Electrical Engineering Distinguished Lecture

Columbia University
Electrical Engineering

Perspectives on the Wireless Century 5G/Internet of Things (IoT) and 6G/Internet of InVivo Things (IoIT)

Speaker: **Professor Richard Gitlin**

Distinguished University Professor
University of South Florida

WHEN March 27, 2019 @3PM

WHERE Davis Auditorium (412 CEPSR)

Host: Professor Xiaodong Wang

ABSTRACT

This presentation provides a perspective on the emerging Wireless Century driven by 5G/IoT and on the contemplated 6G wireless network ---with emphasis on applications and selected research.

The fifth generation (5G) of mobile communication systems will impact our life more than any other wireless technology by enabling a seamlessly connected society and become the Internet of Tomorrow that brings together people, data, and "things" via a myriad of new applications. This presentation will review the expected disruptive market opportunities, demanding applications, and focus on several research challenges and potential technologies needed to meet the ambitious 5G/IoT requirements for broadband networking, low-latency applications [e.g., autonomous vehicles] technologies, and Internet of Things (IoT) scenarios such as Machine-to-Machine (M2M) networking. We will emphasize the central role of Machine Learning in optimizing the latency and throughput of cell-less and edge-based ("Fog") network architectures, synchronization of mmWave networks, novel MAC protocols and NOMA [non-orthogonal multiple access] signal processing for increased throughput in machine-to-machine communications, and methods to enable near-instant recovery from link or nodal failures.

While there is already much early speculation on the applications, or use cases, and technologies for 6G, in vivo wireless communications and cyber-physical networking of biomedical devices has the potential of being a key component of the sixth generation (6G) wireless networks, perhaps as part of the Internet of InVivo Things (IoIT) in advancing health care delivery. This presentation provides an overview of research on characterizing the in vivo wireless RF channel, MIMO in vivo signal processing, as well as two of our experimental biomedical systems that focus on changing the paradigm for minimally invasive surgery and a novel vectorcardiogram, that provides 24x7 diagnostic cardiac capability in a compact wearable device and uses Machine Learning to predict cardiac events.

BIO

Richard D. Gitlin is a State of Florida 21st Century World Class Scholar, Distinguished University Professor, and the Agere Systems Chaired Distinguished Professor of Electrical Engineering at the University of South Florida. He has 50 years of leadership in the communications industry and in academia and he has a record of significant research contributions that have been sustained and prolific over several decades.

Dr. Gitlin is an elected member of the National Academy of Engineering (NAE), a Fellow of the IEEE, a Bell Laboratories Fellow, a Charter Fellow of the National Academy of Inventors (NAI), and a member of the Florida Inventors Hall of Fame (2017). He is also a co-recipient of the 2005 Thomas Alva Edison Patent Award and the IEEE S.O. Rice prize (1995), co-authored a communications text, published more than 170 papers, including 3 prize-winning papers, and holds 65 patents.

After receiving his doctorate at Columbia University in 1969, he joined Bell Laboratories, where he worked for 32-years performing and leading pioneering research and development in digital communications, broadband networking, and wireless systems including: co-invention of DSL (Digital Subscriber Line), multicode CDMA (3/4G wireless), and pioneering the use of smart antennas ("MIMO") for wireless systems At his retirement, Dr. Gitlin was Senior VP for Communications and Networking Research at Bell Labs, a multi-national research organization with over 500 professionals. After retiring from Lucent, he was visiting professor of Electrical Engineering at Columbia University, and later he was Chief Technology Officer of Hammerhead Systems, a venture funded networking company in Silicon Valley. He joined USF in 2008 where his research is on wireless cyberphysical systems that advance minimally invasive surgery and cardiology and on addressing fundamental technical challenges in 5G/6G wireless systems.

Columbia Engineering
The Fu Foundation School of Engineering and Applied Science

March 27, 2019

Perspectives on the Wireless Century
5G/Internet of Things (IoT) and 6G/Internet of *In Vivo* Things (IoIT)

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

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The Wireless 21st Century

- ***5G/IoT*** **r**evolution has begun and with it comes immense amounts of data at unprecedented speeds that will fuel a wide range of data-driven services.
  - Emerging applications, requirements, and networking technologies
  - Spectrum and PHY technologies
  - Network architectures and related research
    - Optimizing Fog Networks
    - SDN/NFV software based networks
    - Resilient and cell-less networks
  - IoT: MAC protocols and NOMA signal processing
  - Machine Learning based Self-Organizing Networks

Mobile World Congress 2019

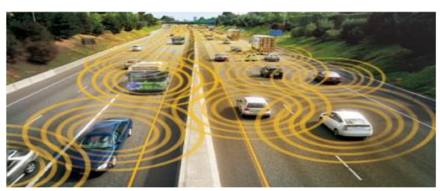
Samsung Foldable Mobile

Nokia Pure View
5 Cameras

Ericsson "stripe" antennas
Massive MIMO

- ***6G*** **and the** ***In Vivo Net of Tomorrow***
  - Current view --pervasive connectivity, densification, more Massive MIMO, mmWave , …
  - A complementary view: *In vivo* communications and networking
    - *In vivo* Channel Characterization/MIMO *in vivo*
    - System Projects
      - ***MARVEL***: New paradigm for Minimally Invasive Surgery
      - Integrated VectorCardiogram (*i*VCG)
      - Synergies between *"Cloud-Fog-Thing"* and *"Brain-Spinal Cord-Nerve"* Networks

Mobile Broadband



Vehicular Networks
(Tactile Internet)

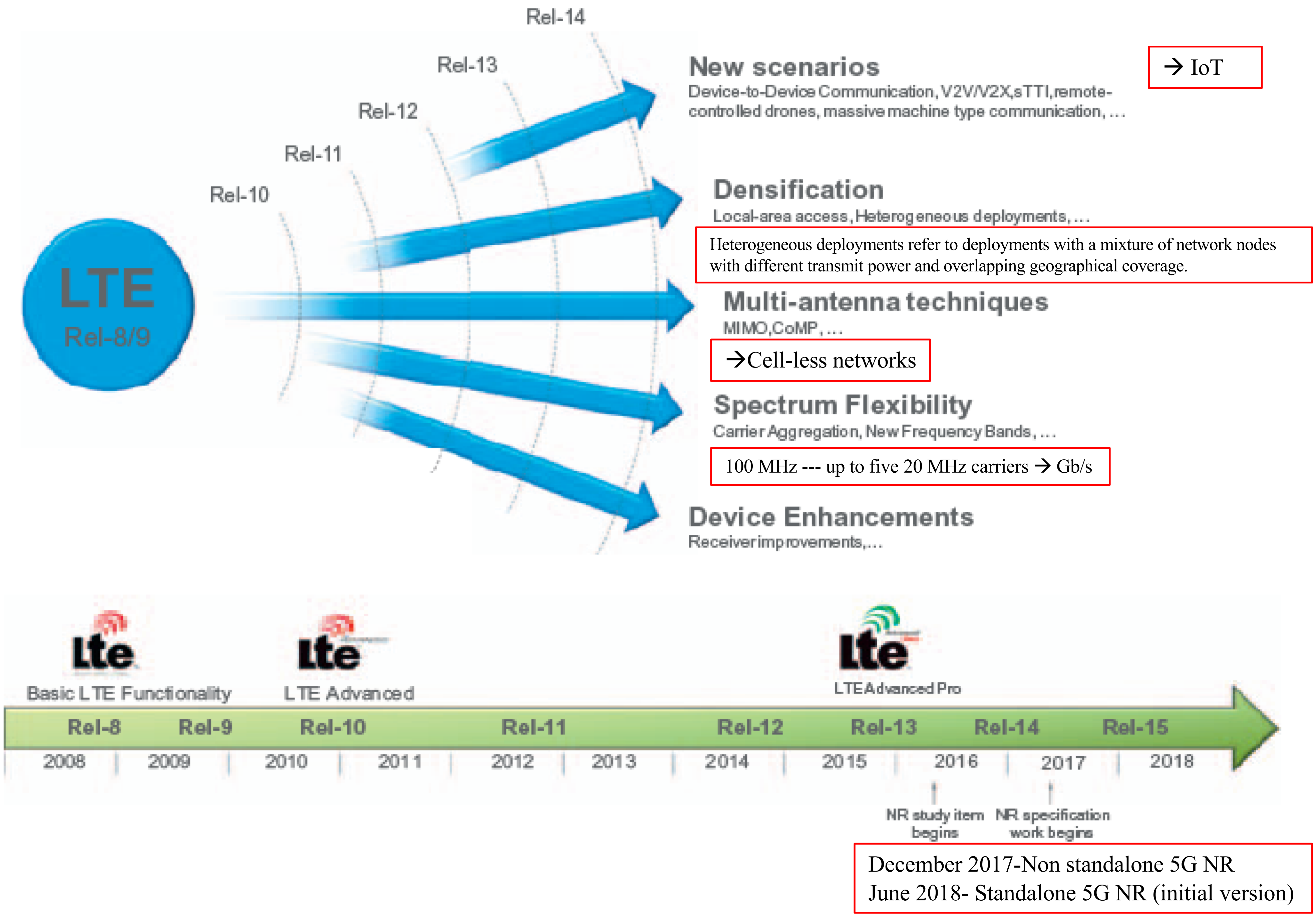
Internet of Things

5G use cases

Cloud Services

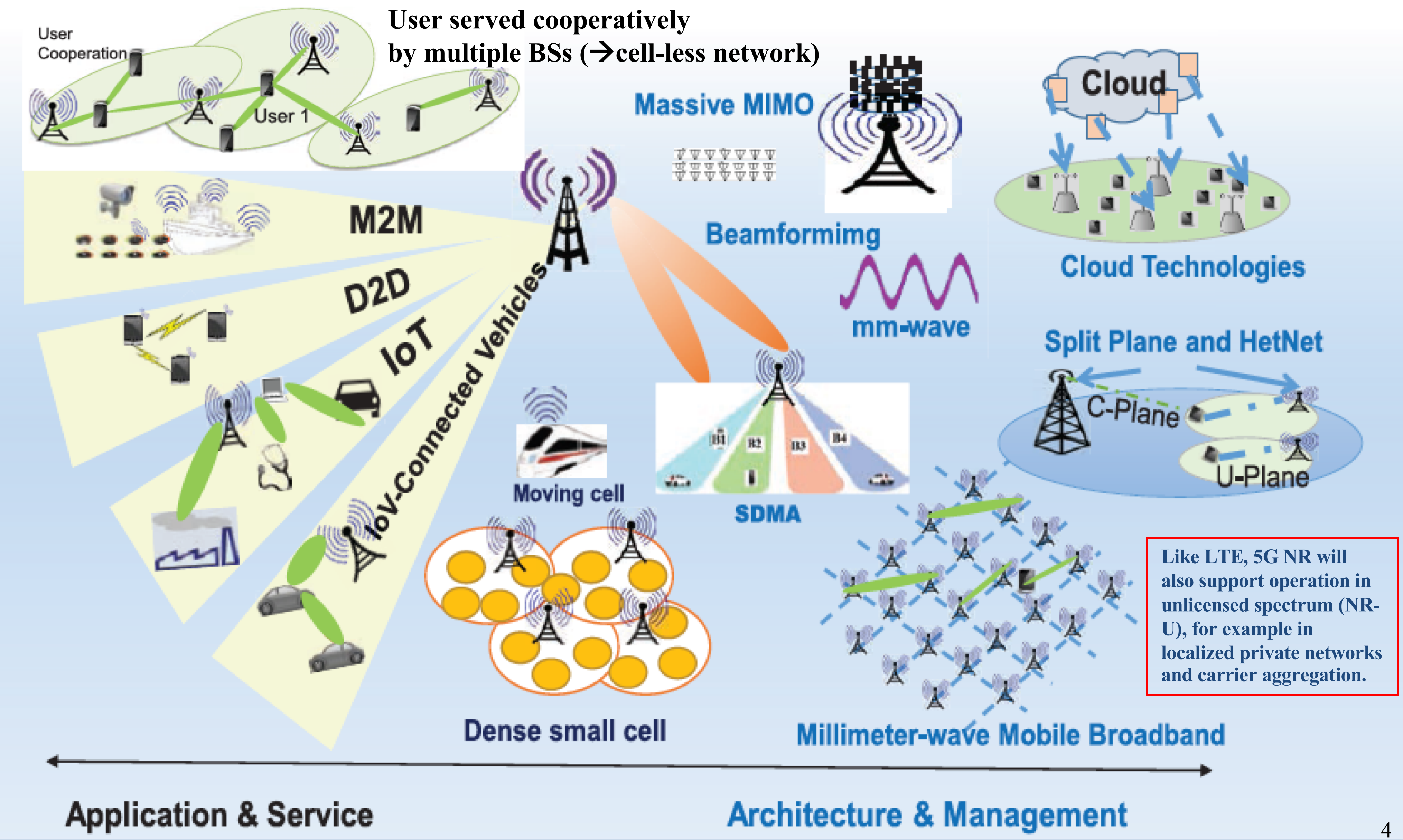
SDN =Software Defined Network
NFV = Network Function Virtualization

LTE Evolution over a Decade



5G Wireless Heterogeneous Networks-The Vision

High data rates (Gb/s), extremely low latency (1ms), significant increase in base station capacity and density, cell cooperation, and cell-less operation, and significant improvement in quality of service (QoS) for a broad array of applications that reflect a paradigm shift to a device/user-centric network.

