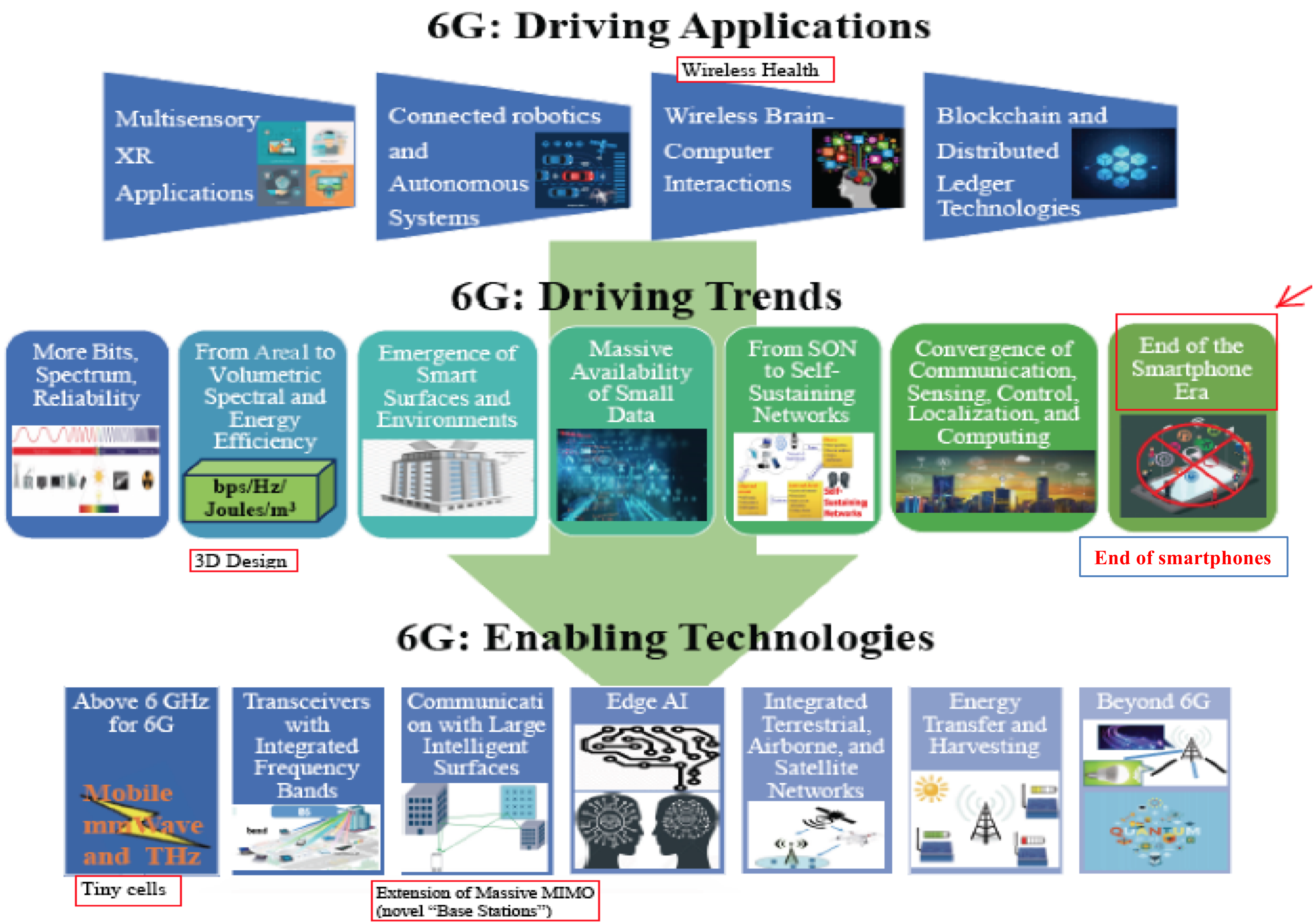
"It's tough to make predictions,
especially about the future." **Yogi Berra**

"Prediction is very difficult,
especially if it's about the future." **Nils Bohr**

The best qualification of a prophet is to
have a good memory. **Marquis of Halifax** (1600's)

- **"Contentional" Vision for the 6G-Internet of Everything (IoE) era:**
  - Pervasive wireless connectivity—always on, accessible anywhere and everywhere.
  - People interacting with billions of connected devices, sensors, machines, and vehicles to share massive amounts of data, high-resolution images, and ultra-HD video.
  - Holographic avatars, 4K/8K HD images, ultra-HD video, and virtual/augmented/mixed reality experienced in real time to enhance entertainment, education, and communication,
- **Technology**
  - Higher data rates→ more mmWave
  - Self Organizing Nets (SON) →Self Sustaining Networks (SSNs)
  - Even more extensive use of artificial intelligence/machine learning …
  - 2D →3D connectivity [ground and air users]
  - MIMO →Communication with large intelligent surfaces (LISs)
  - Smartphones→ Distributed "body" devices (end of the smartphone era?)