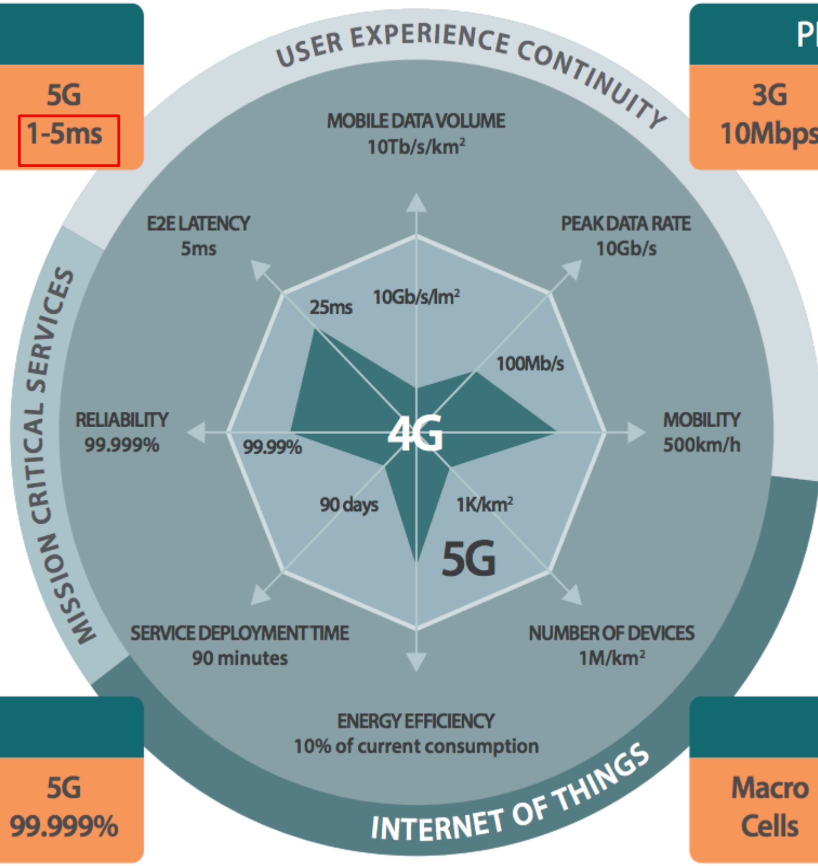


Like LTE, 5G NR will also support operation in unlicensed spectrum (NR-U), for example in localized private networks and carrier aggregation.

5G Network Expectations/Requirements/Research

E2E LATENCY		
3G	4G	5G
100ms	25ms	1-5ms

PEAK BANDWIDTH		
3G	4G	5G
10Mbps	100Mbps	1000Mbps



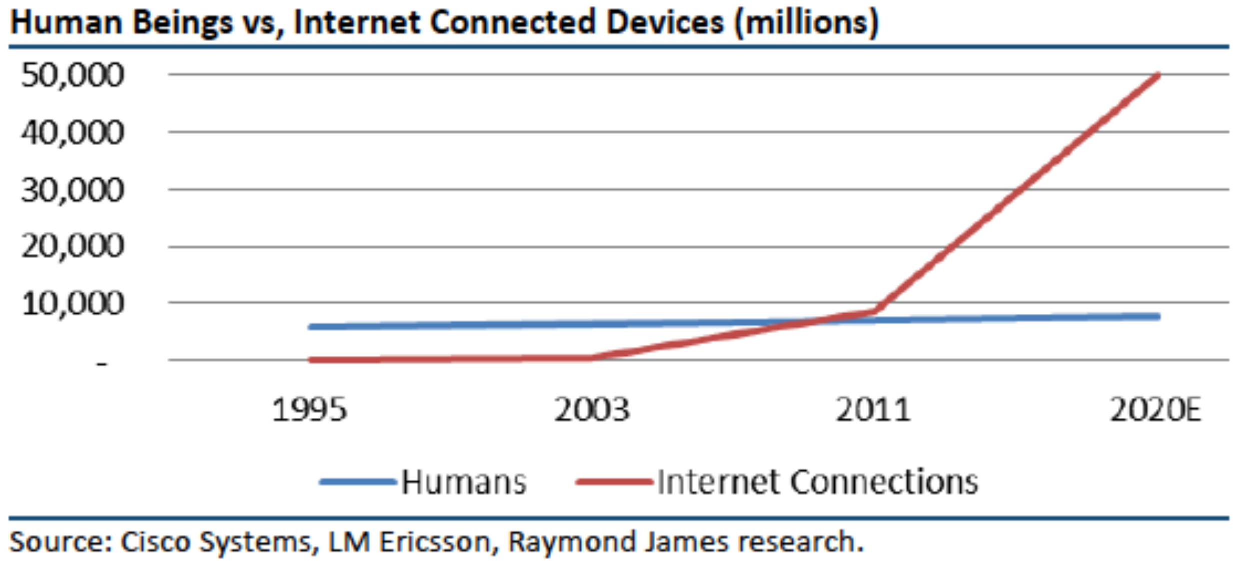
RELIABILITY		
3G	4G	5G
99.9%	99.99%	99.999%

DENSIFICATION		
Macro Cells	Small Cells	Femto WiFi

Research Directions: 5G demands a complete network overhaul to meet the requirements.

- **Architecture:** Multi-tier, dynamic, dense, high capacity and low latency, cooperating/cell-less, and heterogeneous (IoT/M2M).
- **Software-driven networking**: SDN and NFV that enable adaptive and customizable networking and effective network management.
- **Higher capacity/low latency** networks: mmWave systems, Massive MIMO, cell densification, cognitive and non-orthogonal multiple access (NOMA), FDX systems.
- **Security and Authentication** for Device-to-Device, IoT, and networked systems with new models of trust and service delivery in an evolved threat landscape.

Wireless Internet of Things (IoT)



- The number of Internet-connected devices surpassed the number of human beings on the planet in 2011, and by 2020, Internet-connected devices are expected to approach 50 billion.
- For every Internet-connected PC or handset there will be 5-10 other types of devices sold with native wireless Internet connectivity --- cars, tools, appliances, consumer electronics, medical devices, …

5G Emerging Key Networking Technologies

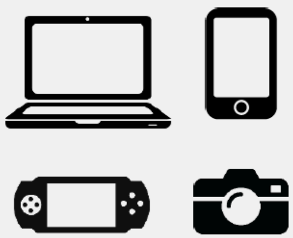
Plus PHY Innovations (mmWave/beamforming, massive MIMO, cell densification, cell-less nets…)

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.

5G Spectrum: Flexible Access Below 6 GHz

- Flexible to support diverging requirements in the same spectrum
- Multiple operating modes (FDD/TDD, indoor/outdoor, star/mesh/D2D)
- Sprint and T-Mobile planning to use “low and mid band” spectrum for Mobile 5G*

Enhanced Mobile Broadband



- Macro and small cells
- 1 ms Latency (air interface)
- Spectrum allocated at WRC-15 may lead up to 8Gbps of additional throughput
- Support for high mobility

Low Power & Complexity

- Low data rate (1~100kbps)
- High density of devices (up to 200,000/km^2)
- Latency: seconds to hours
- Low power: up to 15 years battery autonomy
- Asynchronous access

Ultra-High Reliability & Ultra-Low Latency

- Low to medium data rates (50kbps~10Mbps)
- <1 ms air interface latency
- 99.999% reliability and availability
- Low connection establishment latency
- 0-500 km/h mobility

*Sprint holds 2.5 GHz spectrum licenses and is currently testing mobile 5G in downtown Chicago using Massive MIMO.
T-Mobile plans to use its newly purchased 600 MHz spectrum to develop and build a coast-to-coast 5G network by 2020.
AT&T and Verizon have also set goals for early 5G rollouts, in higher-frequency bands, such as the 28 GHz range, but AT&T likely to start re-farming low-band spectrum for 5G in 2019-2020.

5G Ultra Broadband above 6 GHz (Indoors and Hotspots)

- Frequencies above 6 GHz suffer from much higher path loss
- Massive antenna arrays feasible due to shorter wavelength
  - Leads to compact antenna array structures
  - Beamforming gains overcome high path loss

Free-Space Path Loss

Distance	2.4GHz	28GHz	60GHz
d = 1m	-40 dB	-62 dB	-68 dB
d = 100m	-80 dB	-102 dB	-108 dB

28 dB

- **NO new spectrum allocated to date for 5G**. The next meeting to talk about spectrum allocation will take place at the World Radio Communication Conference (WRC-2019)
- Early results on Verizon's 5G network suggest connections in the 600-800 Mbps download and 250 Mbps upload ranges, albeit on an unloaded network, using aggregation of six 100-megahertz-wide channels of **28 GHz** millimeter wave spectrum. Verizon "Home" targeted at 5G-powered fixed wireless broadband.
- On March 19, 2019 the FCC created a new category of experimental licenses for use of frequencies between 95 GHz and 3 THz.

Key Requirements

- 20 Gbps (peak user throughput)
- 1 ms Latency (air interface)
- Standalone and/or macro-assisted access
- Joint access/backhaul

Key Enablers

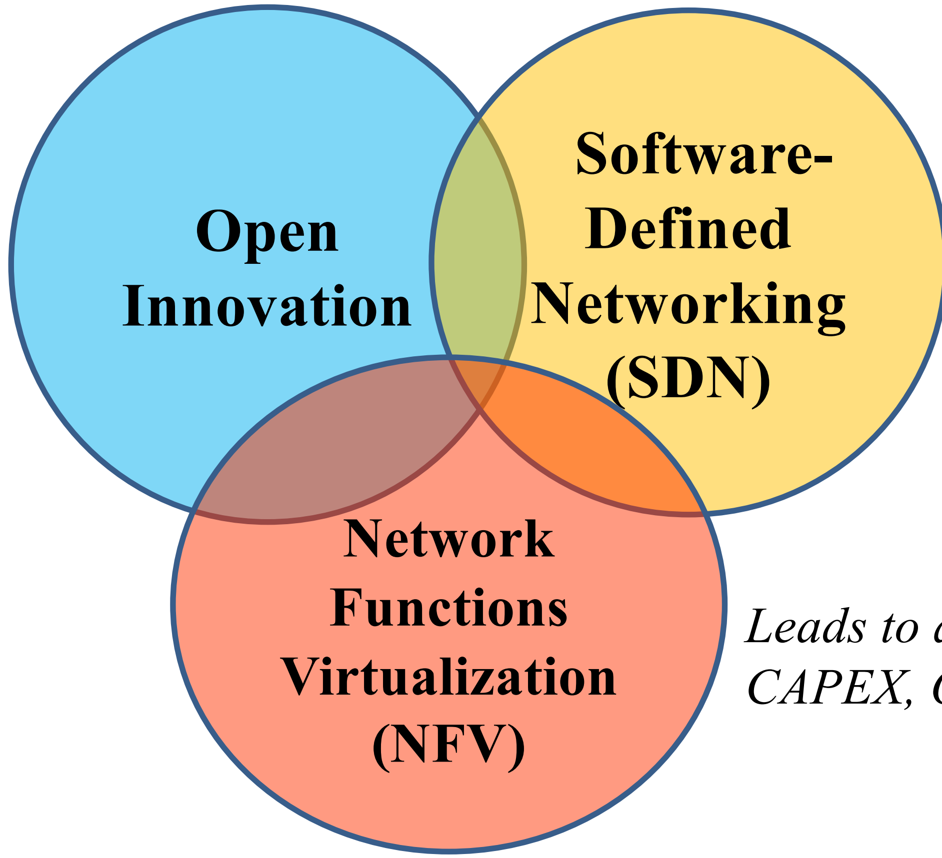
- Large amounts of spectrum
- Massive antenna arrays
- Cell densification

Key Challenges

- Timely availability of globally harmonized spectrum
- Low-cost & low-complexity implementations
- Discovery & initial access
- Frequent & abrupt loss of radio link(s)

5G Strategic Networking Paradigms ---All About Software

Creates competitive supply of innovative applications by third parties



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

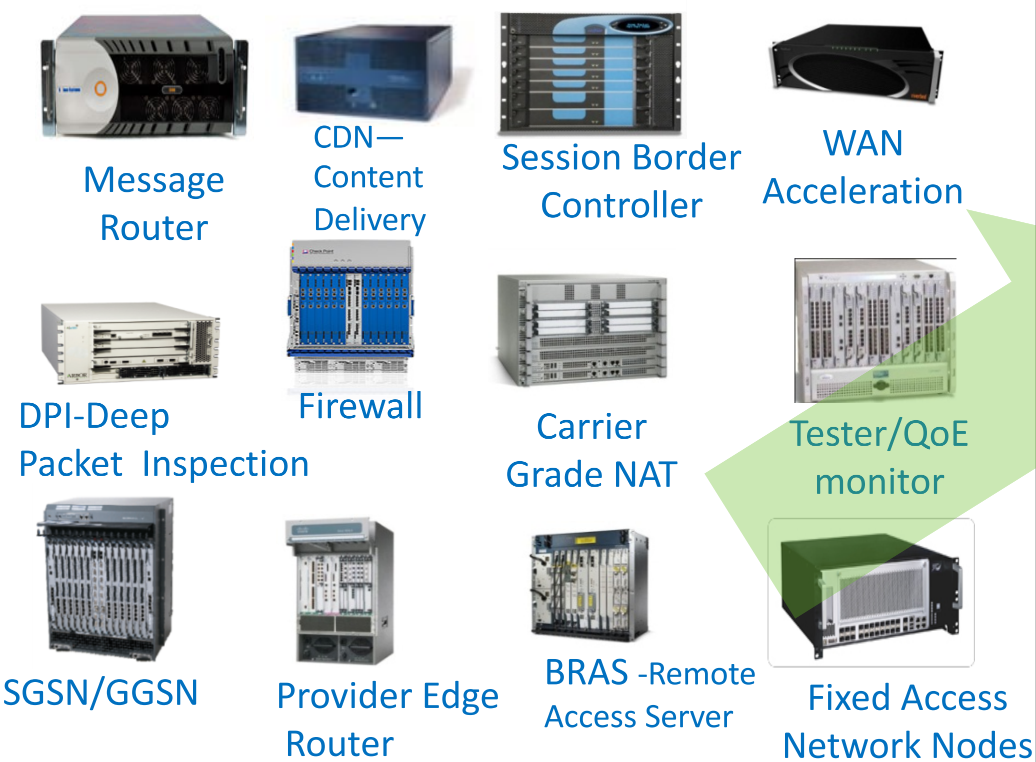
Leads to agility, Reduces CAPEX, OPEX,…

- 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]

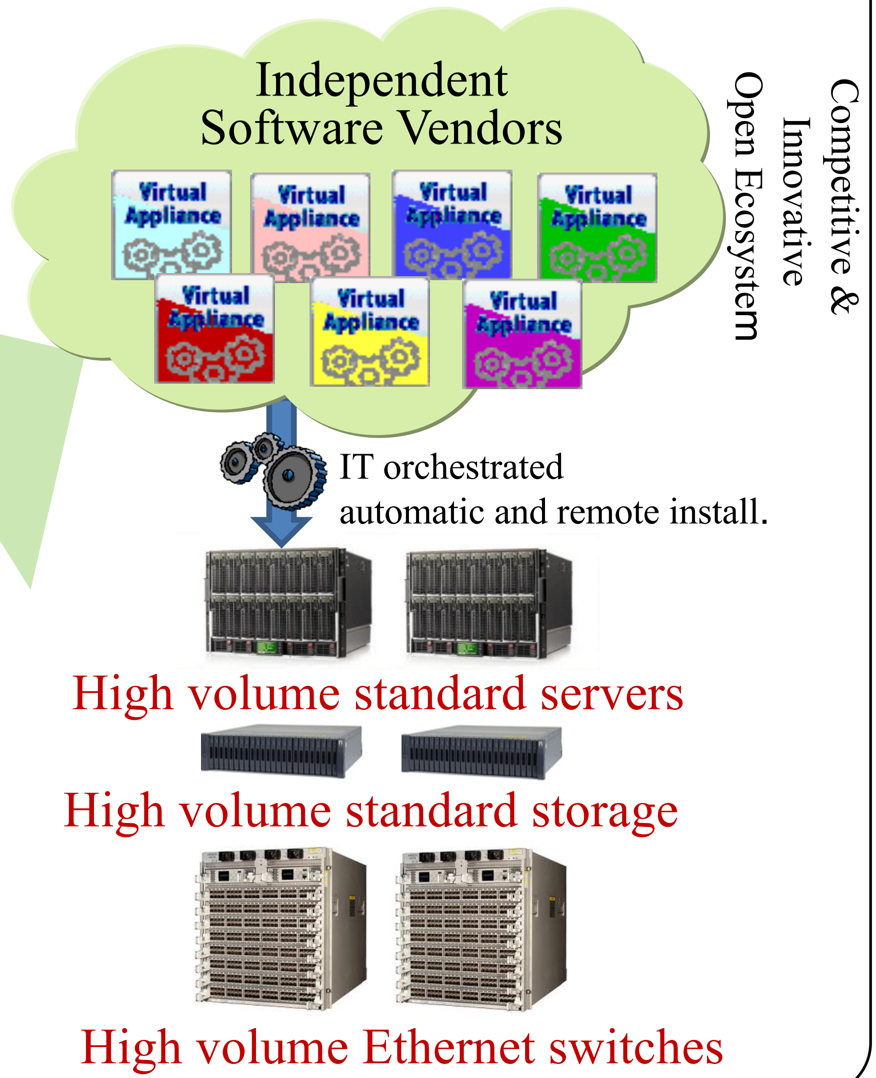
Becoming a Software-Based Network

Classical Network Appliance Approach



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

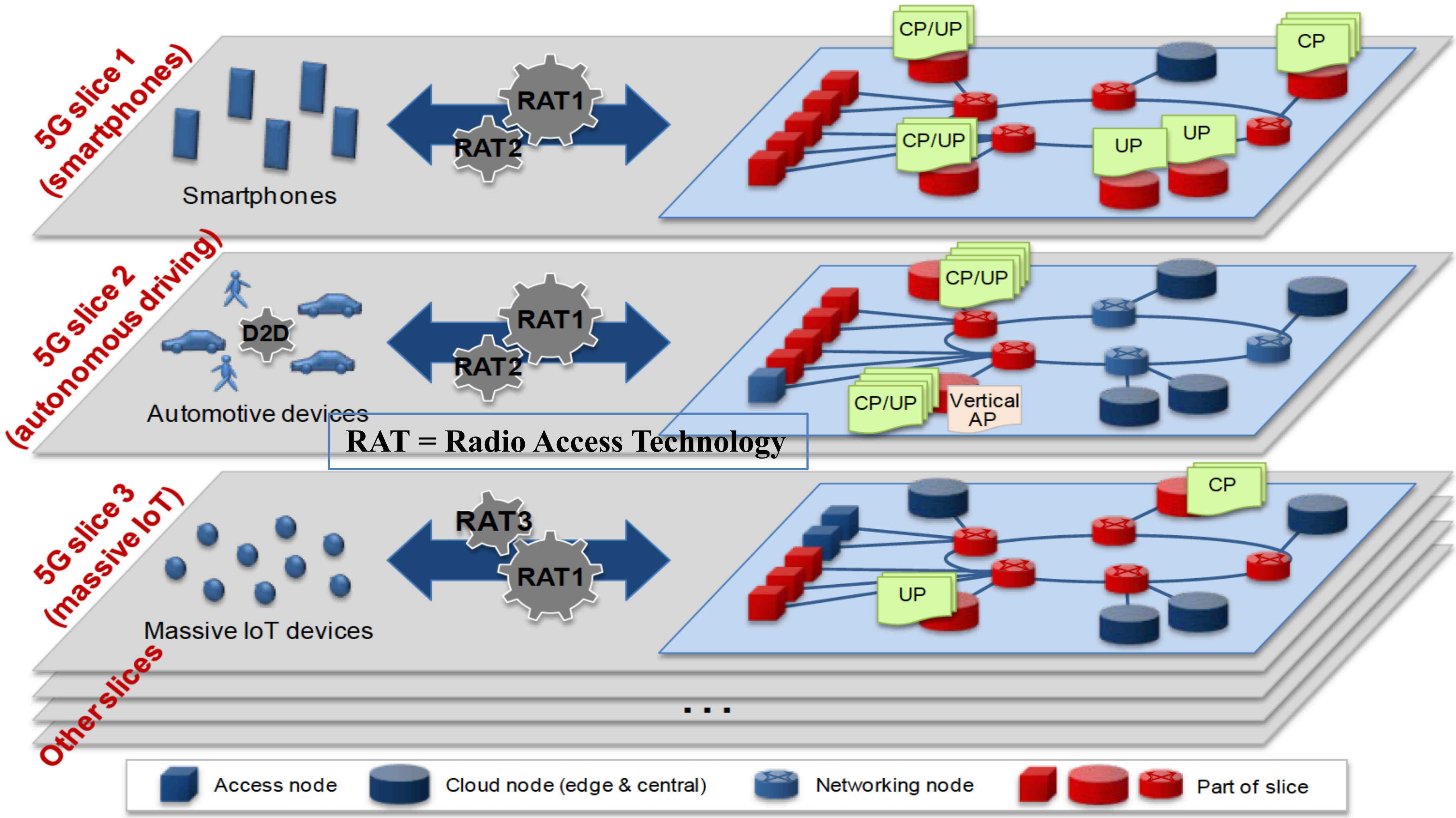
Network Functions Virtualization Approach



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

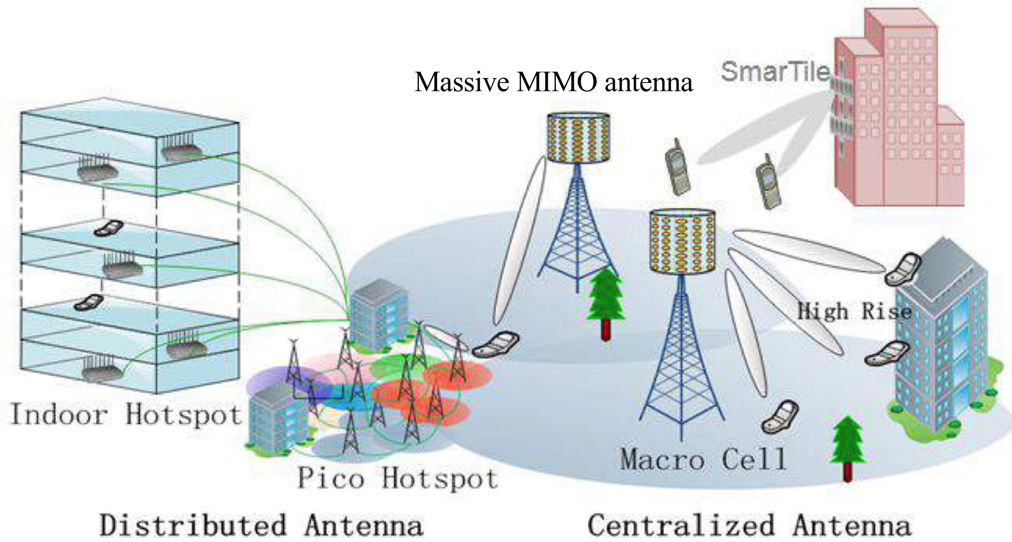
5G NFV: Network Slicing

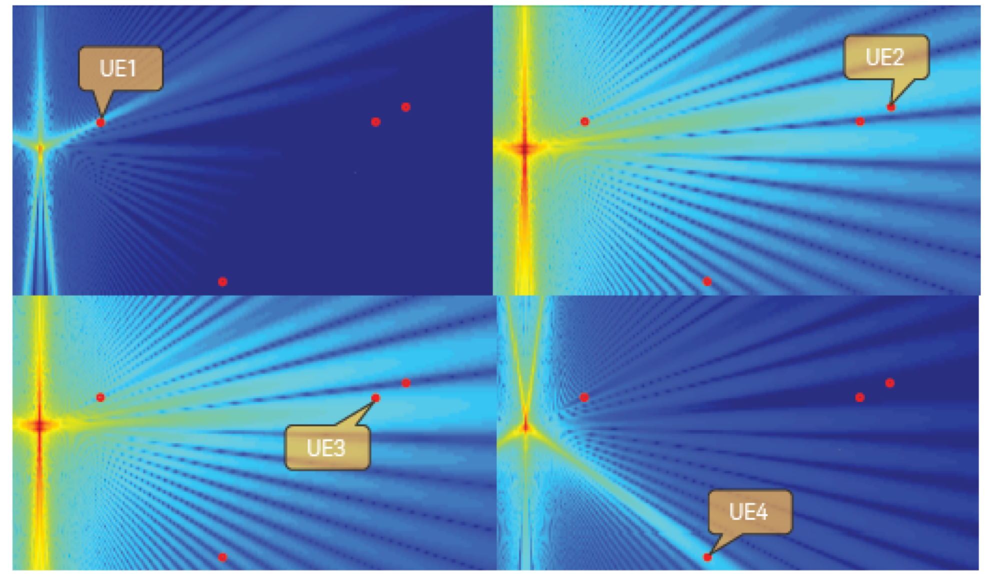
- A network slice is an end-to-end logically isolated network including devices, access, transport and (virtualized) core network functions to support diverse scenarios on a common infrastructure.
- Enables operators to launch a range of highly differentiated network services, each aimed at a distinct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



5G PHY Technology: Massive MIMO [M-MIMO]

Provides Diversity, Directivity, and Spatial Multiplexing





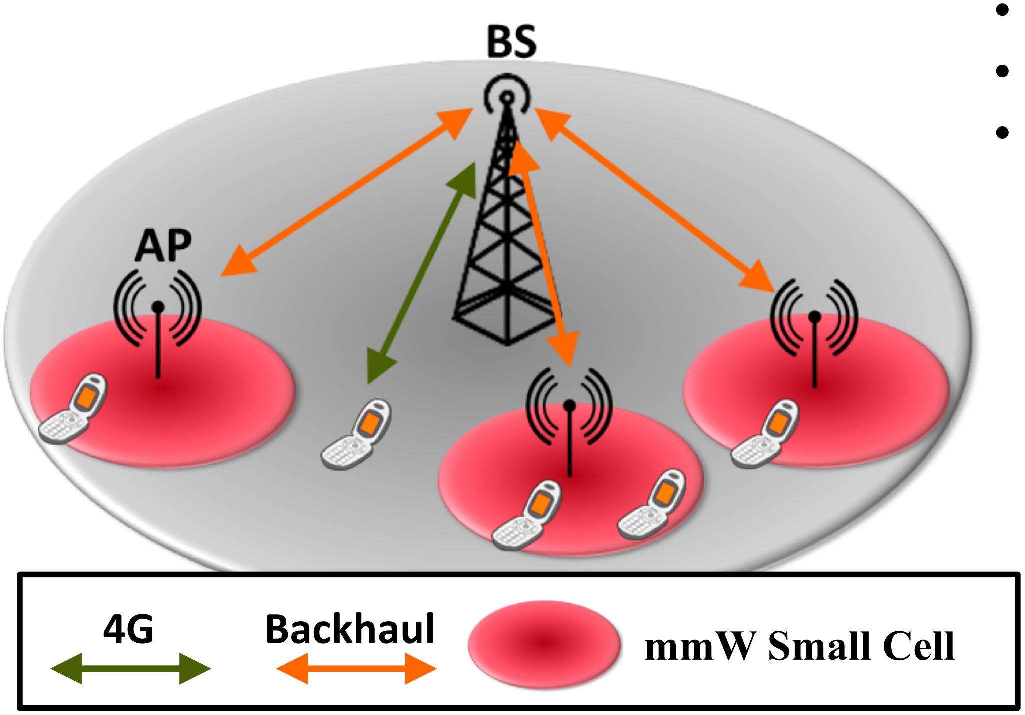
200-antenna massive MIMO provides great precision in the placement of signals and nulls
Courtesy: Keysight.

- 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.