Terrestrial 5/6G networks will support high-altitude balloons and drones

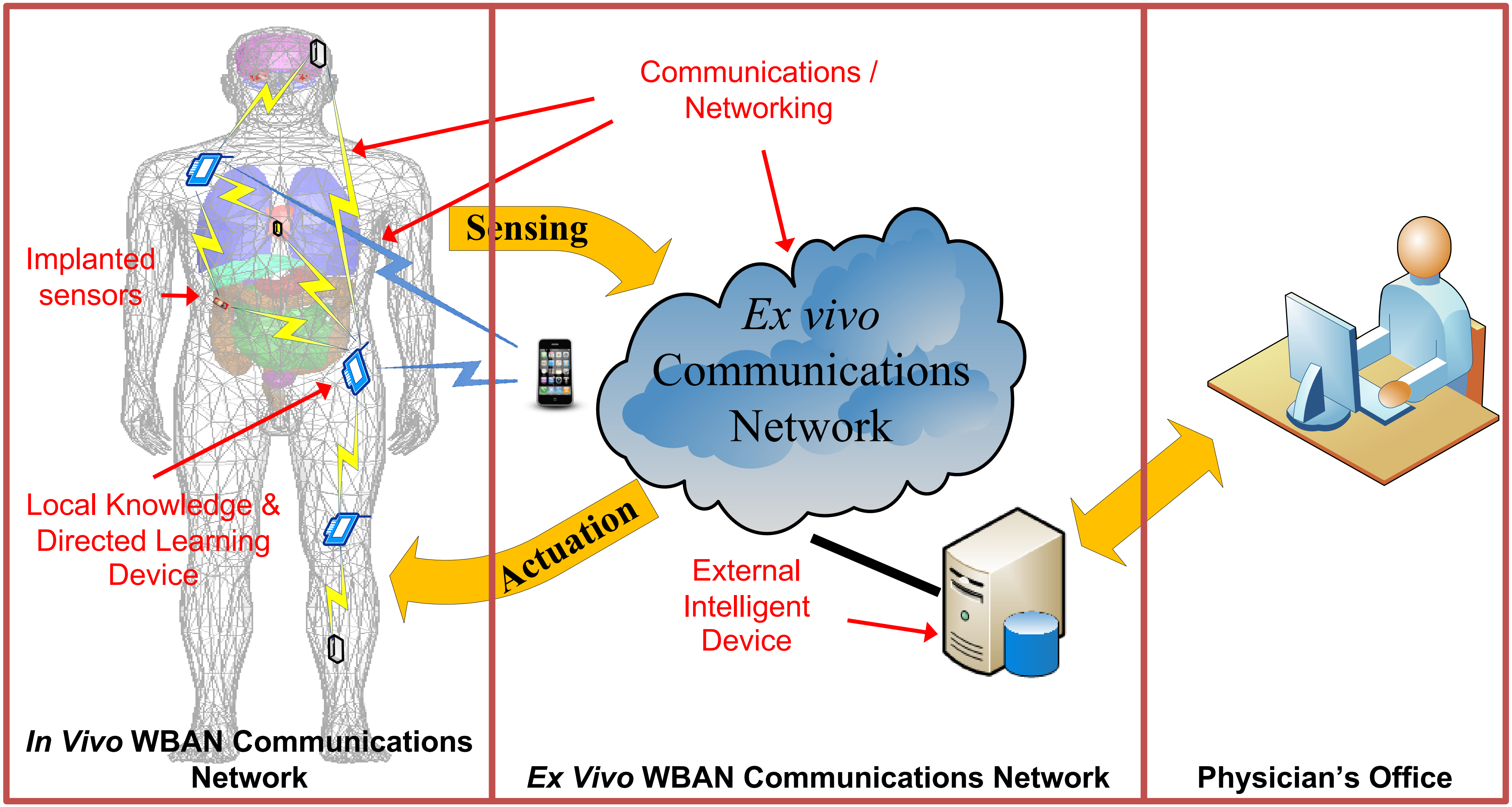


Besides technology advances, there will likely be a wave of societal changes due to massive digitalization of services that will drive novel incentive and business models in addition to telecom regulation and legislation

Source: W. Saad, et al,"A Vision of 6G Wireless Systems: Applications, Trends, Technologies, and Open Research Problems https://arxiv.org/pdf/1902.10265.pdf

6G Vision: Wirelessly Enabled Healthcare System

Wireless technology has the potential to advance and transform healthcare delivery by creating new technology for *in vivo* wirelessly networked cyber-physical systems of embedded devices that use real-time data and machine learning to enable rapid, correct, and cost-conscious responses in chronic and emergency circumstances.

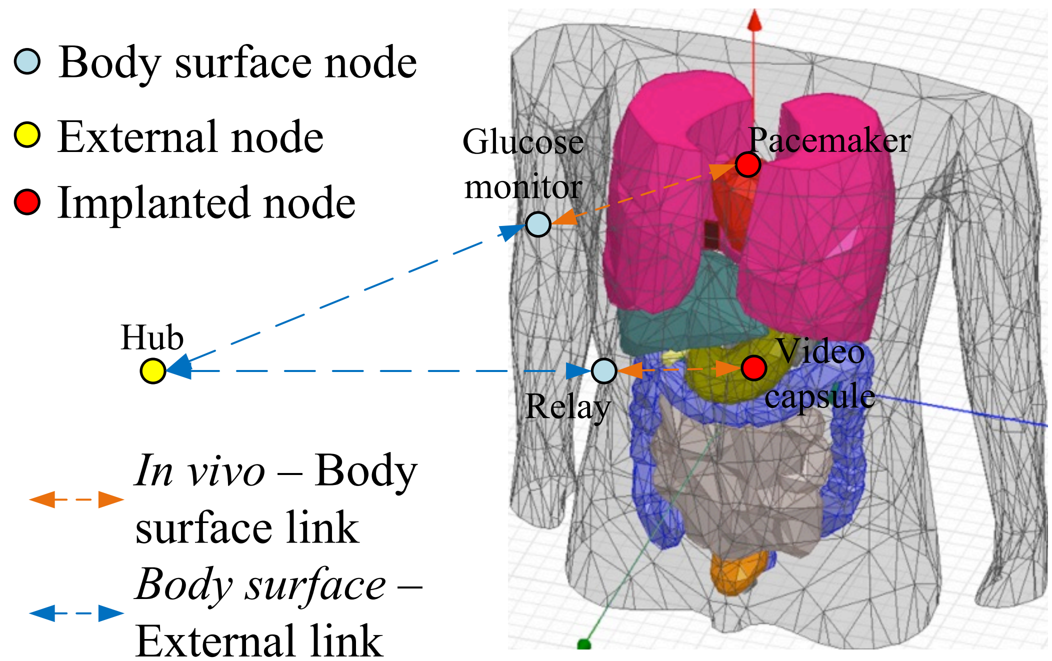


Research opportunities and challenges are abundant

6G: Internet of *In Vivo* Things (IoIT)
Cyber-Physical *In Vivo* Wireless Communications and Networking

- Vision: Wirelessly enabled cyber-physical healthcare
- *In vivo* communications a necessary component of the vision
- *In vivo* communications and networking
  - Characterization of the wireless *in vivo* channel
  - MIMO *In Vivo*

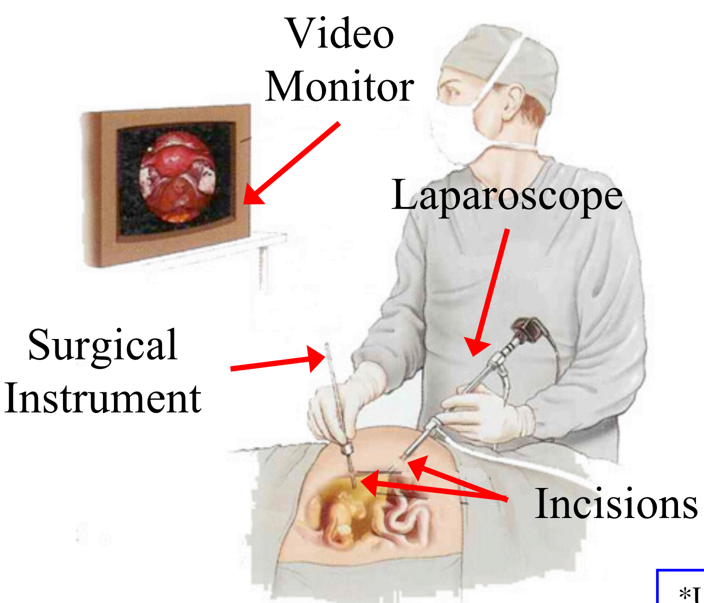
- Systems Research Projects
  - *MARVEL:* Paradigm shift in minimally invasive surgery ---*in vivo* distributed networking
  - *i*VCG: Improving the state of the heart



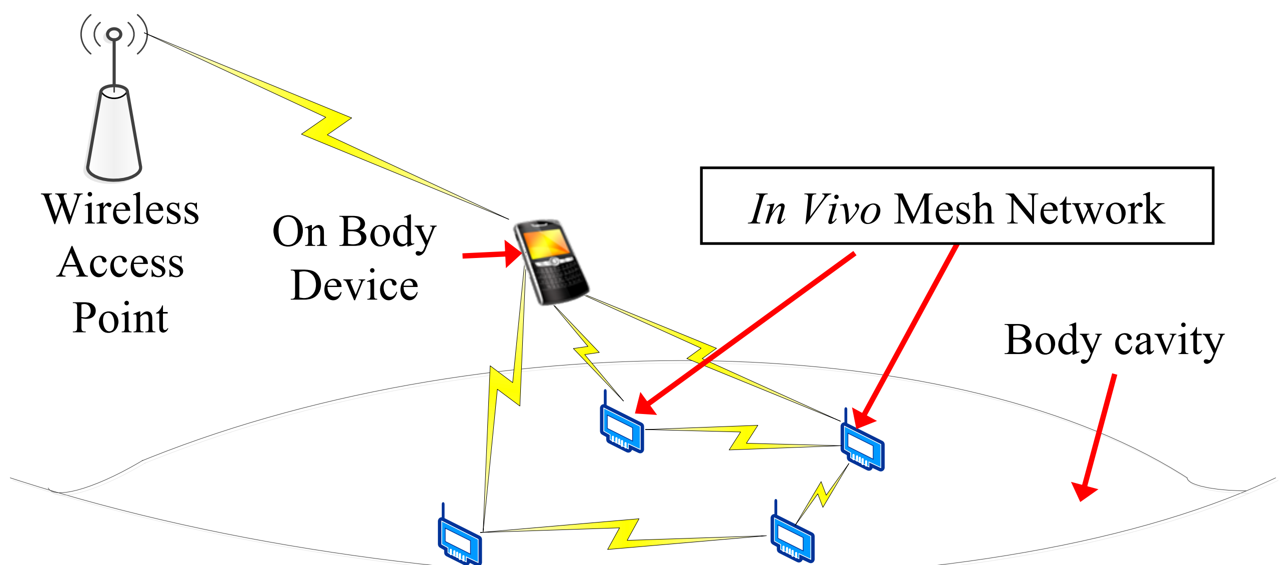
Advancing Minimally Invasive Surgery (MIS) via Wirelessly Networked Devices*
A paradigm shift in MIS surgery by eliminating the laparoscope