5G PHY Technology: mmWave HetNets

Heterogeneous Networks: small cells within macro cells

- Improve user data rate near the access point
- Offload data from the macro cell to the small cell
- Reduce transmit power (terminal and BS)
- Flexible deployment in dense areas



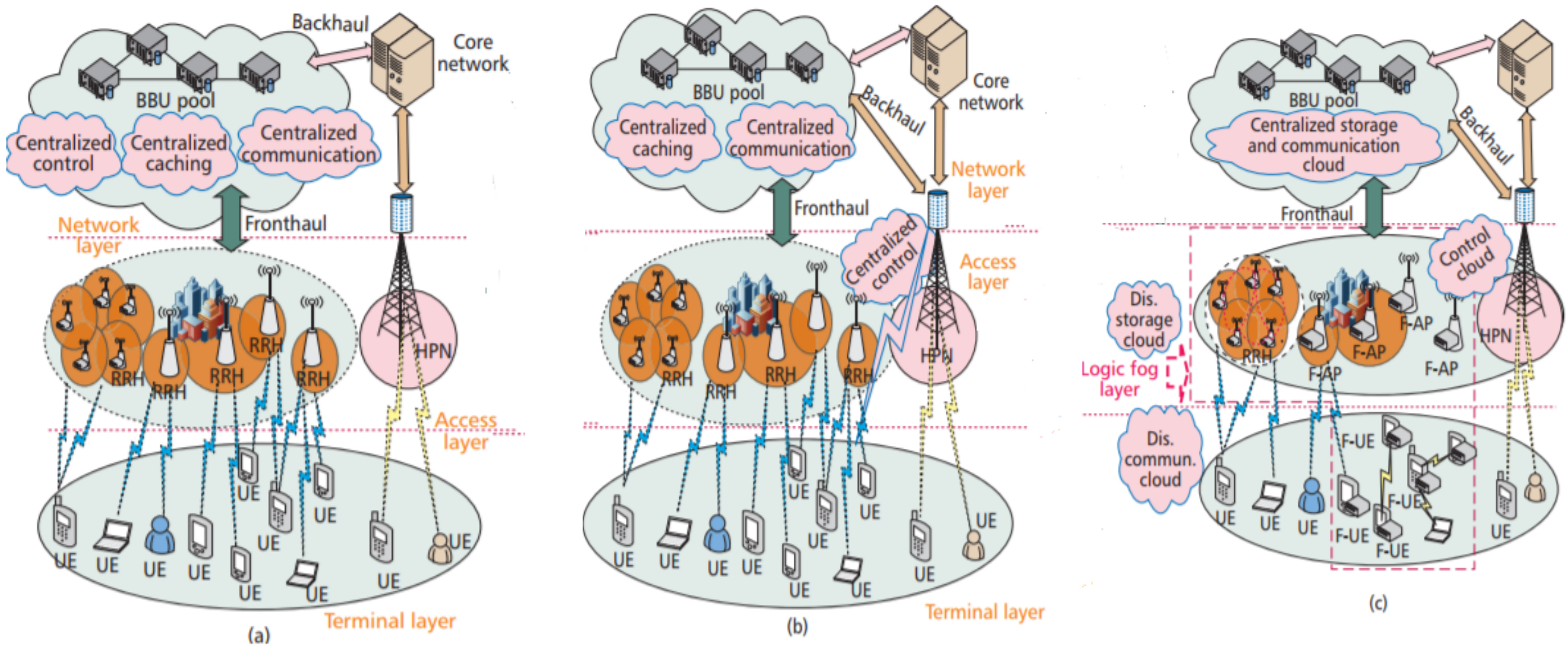
Millimeter-wave small cells

- Supports wireless backhaul and 5G access
- Multi-Gbps data rates
- No interference with macro cell
- Beamforming sends a single focused signal to each and every user in the cell

Challenges for mmWave Access

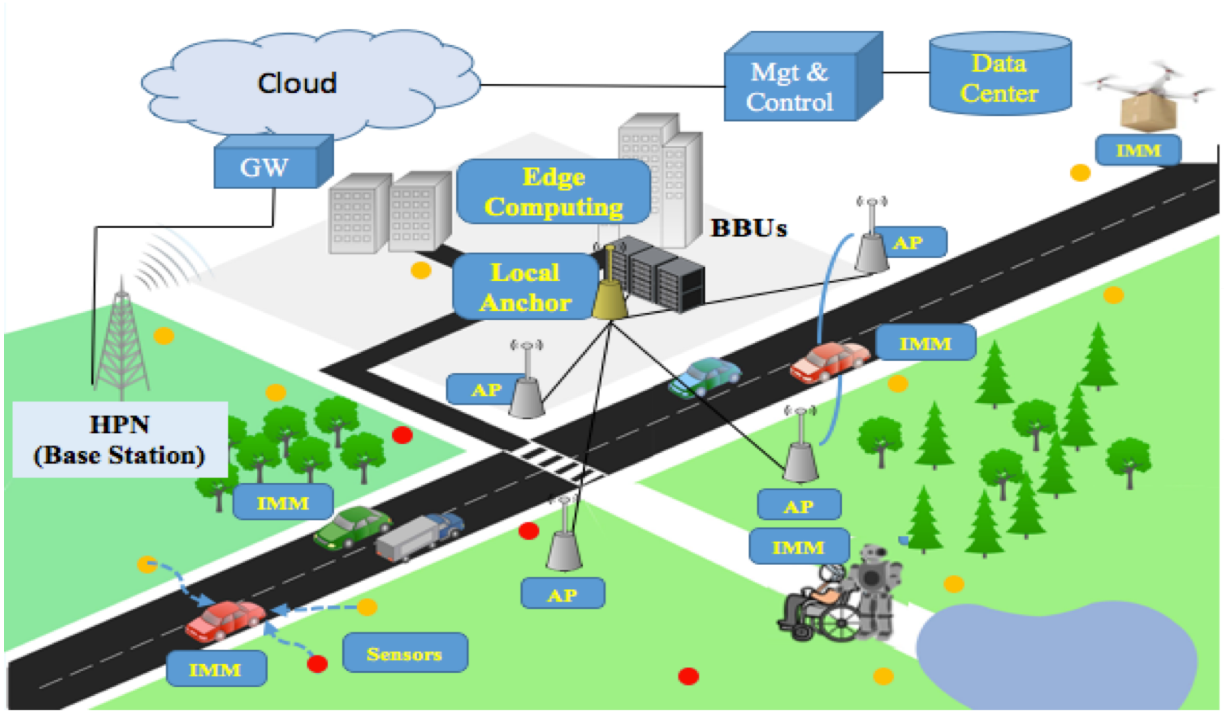
- **Radio**: Lower Tx power and Rx sensitivity
- **Antennas**: Directive antennas with beamforming
- **Propagation**: Building penetration, blockage effects, foliage, precipitation

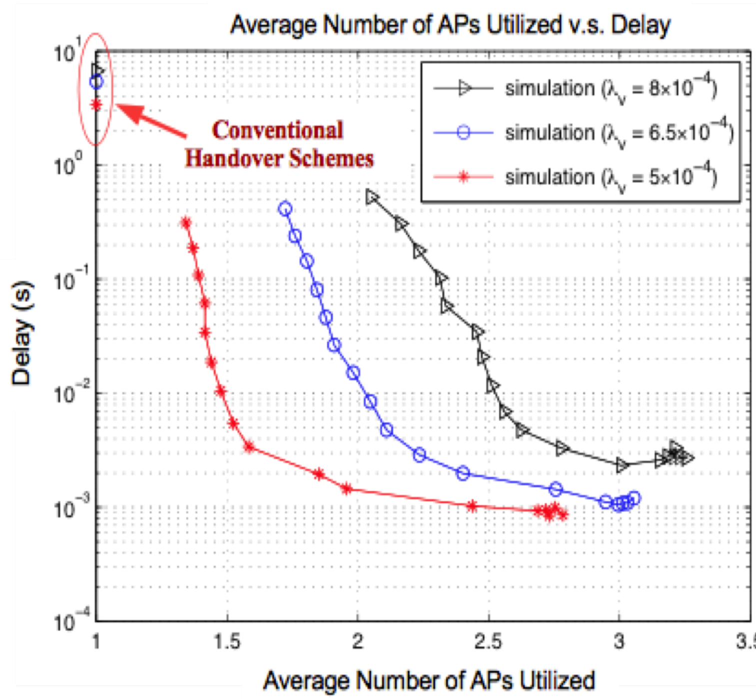
Proposed 5G RAN Architectures Based on Cloud and Fog Networking*



	CRAN	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**
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?

Research: F-RAN Achieving 1ms Latency for Intelligent Mobile Machines*



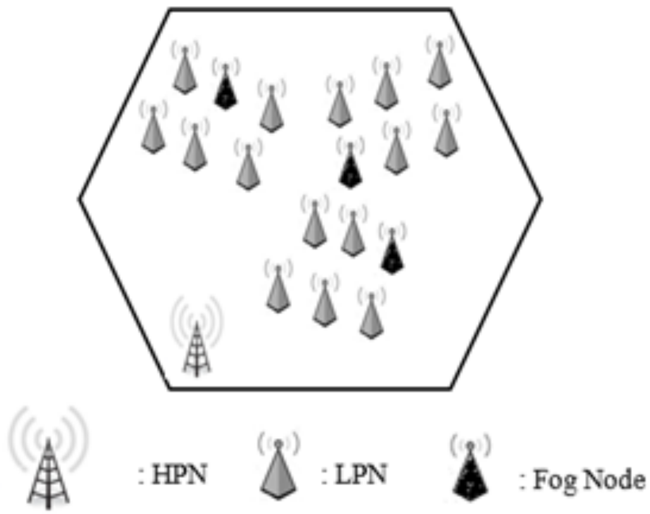


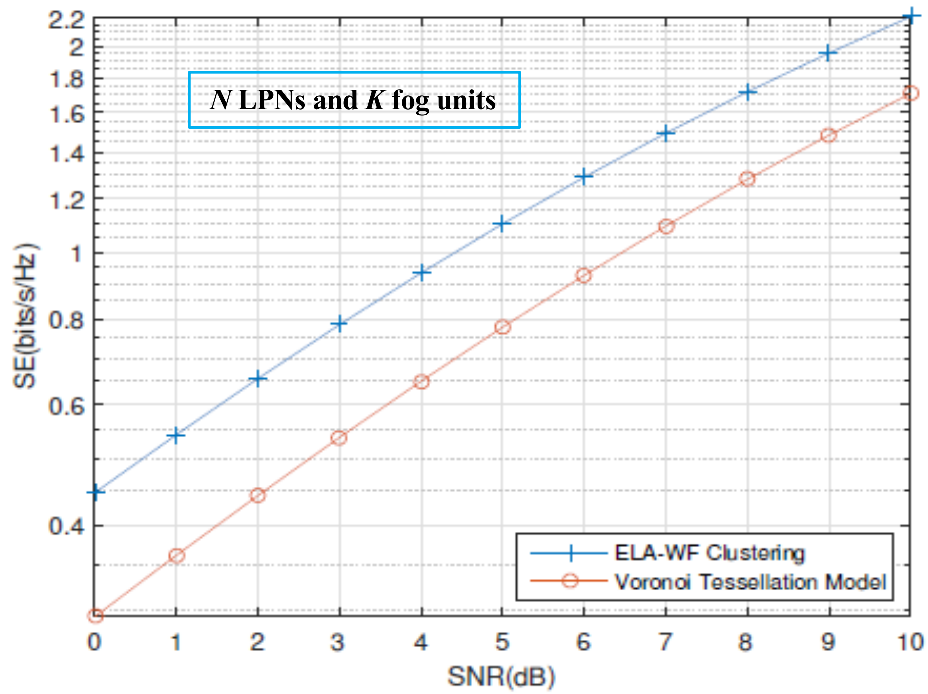
- A two-tier architecture with dense APs (low power) and HPNs (high power) macro-cell nodes is promising for RAN for connectivity to achieve coverage, high-bandwidth and low latency.
- A Fog RAN (F-RAN) with distributed small-cells and edge computing is appropriate for most real-time, low latency applications.
- **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, Richard D. Gitlin, and Gerhard Fettweis "Ultra-Low Latency Mobile Networking," *IEEE Network 2019 (accepted)*
* 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 5G F-RAN HetNets*

- 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.





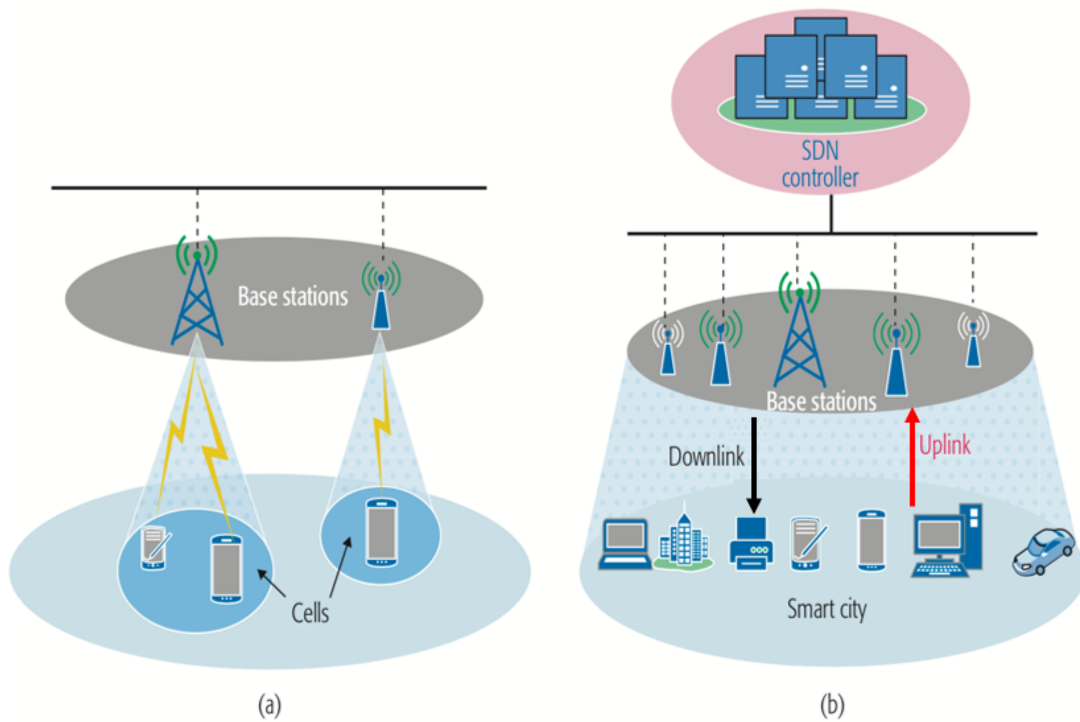
- Two types of clustering considered:
  - Hard clustering *K*-means clustering algorithm based on Voronoi Tessellation mode, where each small cell is connected to **one** fog node at the closest Euclidean distance
  - Soft clustering, edge location assisted soft clustering, water-filling algorithm (ELA-WF) 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

Cell-Less Network: A New 5G Network Paradigm

- Compared to the conventional cell networks, cell-less communication networks have many advantages:
  - **Avoiding Frequent handovers**
    When the cell size is reduced in 5G cellular networks (e.g. mm-wave), fast moving terminals lead to frequent handovers in 5G cellular networks. In cell-less communication network, a mobile terminal need not associate with any fixed BS. Hence, frequent handovers between cells are reduced.
  - **Improved coverage**
    Considering small BSs in 5G mobile communication system. As the size of cell is reduced the coverage becomes smaller. In cell-less networks, the coverage is increased by grouping the cooperative BS.
  - **Improved energy efficiency**
    Cell-less communication networks save energy not only at BSs but also at the mobile terminals.

When there are data to be sent to a specified mobile terminal, the SDN controller in the cloud decides which one or more of the BSs are chosen to form a cooperative group (CoMP) to perform downlink joint transmission.

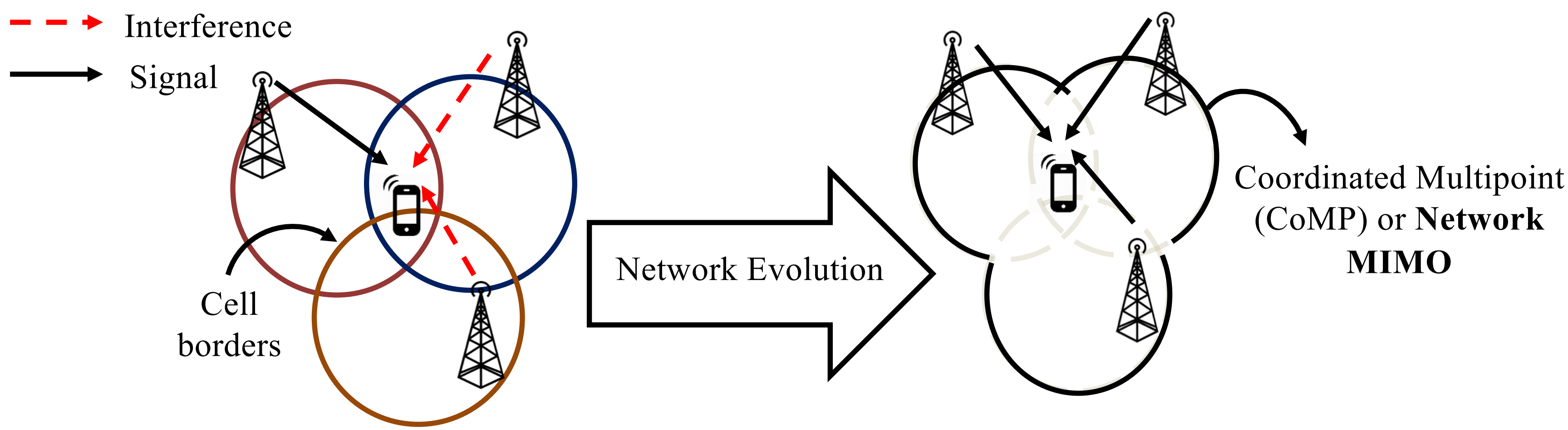


(a) conventional cellular network, (b) cell-less network using CoMP [1].

[1] T. Han, X. Ge, L. Wang, K. S. Kwak, Y. Han and X. Liu, "5G Converged Cell-Less Communications in Smart Cities," in IEEE Communications Magazine,, March 2017.

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.

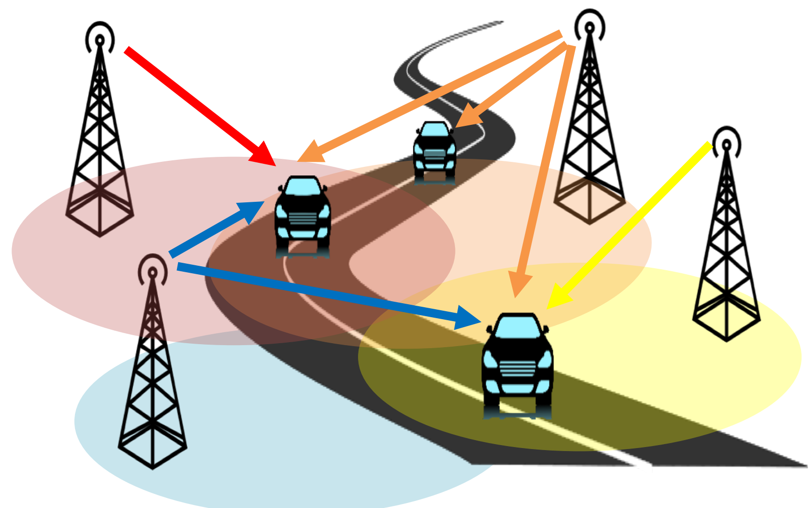


Research: Dynamic CoMP*

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: Proactive Mobility Management

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

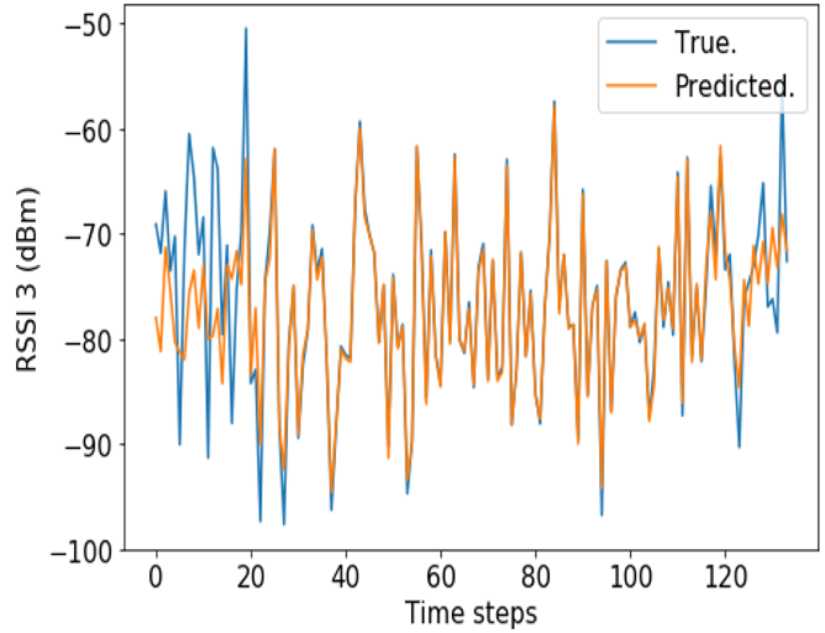
Impact/Benefits

- 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).

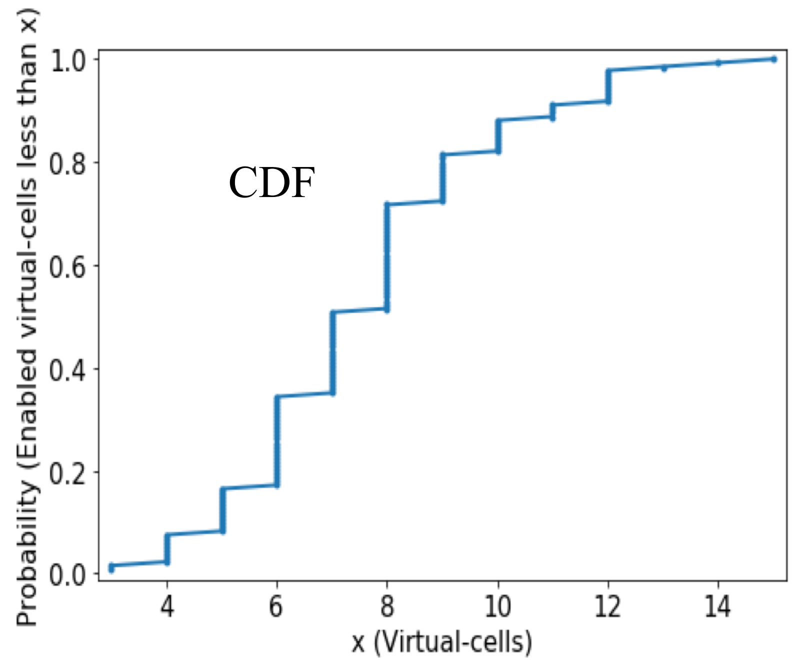
* M. Elkourdi, A. Mazin and R. D. Gitlin, "Optimization of 5G Virtual Cell Based Coordinated Multipoint Networks Using Deep Machine Learning," International Journal of Wireless & Mobile Networks (IJWMN) Vol. 10, No. 4, August 2018

Research: Dynamic CoMP Results

- The figure shows the **True** and **predicted Received Signal Strength** (RSS) BS values.
- The GRU-RNN model achieves an **accuracy of > 92%** in predicting the triggering conditions for **enabling and disabling virtual cell mode** as required based on the mobility of users.

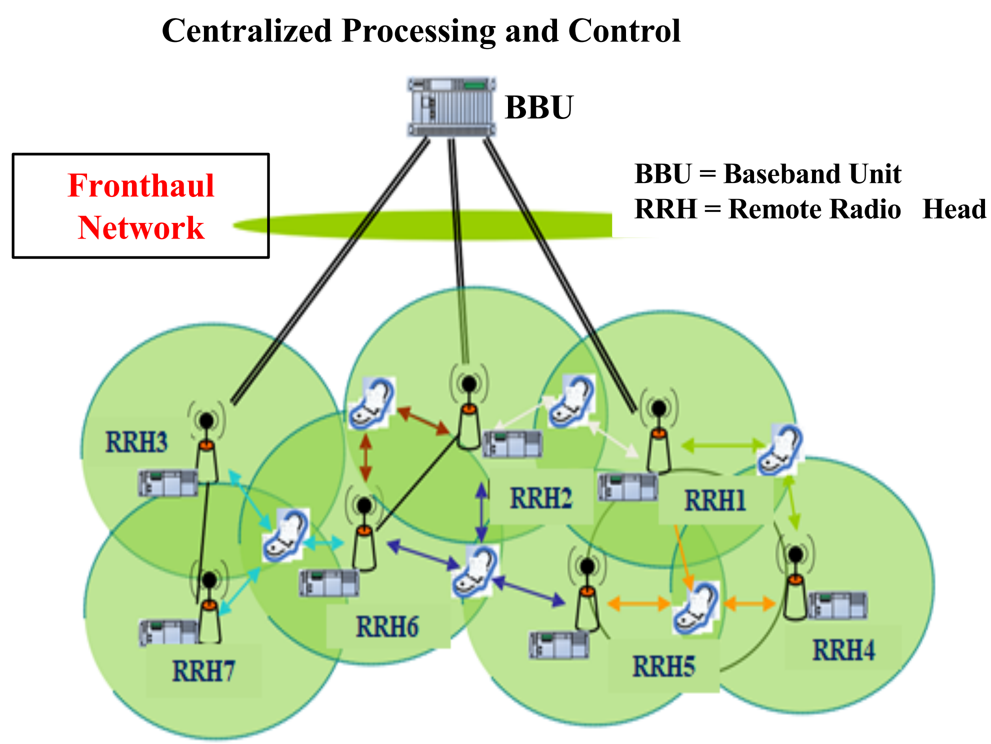


- The cumulative distribution function (**CDF**) of the **number of enabled virtual cells** when the GRU-RNN predictive model is applied.
- Note that the virtual-cell mode is enabled as much as **14 times** during the whole duration of time that nodes spend within the network with a probability approximately of **0.95**, **instead of relying on a static virtual cell**.
- The results of this research are significant for 5G networks since the use of ML-driven Dynamic CoMP can:
  - Minimize battery power consumption
  - Optimize cell-edge performance
  - Enable "cell less" 5G networks.



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.

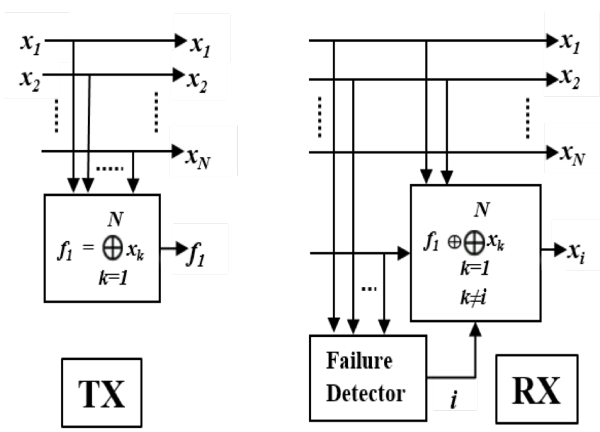


5G Cloud Radio Access Network C-RAN

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

Diversity Coding (DC)

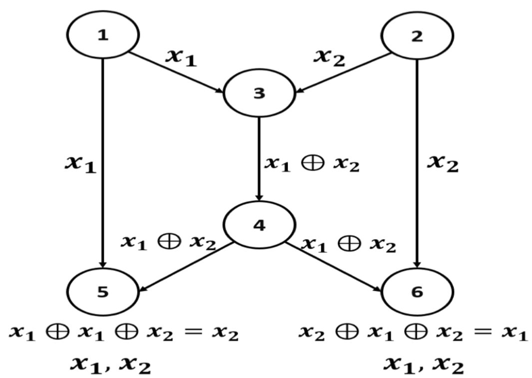
- Diversity Coding enables reliable networking with near-instant recovery from a link failure where a feedforward network design uses forward error control across spatially diverse paths at the expense of redundant transmission facilities.



Diversity Coding

Network Coding (NC)

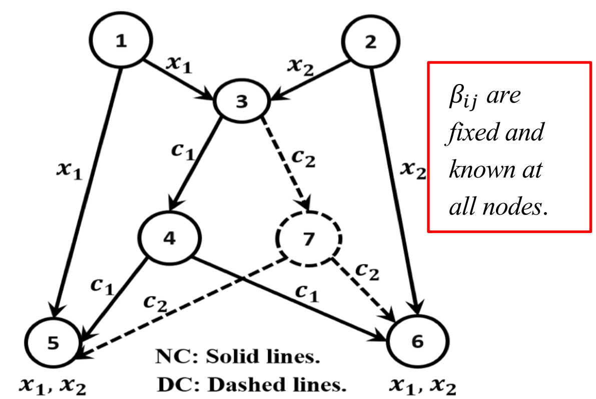
- Network Coding uses coding at a network node to increase network throughput and provide bandwidth for data broadcasting/multicasting applications.
- **In this example network, the throughput is increased by one-third.**
- However, any link failure can strongly impact reliability, and nodes 5 and 6 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.