- A cyber-physical mesh network of wirelessly connected *in vivo* devices that enhances and enables innovative MIS surgical and other procedures.
  - Network is comprised of a plurality of communicating devices --- including imaging devices, sensors and actuators, power sources, “cutting” tools.
  - Wirelessly addressable and controllable distributed network.
  - ***MARVEL*** Camera Module is the first device and requires *in vivo* bit rates (~100 Mbps) supporting HD video with low latency (<25ms). **Replaces laparoscope.**

MARVEL **=** ***M****iniature* ***A****nchored* ***Robotic V****ideoscope for* ***E****xpedited* ***L****aparoscopy*



Current laparoscopic technology



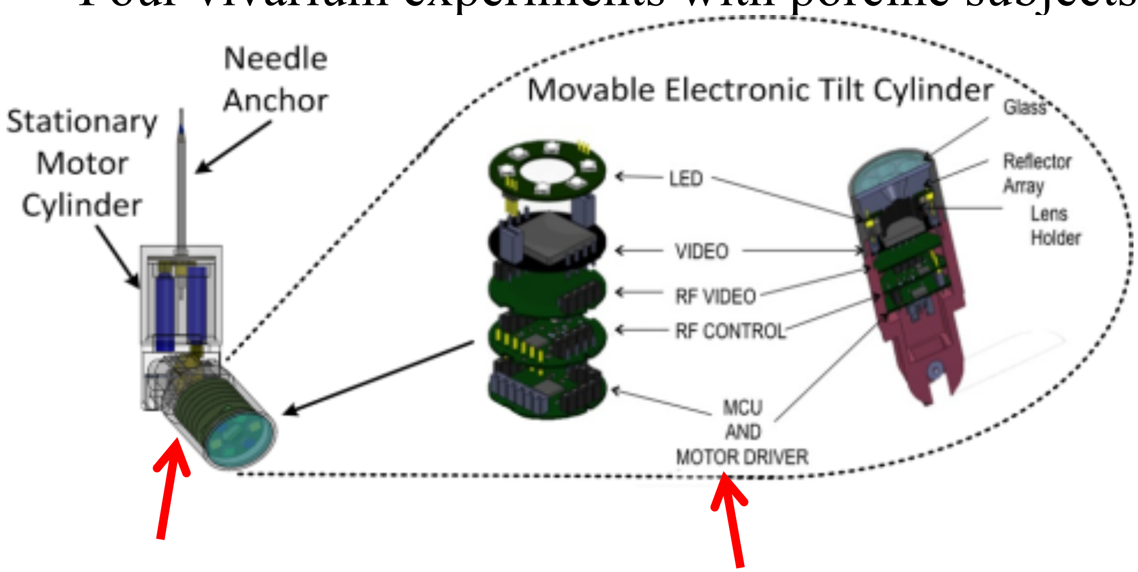
*US Patent No. 8,358,981, *Minimally Invasive Networked Surgical System*
A Wireless Miniature Robot for Networked Expedited Laparoscopy, C. A. Castro, S. Smith, A. Alqassis, T. P. Ketterl, Yu Sun, S. Ross, A. Rosemurgy, P. P. Savage, and R. D. Gitlin, "*A Wireless Miniature Robot for Networked Expedited Laparoscopy*," *IEEE Transactions on Biomedical Engineering (TBME), April 2013*

MARVEL: Research Challenges Included

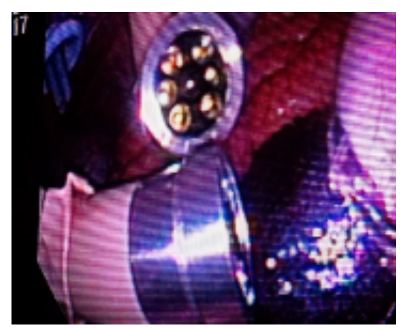
- Reliable, high-throughput and low-latency intra-body wireless communications.
- New networking paradigms for devices which are very limited from a communication and computing standpoint.
- Sensing, actuation, privacy, and security for such devices of limited complexity.
- Electronic, optical and mechanical miniaturization of complex systems.

<u>Experimental Results</u>

- The figures illustrate the ***MARVEL*** design and USF vivarium results.
- Four vivarium experiments with porcine subjects have taught us a lot ☺



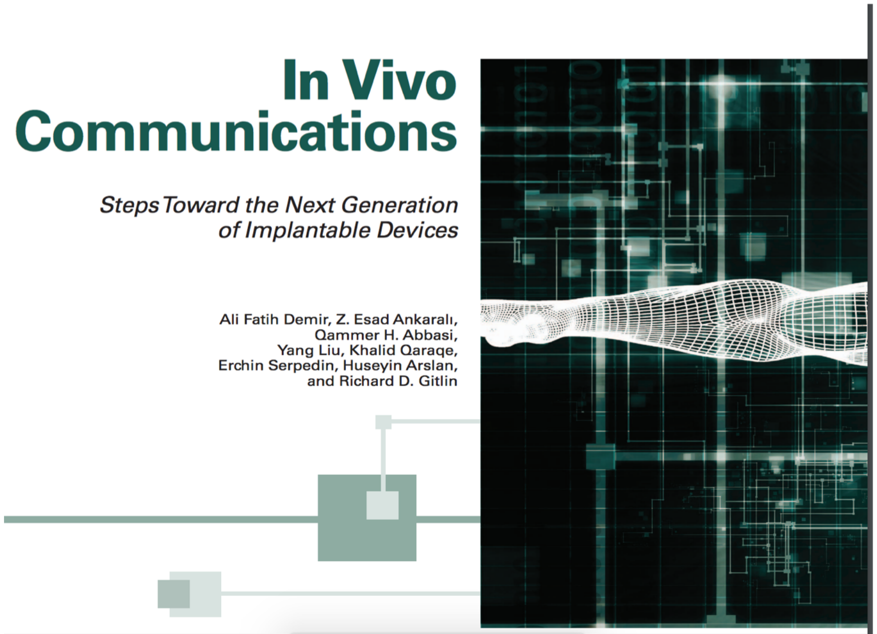
***MARVE*L CAD model and exploded circuit board stack

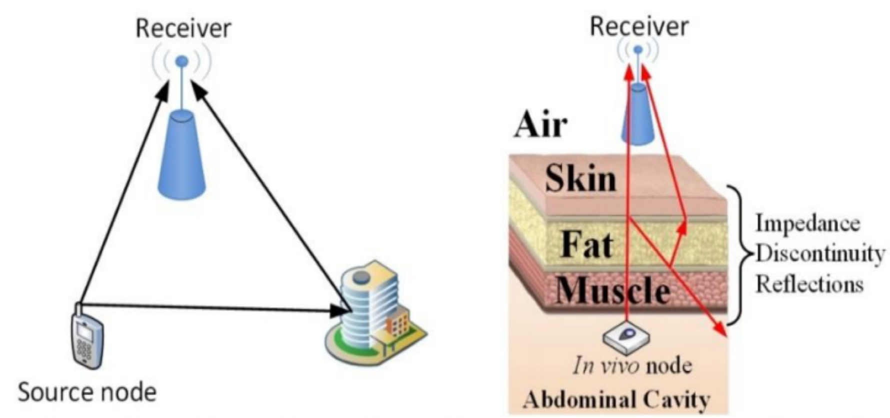


MARVEL units in a porcine abdominal cavity

Image of internal organs captured by ***MARVEL*** unit

In Vivo Channel Modeling



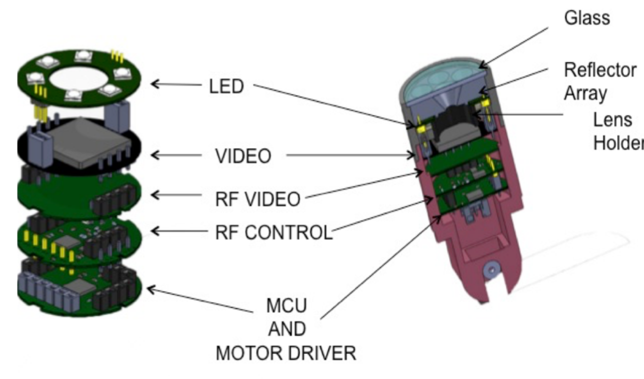


- *IEEE Vehicular Technology*, June 2016
- *Advances in Body-Centric Wireless Communication: Applications and State-of-the-art*, IET, 2016, ISBN: 978-1-84919-989-6

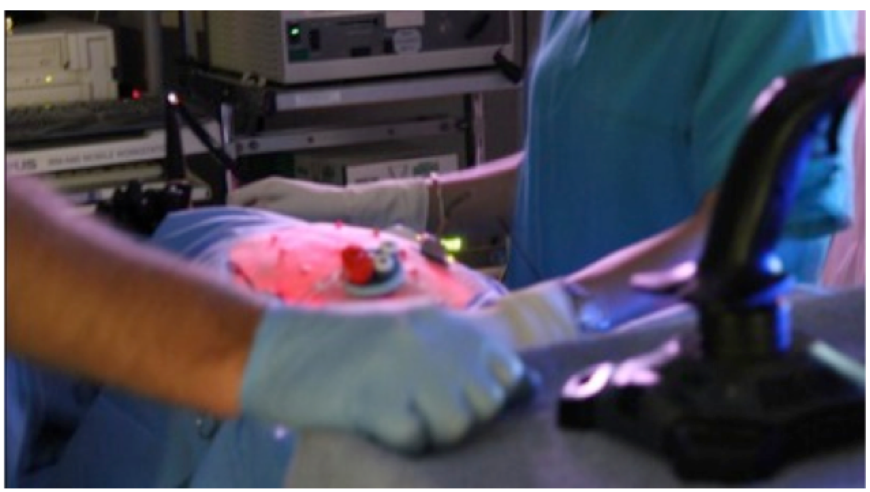
- Many research issues in media characterization and modeling including:
  - Far-field channel models of classic RF wireless communication systems are not generally valid for the *in vivo* environment (near-field effects).
  - Multi-path scattering with varying propagation speed through different types of human organs and internal structures.
  - Localized and average power Specific Absorption Rate (SAR) limit will affect the location and directionality of the antennas [SAR limit on nearest organs].

Characterizing *in vivo* wireless propagation is critical in optimizing communications and requires familiarity with both engineering and the biological environments.

MARVEL Vivarium Experiments



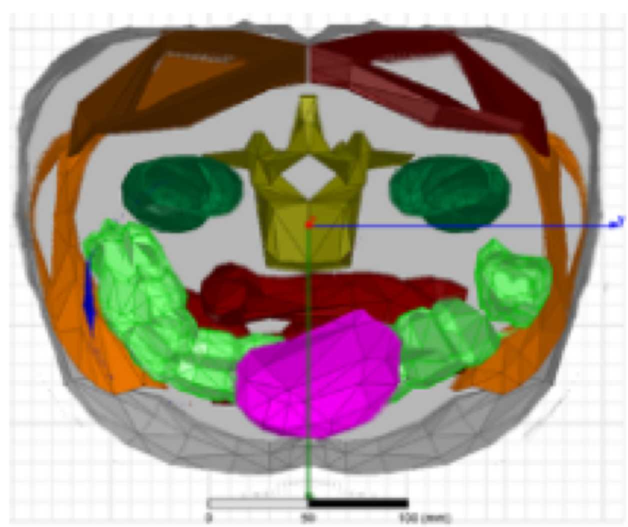
- Wireless actuator control
- 10x42mm camera housing platform
- Wireless illumination control
- Enhanced view inside abdominal cavity
- Needle power and anchor subsystem
- Wireless and cable-free videoscope
- 1080p HD video, 30fps, near-zero (15ms) latency



Two MARVEL CMs are shown. The surgeons have independent control of each Camera Module.

In Vivo Simulation with the Human Body Model (HBM)

- ANSYS HFSS-HBM is a 3D electromagnetic (EM) field simulator that utilizes a frequency domain field solver to compute the electrical behavior of the human body model with over 300 muscles, organs, and bones with a geometrical accuracy of 1 mm.
- HFSS calculates the complete EM fields created by a radiating element which includes the entire EM field (near, far, and intermediate fields).
- Frequency dependent parameters (conductivity and permittivity) for each organ and tissue are included from 10 Hz to 10 →100 GHz.
- **TX/RX antennas, or arrays, can be placed at any position inside/outside the model and the RF propagation characteristics of the medium determined.**

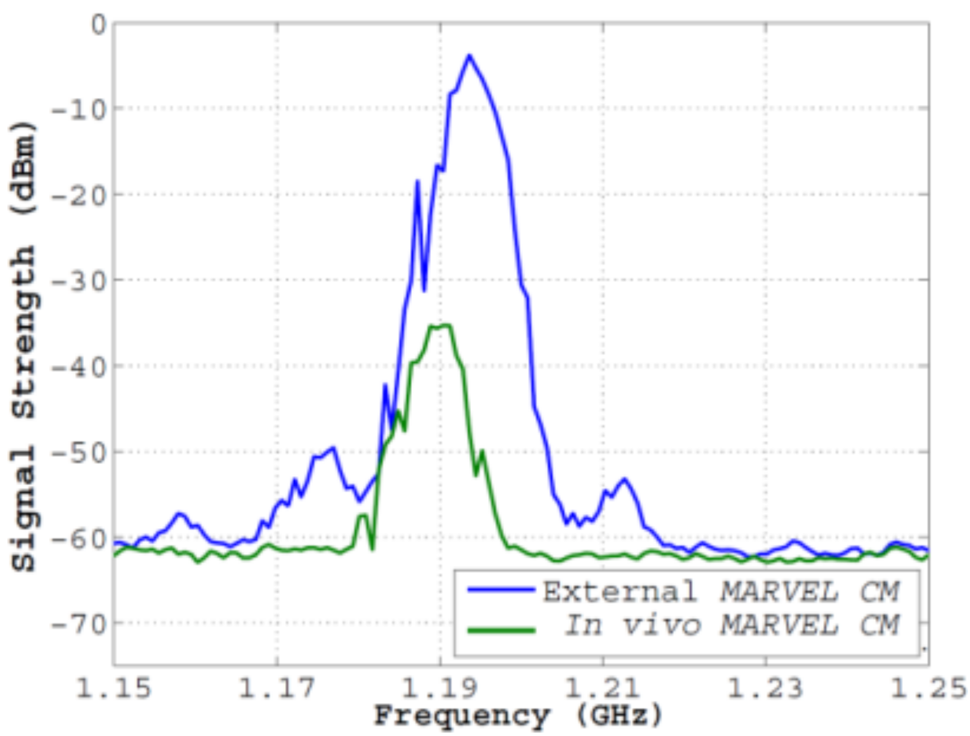


Top-down view of the human body showing locations of internal organs, muscles, and bones