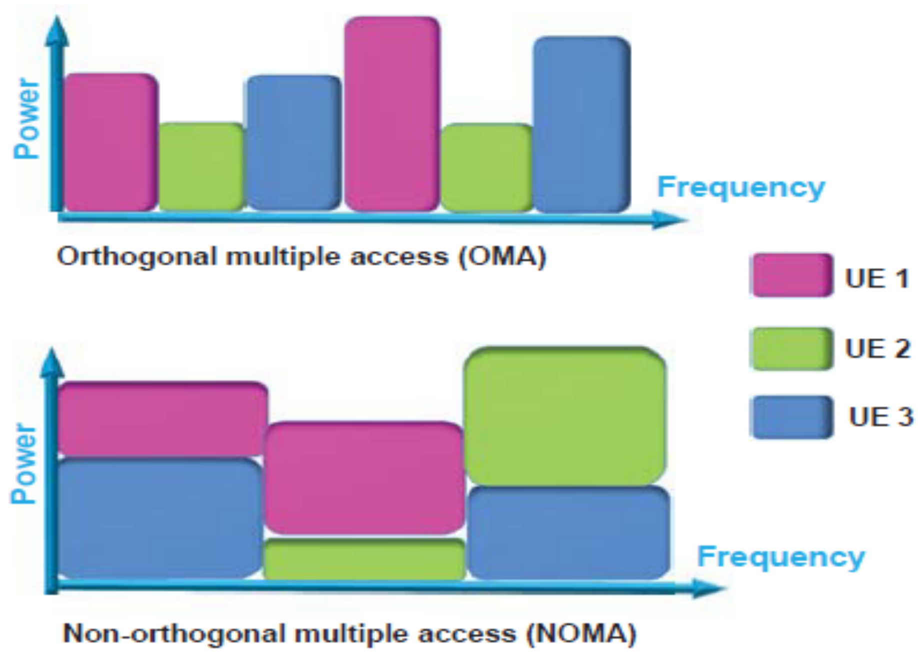


DC-NC network

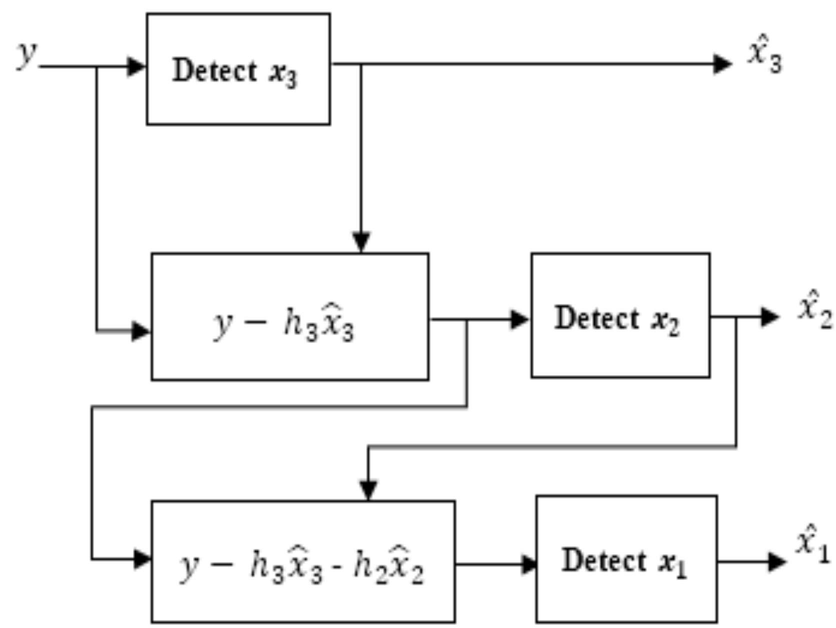
*N. I. Sulieman, E. Balevi, K. Davaslioglu, and R. D. Gitlin, "Diversity and Network Coded 5G Fronthaul Wireless Networks for Ultra Reliable and Low Latency Communications," IEEE International Symposium on Personal, Indoor and Mobile Radio Communications 2017.

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.

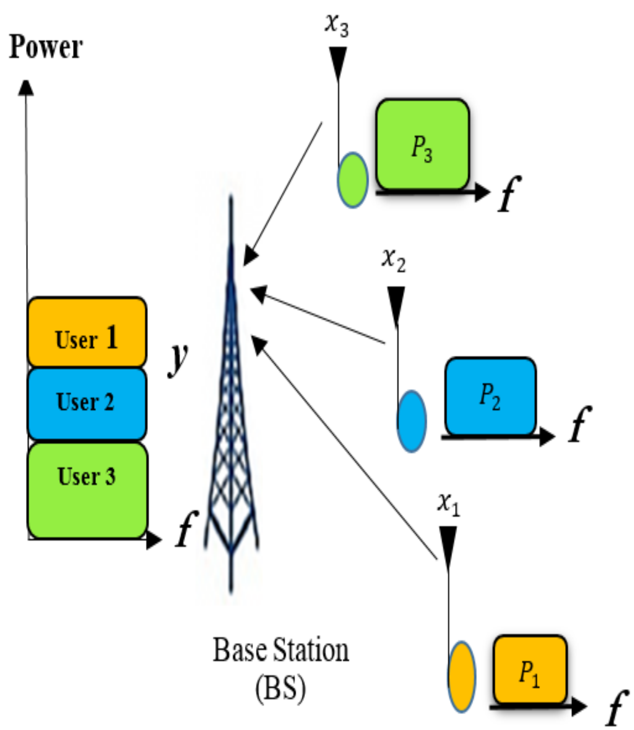


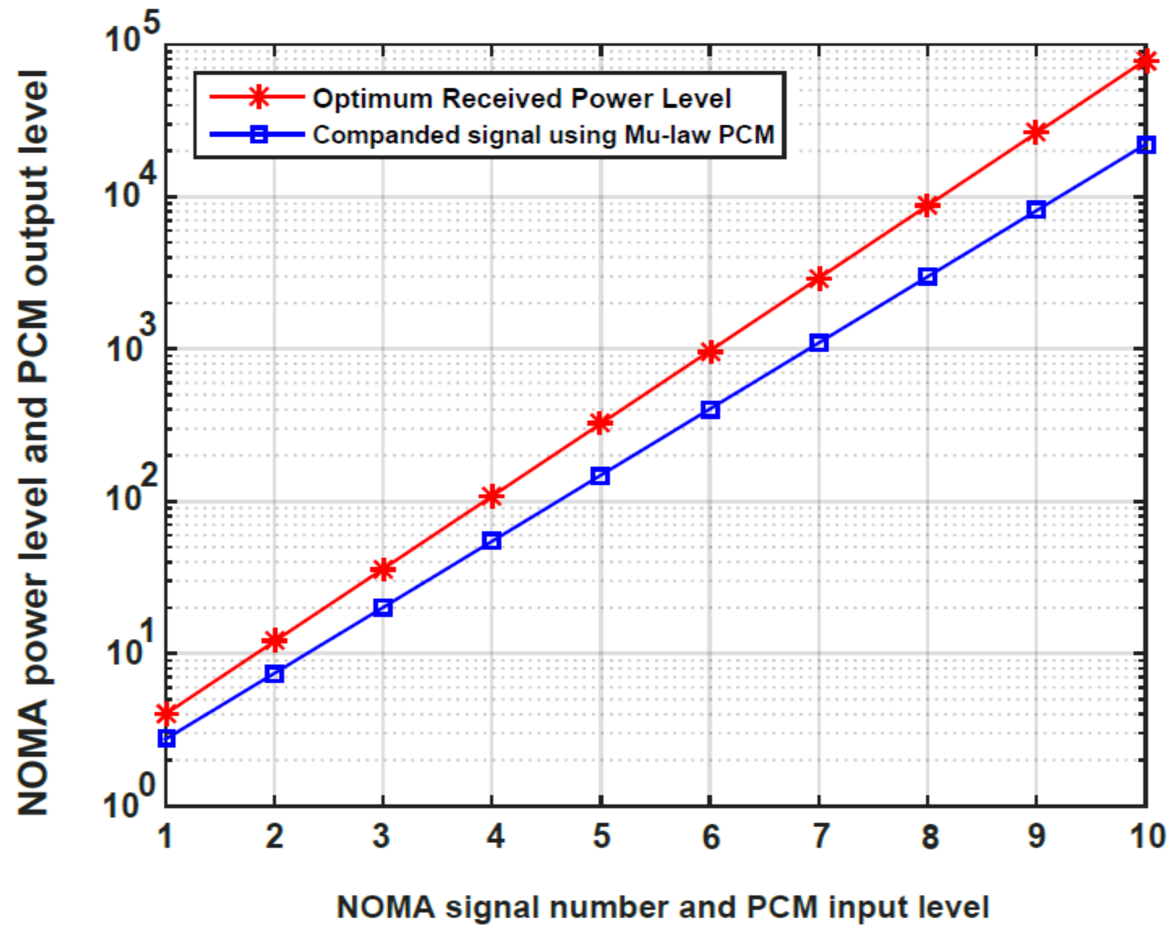
Power-Domain NOMA vs. OMA



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

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



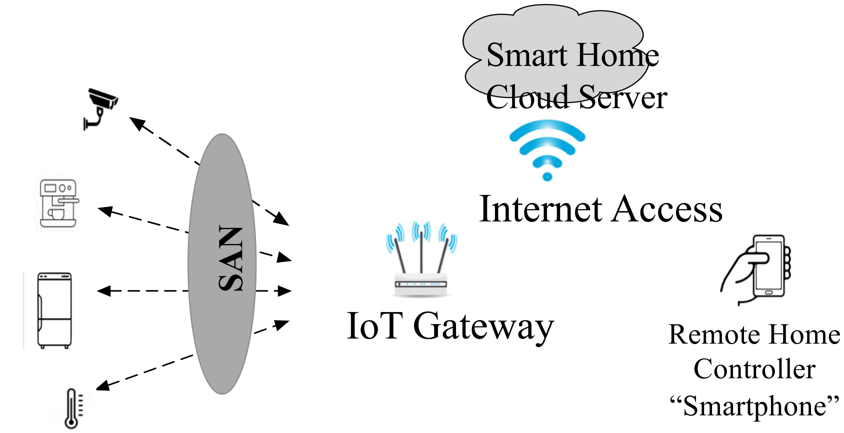


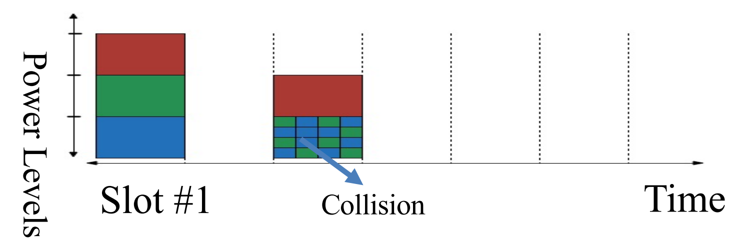
- The optimum received power level is determined for each signal so as to achieve the same bit error rate (BER) for each received signal assuming ideal SIC performance.
- With this criteria of constant SINR per signal, the optimum power levels are very similar to those of μ-law encoders used in pulse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

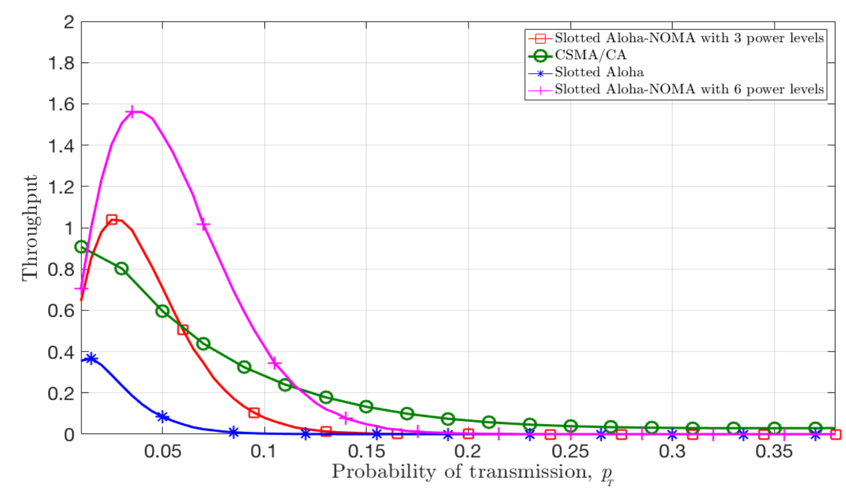
*F. Al Rabee, K. Davaslioglu and R. Gitlin, "The optimum received power levels of uplink non-orthogonal multiple access (NOMA) signals," IEEE WAMICON 2017.

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.