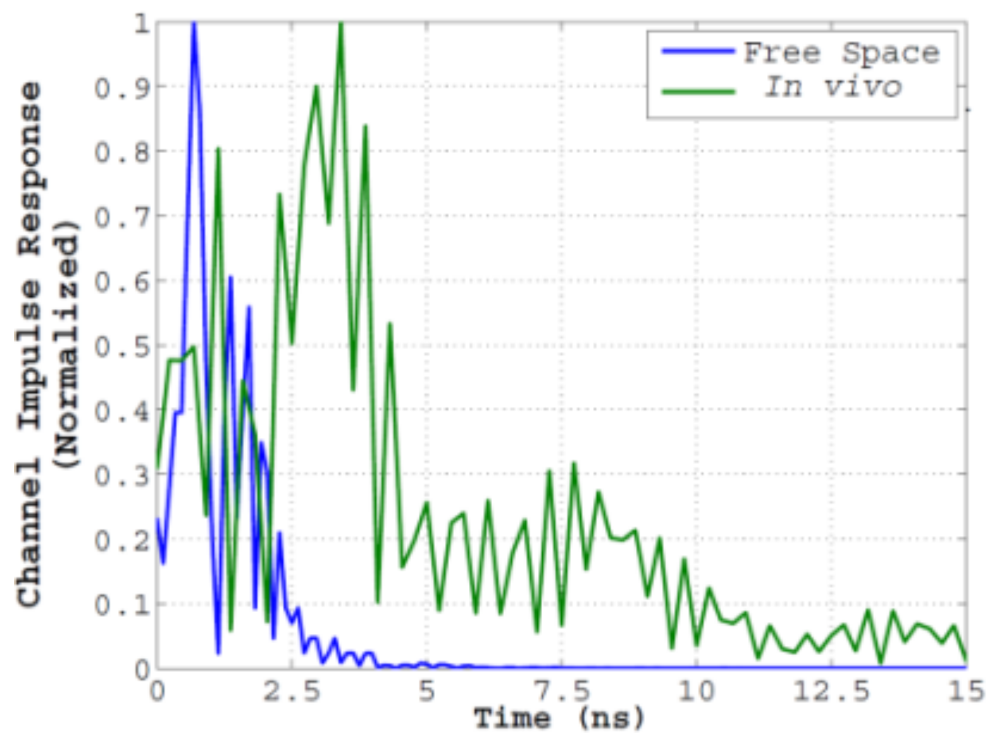
Human Body Model

In Vivo Attenuation and Dispersion - Vivarium Experiment

- Carrier frequency 1.2 GHz, video bandwidth 5 MHz and FM modulation bandwidth of 11 MHz.
- Approximately 30 dB of attenuation through the organic tissue.
- *In vivo* time dispersion is much greater than expected from the physical dimensions (owing to the lower *in vivo* speed of propagation).



External vs. *in vivo* attenuation versus frequency

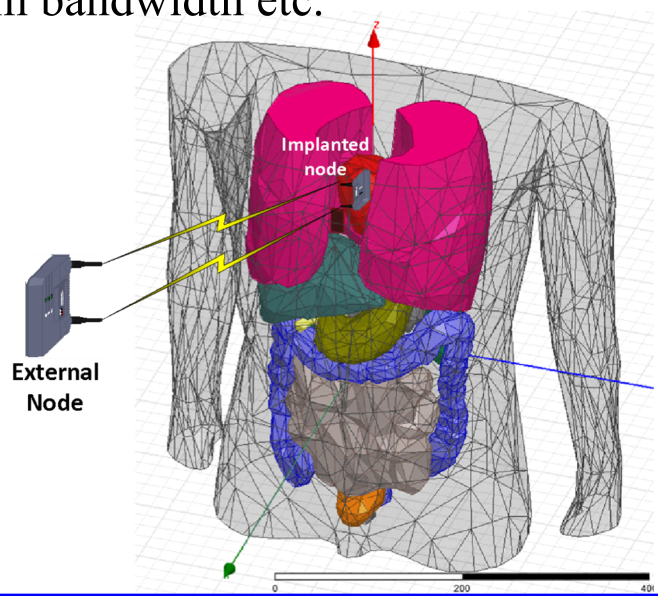


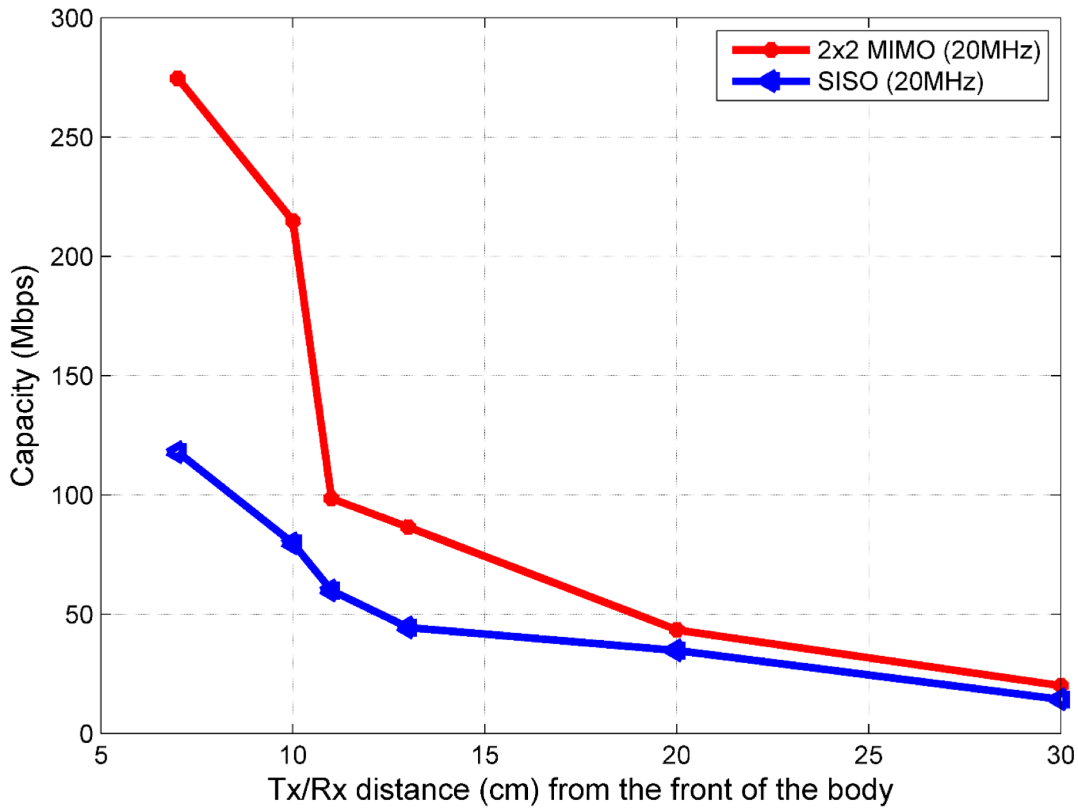
Normalized channel impulse response for free space and the porcine abdomen environments

MIMO *In Vivo**

- Due to the lossy and highly dispersive nature of the *in vivo* environment, achieving high data rates with reliable performance is a challenge [see ***MARVEL*** application].
- Signal power is limited by the specified specific absorption rate (SAR) limit, which is the rate at which RF energy is absorbed by a body volume or mass and has units of watts per kilogram (W/Kg). The FCC limit on the local and average SAR are 1.6 W/kg and 0.08 W/kg, respectively

- Capacity provides insight into how well the system can ultimately perform and provide guidance on how to optimize the MIMO *in vivo* system.
- Various factors affect capacity including antenna type, position and correlation, system bandwidth etc.





- Capacity decreases rapidly with the distance between the TX and RX antennas.
- For the required ***MARVEL*** data rate of ~100 Mbps, the distance must be ≤11cm.

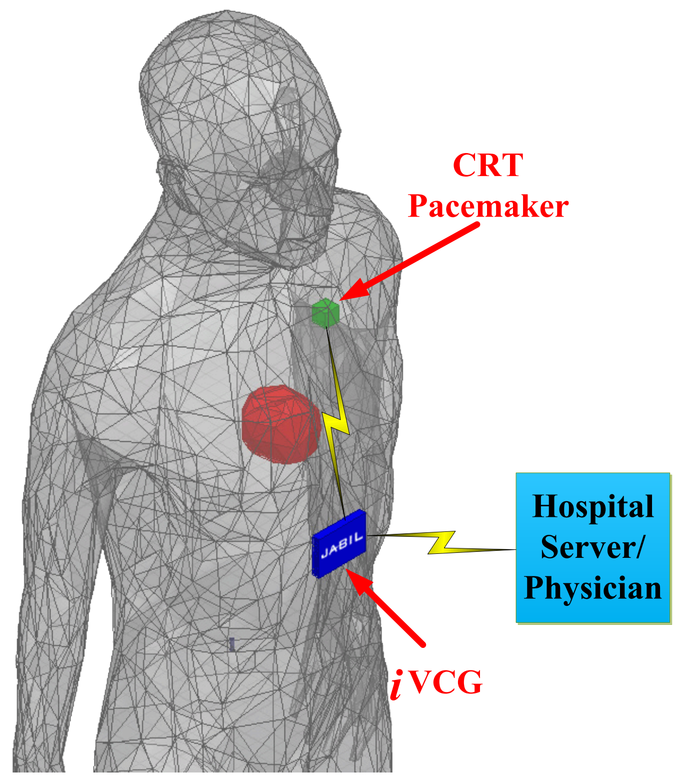
*MIMO *In Vivo*, C. He, Y. Liu, T. P. Ketterl, G. E. Arrobo, and R. D. Gitlin, "MIMO in vivo," *IEEE WAMICON*, 2014.

Improving the State of the Heart --- Vectorcardiogram (*iVCG*)*

Personalized 24x7 Diagnostic-Quality Cardiac Monitoring System

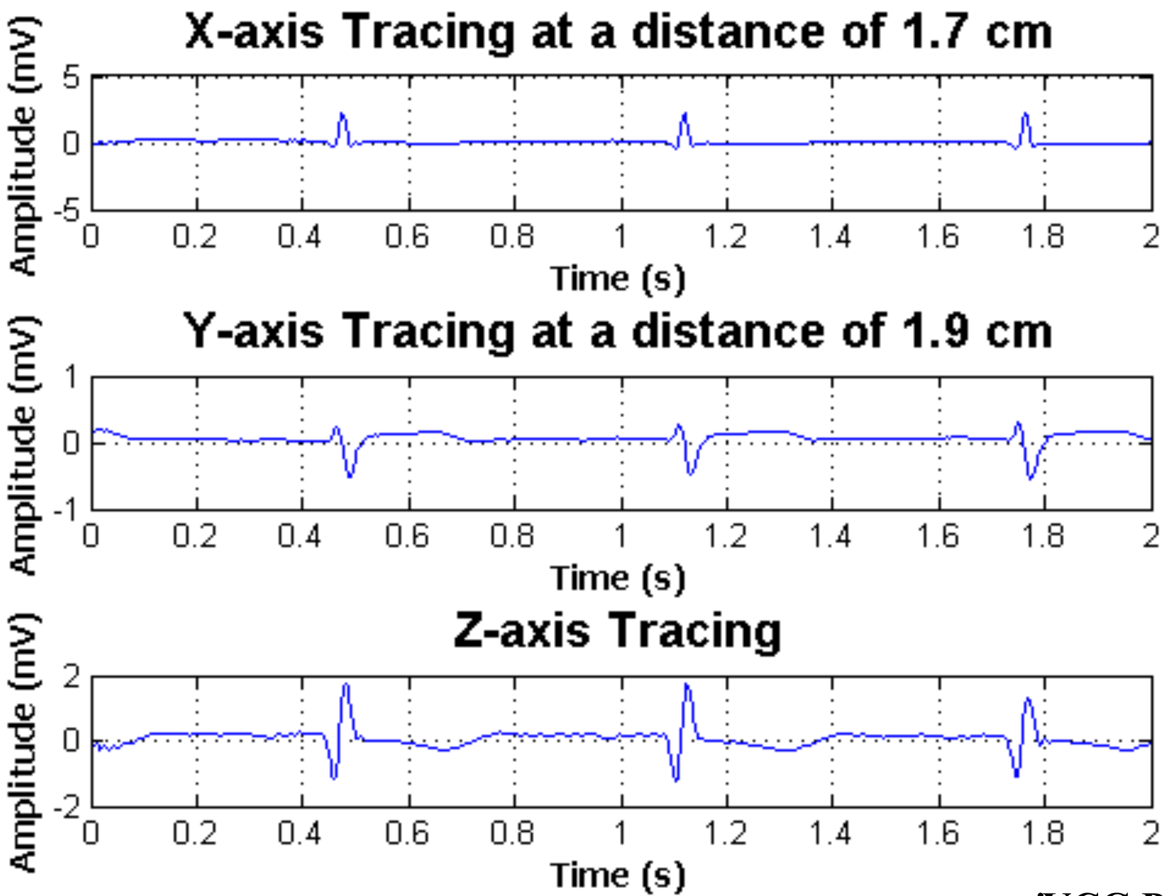
- The 3-lead diagnostic quality Vectorcardiogram (VCG) was invented in the 1950s and provides ≥ information than the 12-lead ECG.
- The VCG uses three orthogonal systems of leads to obtain the 3D electrical representation of the heart. To date, the VCG has only been a pedagogical tool.
- A system may be comprised of an integrated wireless VCG (***i*VCG**), a pacemaker, and an associated server.