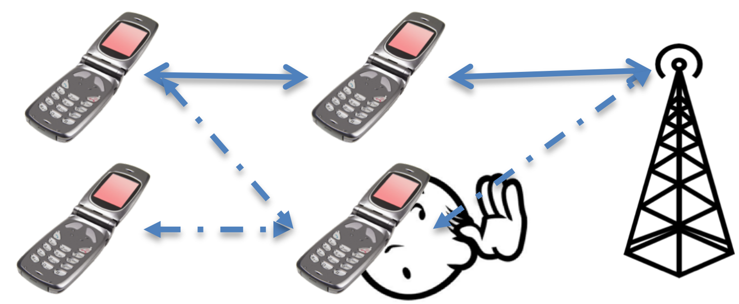
*Asim Mazin, Mohamed Elkourdi and R. D. Gitlin, "SAN- Slotted Aloha-NOMA a MAC Protocol for M2M Communications," Information Theory and Applications (ITA 2019): San Diego, February 11-15, 2019

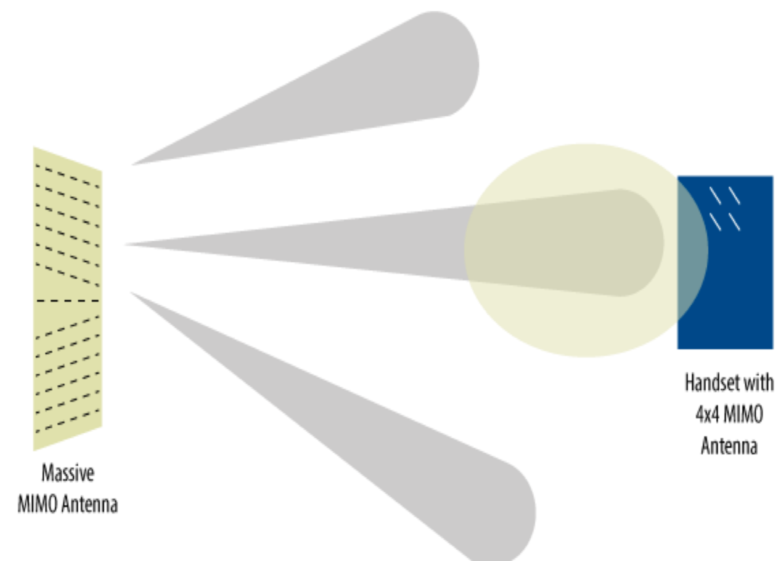
Physical Layer Security and Key Management

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

Advantages of PHY layer security

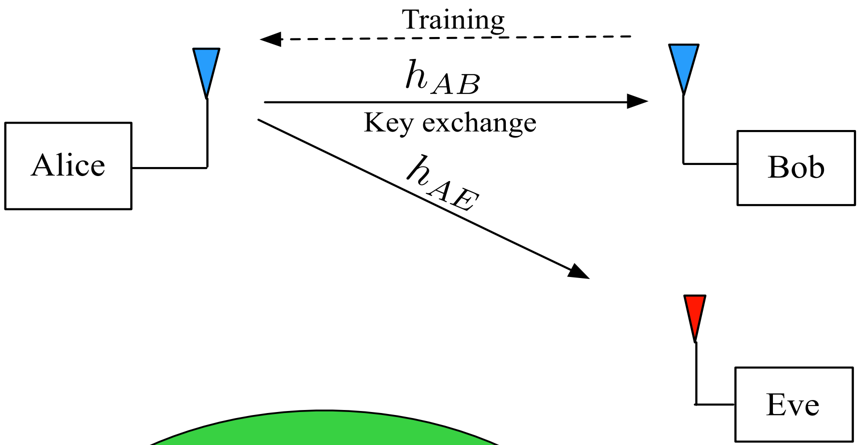
- PHY layer security does not depend on adversary's computational complexity
- PHY-layer security can enable direct secure data communication and/or can facilitate the distribution of cryptographic keys in 5G network.
- **5G Massive MIMO/Beamforming advantages**
  - **More directivity at mmWave frequencies**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

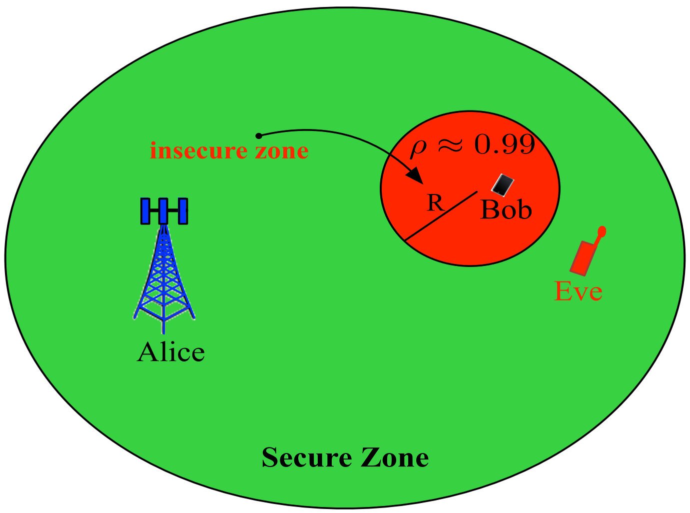


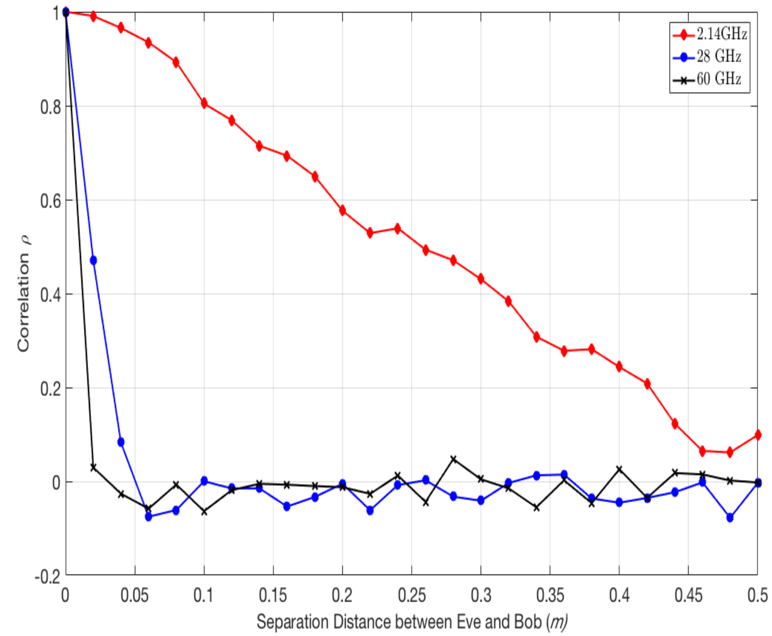


Prior art: Keys derived from Channel CSI or RSS values----limited size keys and consistency of key info at BS and UE.

Research: PHY Key Management Scheme







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.

Data Driven Beam Sweeping for 5G mmWave Cellular Systems

Problem

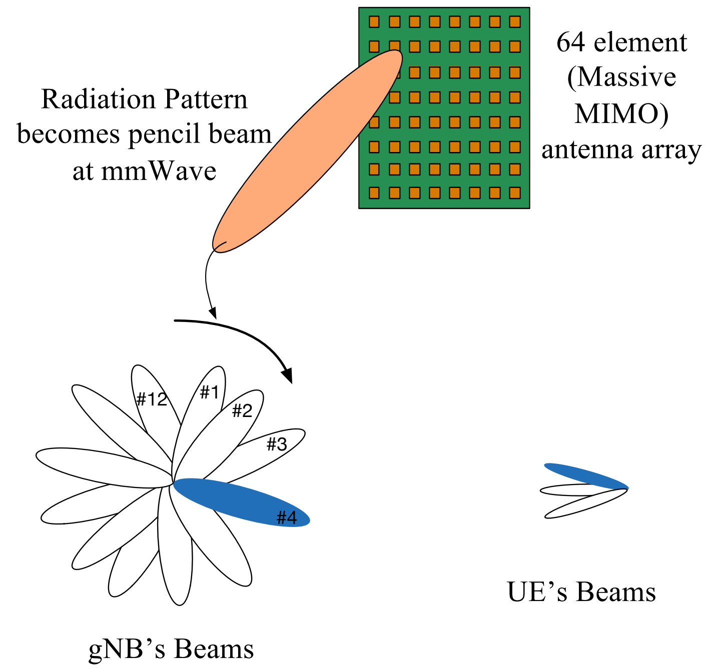
- The reliance on directional beamforming makes cell discovery by a UE challenging since the best aligned beam pair is not known.

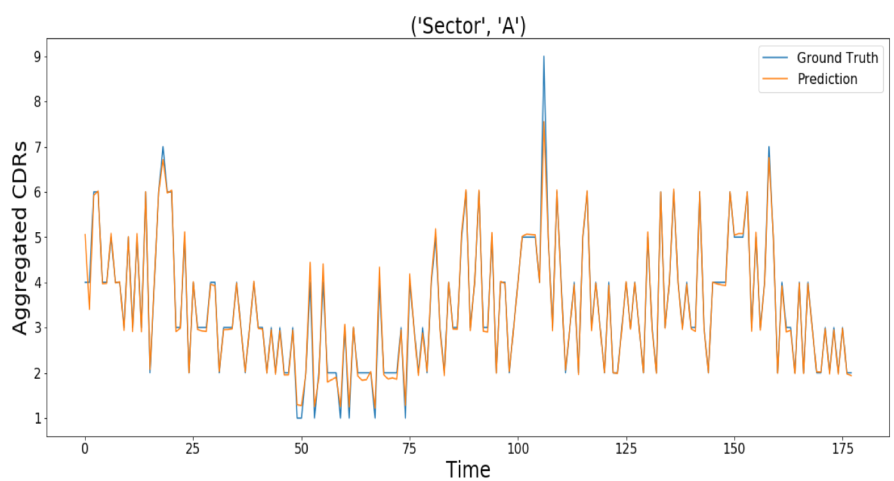
Standard Approach

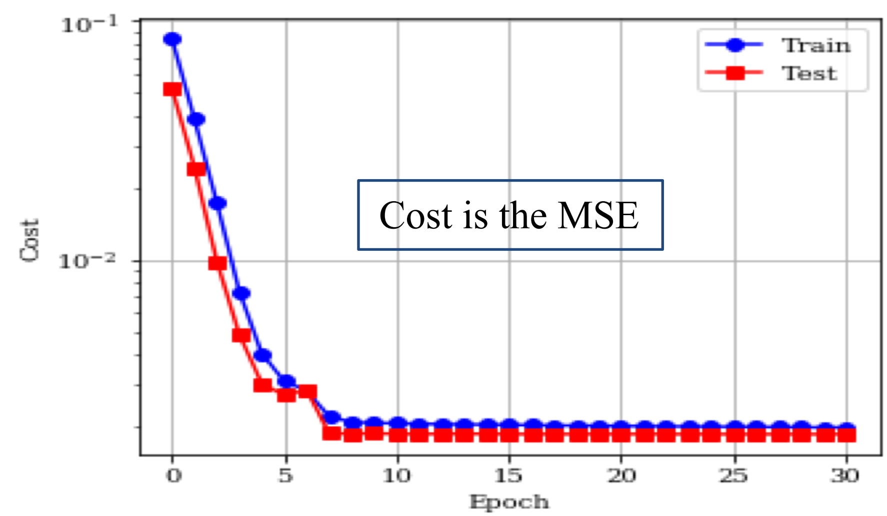
- Sequential beam sweeping is performed to transmit synchronization signals using a Random Starting Point (RSP)

Approach

- **Machine learning,** using 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.





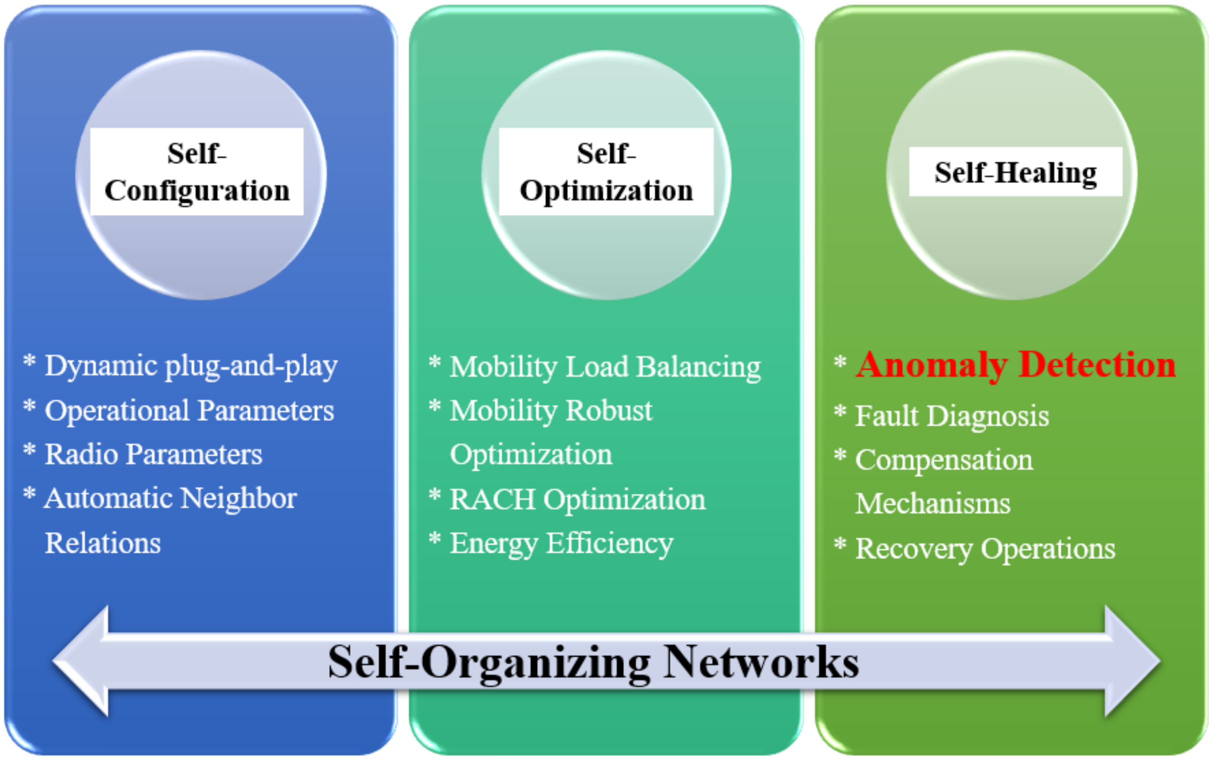


A. Mazin, M. Elkourdi and R.D. Gitlin, "Comparative Performance Analysis of Beam Sweeping Using a Deep Neural Net in mmWave 5G New Radio," UEMCON2018

Self-Organizing Networks (SON) for 5G

- **SON domains** – self-configuration, self-optimization, and self-healing
- **Current standardization** – 3GPP Release 16 study items include studying and upgrading SON functions to meet the complexities of 5G networks.
- The need for automation is higher for 5G than the previous generations of mobile networks, since the ultra-dense deployment of network nodes will need an intelligent SON solution to enable a stable and efficient network management system.