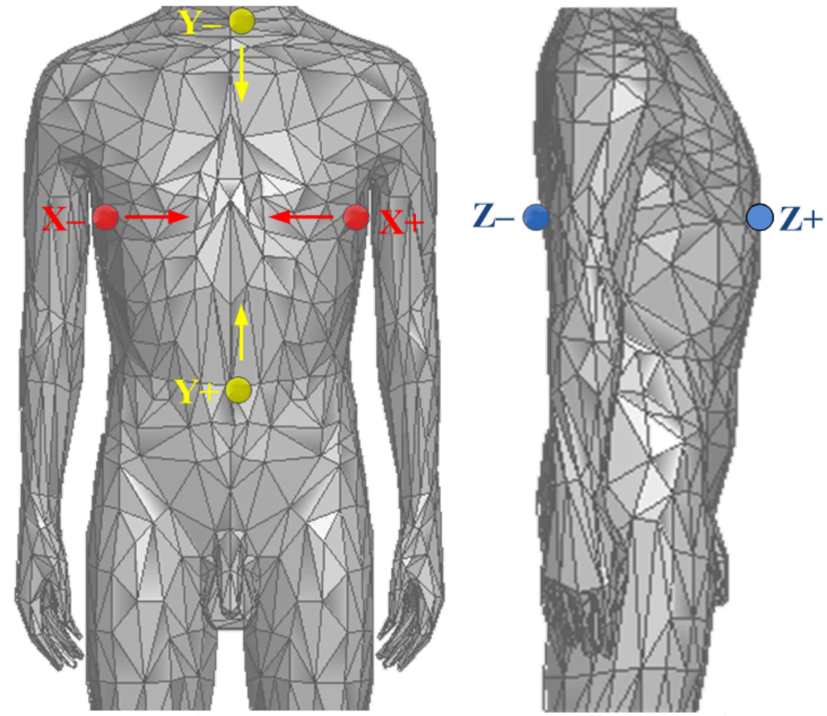
- The ***iVCG***, can enable 24x7 diagnostic-quality long term cardiac data collection [“BIG DATA”] to be continuously wirelessly received and processed using Machine Learning. This capability has never been available before.
- **Project Objectives**:
  - A 24x7 on body wireless *iVCG* with machine learning capabilities, the size of a band aid and with the diagnostic capability ≥ ECG.
  - **Predictive capabilities** (with associated servers)

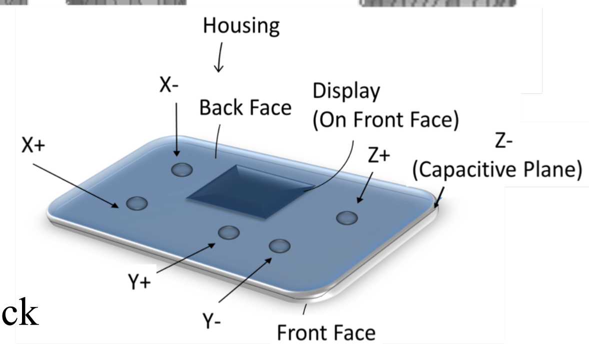


*G. E. Arrobo, C. A. Perumalla, Y. Liu, T. P. Ketterl, R. D. Gitlin, P. J. Fabri, "A Novel Vectorcardiogram System," 2014 *IEEE Healthcom*.
*D. S. Wickramasuriya, C. A. Perumalla, and R. D. Gitlin, "Predicting Episodes of Atrial Fibrillation using RR-Intervals and Ectopic Beats," *IEEE/EMB International Conference on Biomedical and Health Informatics (BHI),* 2017.

VCG Electrodes at Minimum Distances Provide Diagnostic Quality





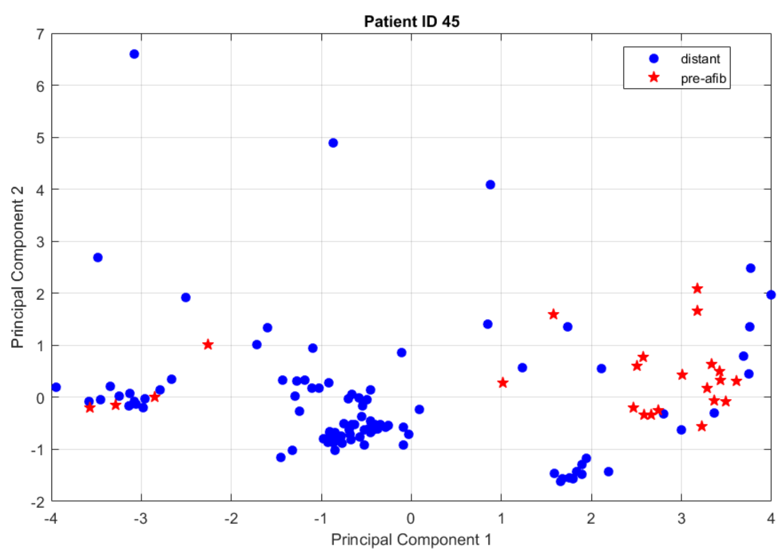


***i*VCG Prototype**
Target Dimensions:
4x4 cm and 1 cm thick

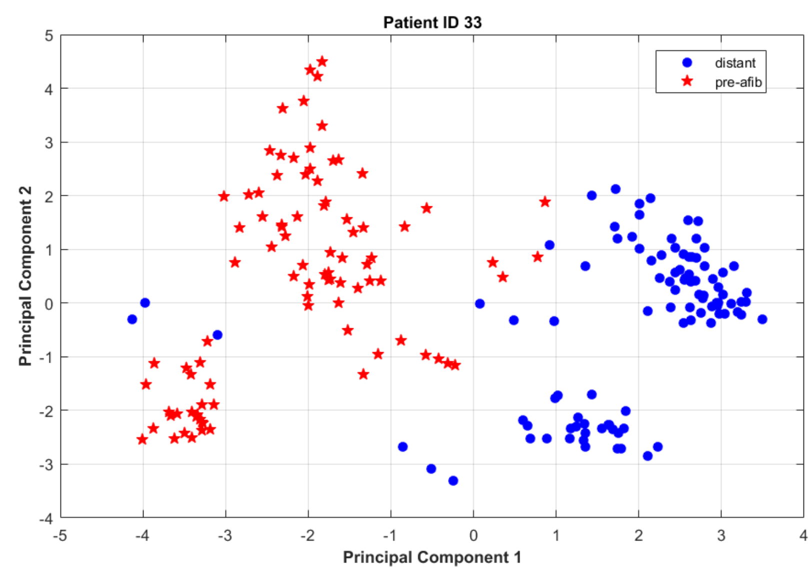
- As the proximity between the leads is decreased, the signals suffer a loss of amplitude and distortion (orthogonality) and are degraded relative to that of a 12-lead ECG.
- Compensate for proximity effects via post-reception signal processing techniques.
- **Diagnostic quality VCG signals at <2cm distances → personalized device.**

*i*VCG Predictive Analytics – Atrial Fibrillation: Initial Results

- Atrial Fibrillation (AF) is a common cardiac arrhythmia affecting over 5M people in the US
  - Upper chambers of the heart unable to contract effectively --< risk factor for stroke
  - Can be asymptomatic as well →need for long-term monitoring for diagnosis
- **Can we predict AF episodes?**
- Computers in Cardiology Challenge 2001:AF prediction high scores in the 60-80% range
- Our approach – Patient-specific Support Vector Machine (SVM) classification
  - Long-term Atrial Fibrillation Database
  - 2 minute recordings just before and far away from AF episodes
  - 3 different types of features – Statistical outliers of RR-intervals, Autoregressive coefficients of RR-intervals, Ectopic beats and rhythms
  - So far with limited data, prediction at 1 minute away from event is encouraging with substantial variance



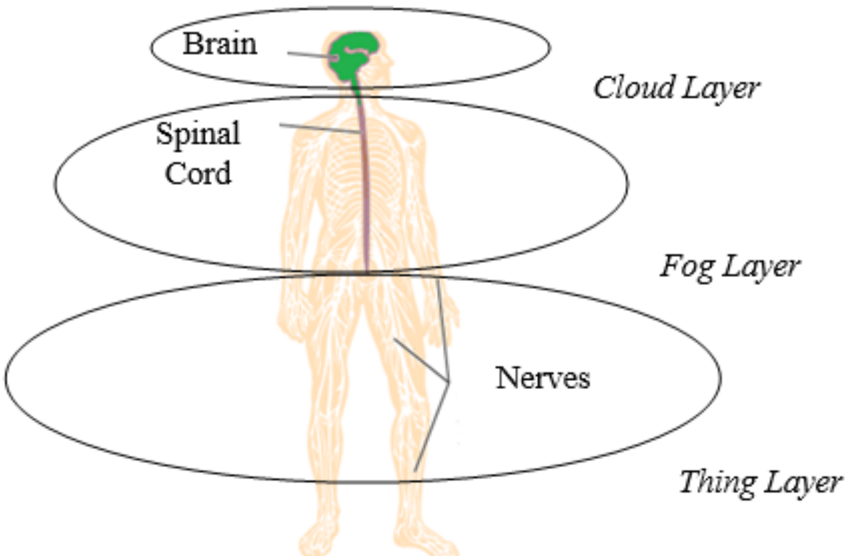
One minute before onset



Just before onset

Really Pushing the Envelope: Brain-Spinal Cord-Nerve Network*

An analogous network architecture to the *"cloud-fog-thing"* exists in the central nervous system and is dubbed the *"brain-spinal cord-nerve"* network.



Brain ⟷ *Cloud Layer*

Spinal cord ⟷ *Fog Layer*

Nerve ⟷ *Thing Layer*

Each fog node should have **communication**, **computation** and **storage** capabilities.

The spinal cord has the capabilities of:

- **Communication**: Conveying messages between the brain and the nerves
- **Computation**: Spinal reflexes, e.g., immediately pulling the hand away from a hot object
- **Storage**: Motor skills developed through practicing such as driving, biking, swimming are stored in the spinal cord.

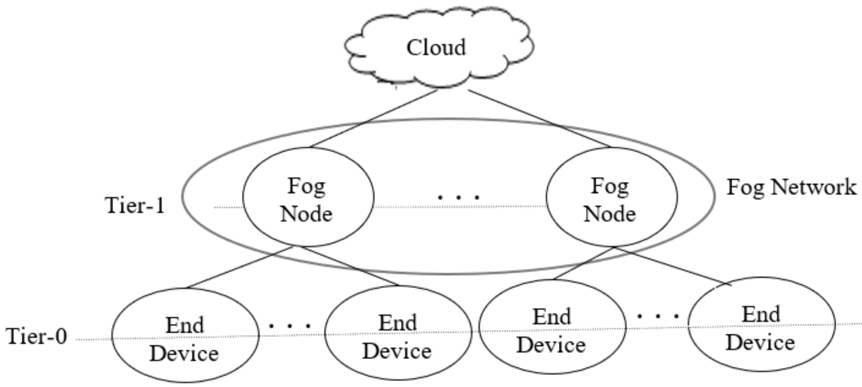
* Eren Balevi and R. D. Gitlin, "An Inherent Fog Network Brain-Spinal Cord-Nerve Networks," IEEE Access, Dec 2018
Eren Balevi and R. D. Gitlin, "Synergies between Cloud-Fog-Thing and Brain-Spinal Cord-Nerve Networks," ITA 2018

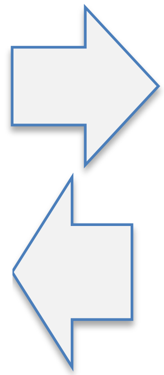
Similarities between *"Cloud-Fog-Thing"* and *"Brain-Spinal Cord-Nerve"* Networks

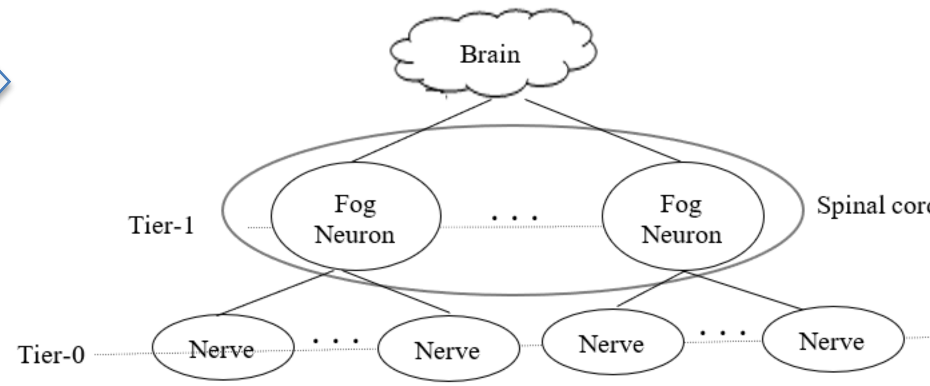
Can we use knowledge of one of these systems/networks to benefit the understanding, modeling, performance, and design of the other???

Fog Networking	Spinal Cord
Close to end devices	Close to nerves
Have distributed nodes	Spreads from the medulla to the lumbar region of the vertebral column
Location and content aware services	Location and content aware services, e.g., C5 and C6 pairs of the spinal cord control the shoulder and arm.
Low latency services	Faster responses like reflexes
Store popular files	Store motor skills such as driving, biking, swimming

Are there Synergies/Lessons from "Cloud-Fog-Thing" to/from "Brain-Spinal Cord-Nerve" Networks that Benefit both Models?







- *cloud-fog-thing* → *brain-spinal cord-nerve*

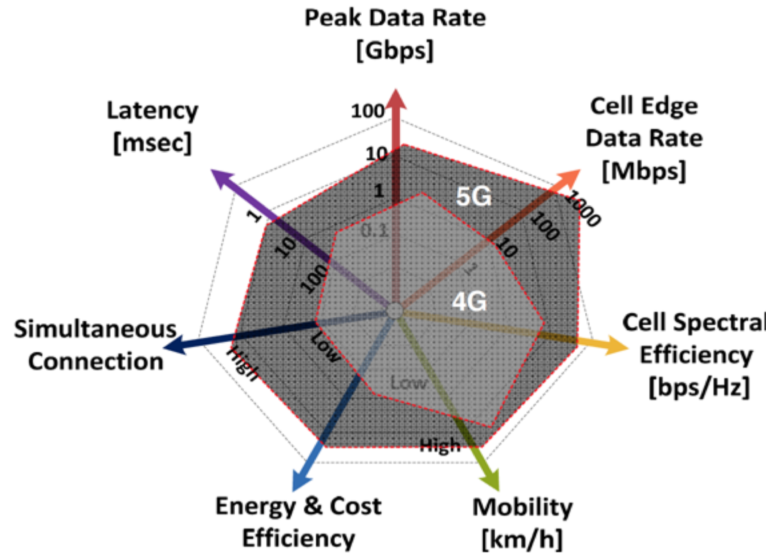
> - Can the central nervous system be better modeled considering the duality with the cloud and fog nodes?
> - The analysis for fog networking that specifies
>   - The optimum number of fog nodes
>   - The location of fog nodes
>
> may be used to localize the causes of disorders in the central nervous system.

- *brain-spinal cord-nerve* → *cloud-fog-thing*

> - Novel algorithms/protocols can be inspired from the central nervous system for fog networks.
> - For example, brain inspired coded caching.

Concluding Remarks

5/6G + IoT/IoE = A Century of Connectivity, Applications, and Opportunity



Meeting the 5G/6G challenges will impact the way we live, work, play,…

- To succeed the 5G/6G/IoT/IoE network(s) must be flexible, exceptionally capable, secure, and economical enough to address the concerns of skeptics and successfully navigate all of the expected and unexpected scenarios.
- We are at a point of inflection created by the synergies of gigabit wireless connectivity and pervasive broadband connectivity for everyone and everything.
- Expected to be extended in 6G both in technology and range of applications.
- Impact of 5G and 6G will be transformational and will be central to everything we do, forever altering how people access and use information.

The Internet of Tomorrow (5G/IoT) is arriving and the Internet of Everything (6G/IoE) is Next!

http://iwinlab.eng.usf.edu (slides here)