Machine learning (ML) can help achieve the above goal.



- **Anomaly detection →** Automatic detection of network node failures and outages is crucial to ensure fast and seamless recovery.
- The state-of-the-art approaches for anomaly detection lack the knowledge of **Quality of Experience (QoE)** observed by end-users.

Research: QoE-driven Anomaly Detection*

- **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 overengineering.
- **Steps:**
  - Train a machine learning model to learn and predict QoE scores of all users in a network.
  - Use the QoE scores to detect dysfunctional network nodes for anomaly detection.
- For the dataset used in this work, accuracy of:
  - **99.5%** is achieved using ***SVM*** regression
  - **99.4%** is achieved using ***k-NN*** regression
  - **100%** is achieved using ***decision tree*** regression.
- Each ML method has drawbacks and the algorithm choice depends on the nature of the dataset.
  - Complexity of *SVM* is higher.
  - *k-NN* is sensitive to localized data where localized anomalies can affect outcomes significantly.
  - *Decision tree* has a high probability of overfitting and needs pruning for larger datasets.

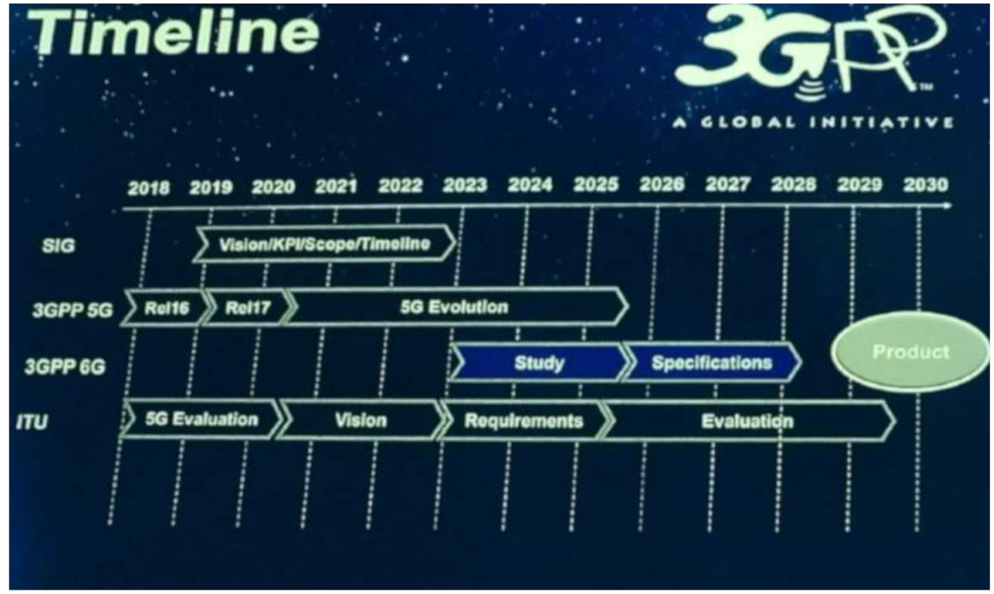
* Chetana V. Murudkar and Richard D. Gitlin, "QoE-driven Anomaly Detection in Self-Organizing Mobile Networks using Machine Learning"- Accepted for *IEEE Wireless Telecommunications Symposium (WTS)*, April 2019.

* Chetana V. Murudkar and Richard D. Gitlin, "Machine Learning for QoE Prediction and Anomaly Detection in Self-Organizing Mobile Networking Systems" - Accepted for publication in *International Journal of Wireless & Mobile Networks (IJWMN)*, April 2019.

A Pragmatic View of 5G Deployment

On to 6G!

6G at Mobile World Congress (MWC)-February 2019



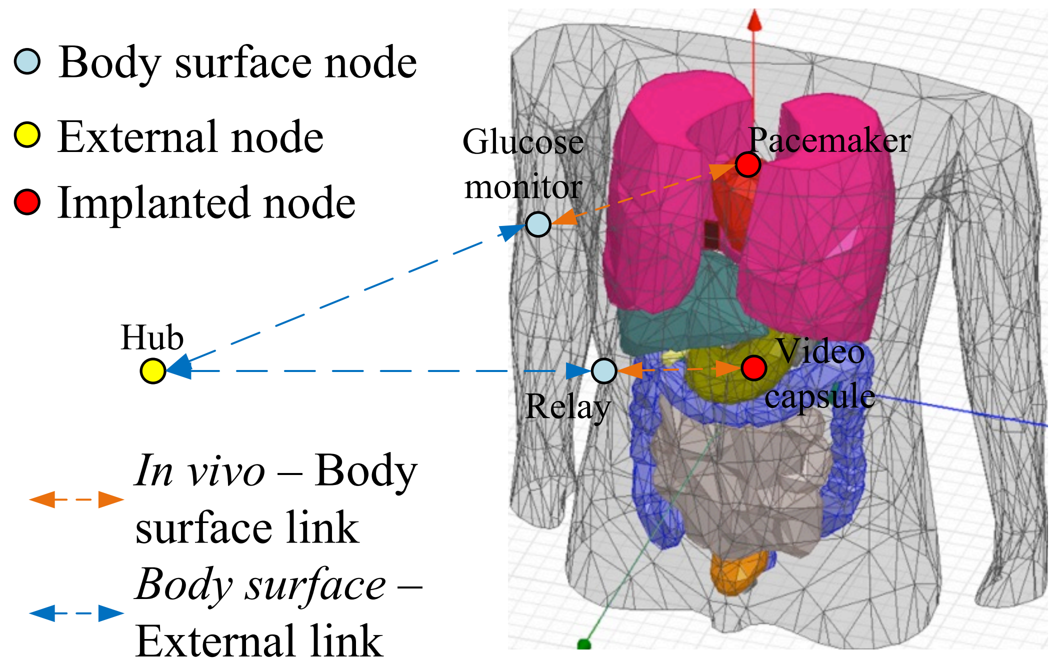
- Finland's scientists announced their plan "6Genesis"at MWC 2019.
- Oulu University's Prof Ari Pouttu said that 6G will satisfy the requirements not yet met by 5G as well as new expectations fusing AI inspired applications with ubiquitous wireless connectivity with **four anticipated technology trends:**
  - Evolution of disruptive 5G: **Densification ("cell-less"), Massive MIMO, mmWave, Tbps.**
  - Edge computing essential to enable time critical and trusted apps. **Low latency.**
  - Disruptive value networks enabled by multidisciplinary research across industry verticals, in contrast to the current siloed approach to R&D. **Evolved Network Slicing [NFV/SDN].**
  - Current semiconductors will not be able to operate on super high-frequencies above 500 GHz or even at terahertz level. **New materials will be needed to replace silicon**.

Next: A complementary 6G trend—Internet of *In Vivo* Things (IoIT)

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

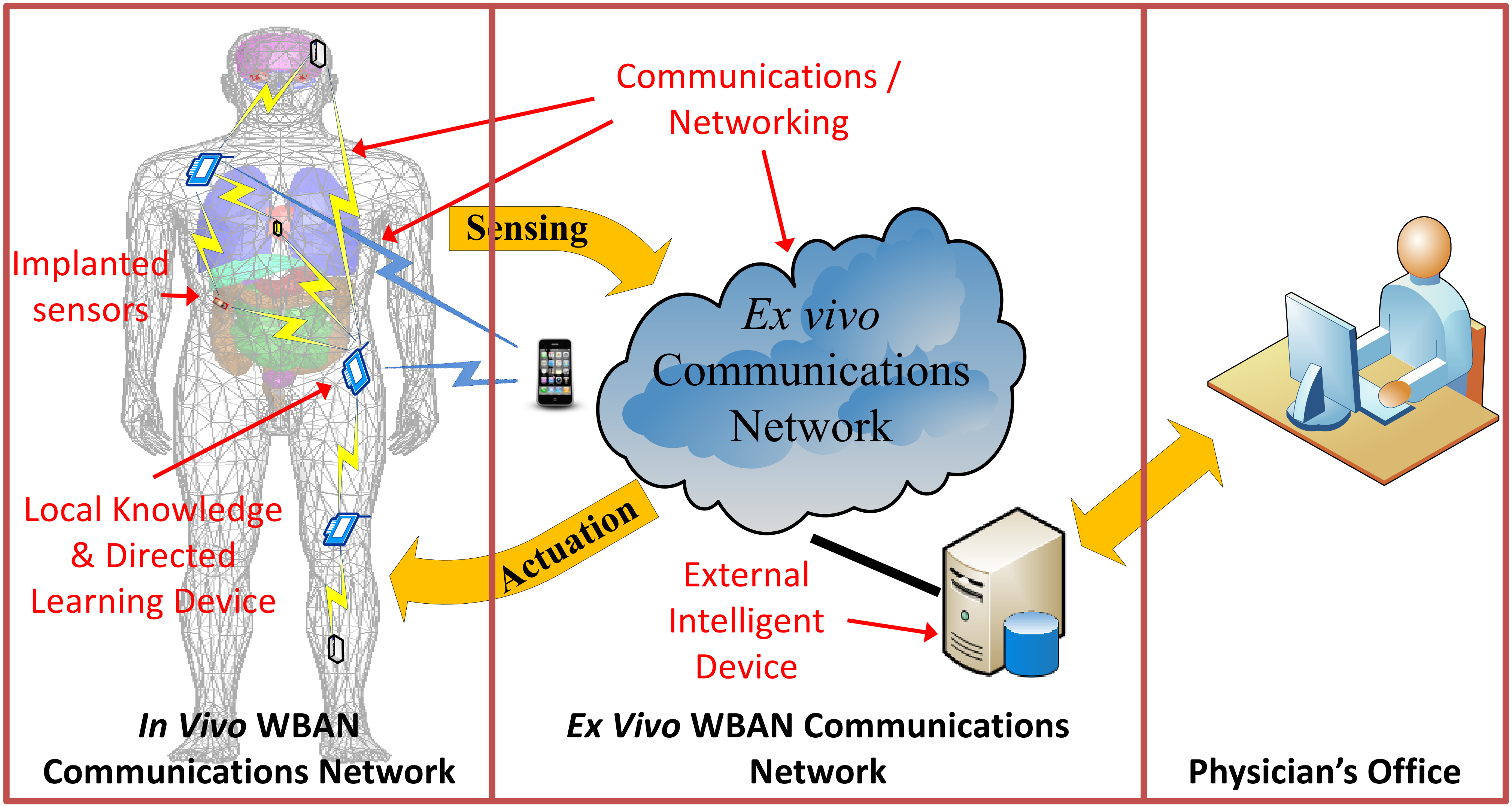
- Vision: Wirelessly enabled cyber-physical healthcare
- *In vivo* communications a necessary component of the vision
- *In vivo* communications and networking
  - Characterization of the wireless *in vivo* channel
  - MIMO *In Vivo*

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



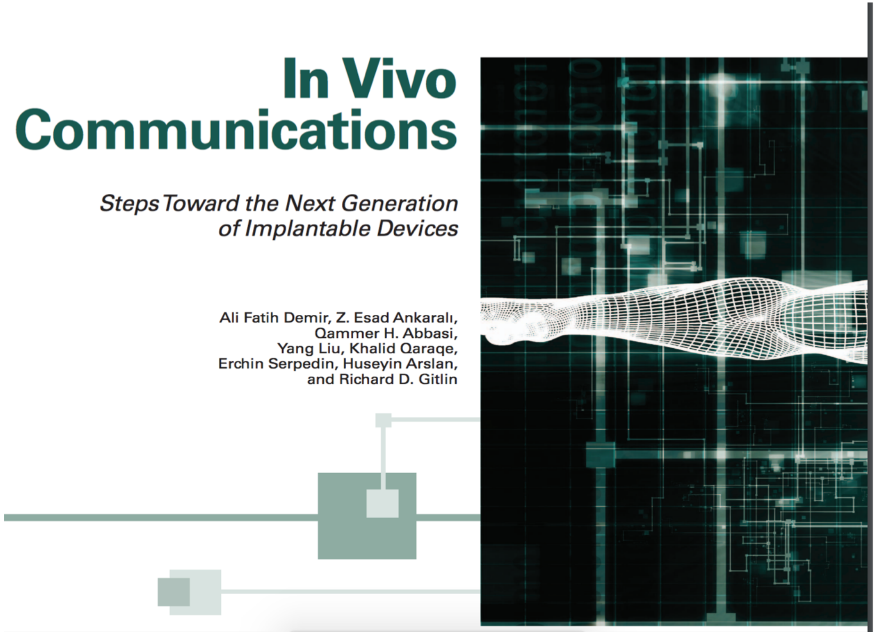
Research Vision: Wirelessly Enabled Healthcare System

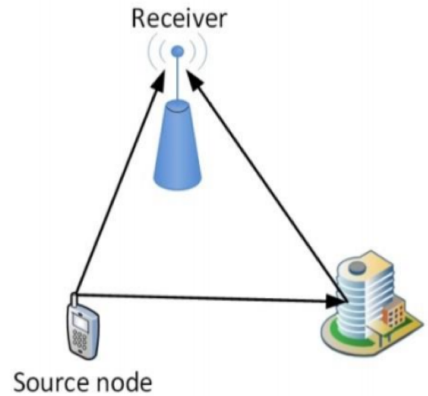
Wireless technology has the potential to advance and transform healthcare delivery by creating new technology for *in vivo* wirelessly networked cyber-physical systems of embedded devices that use real-time data and machine learning to enable rapid, correct, and cost-conscious responses in chronic and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

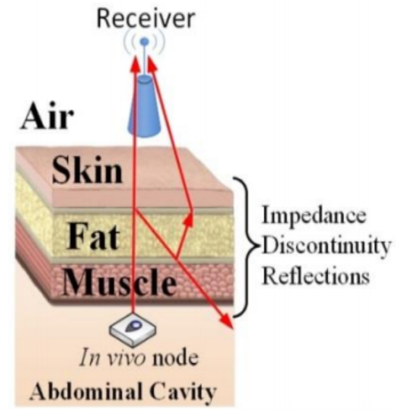


Research opportunities and challenges are abundant

In Vivo Channel Modeling







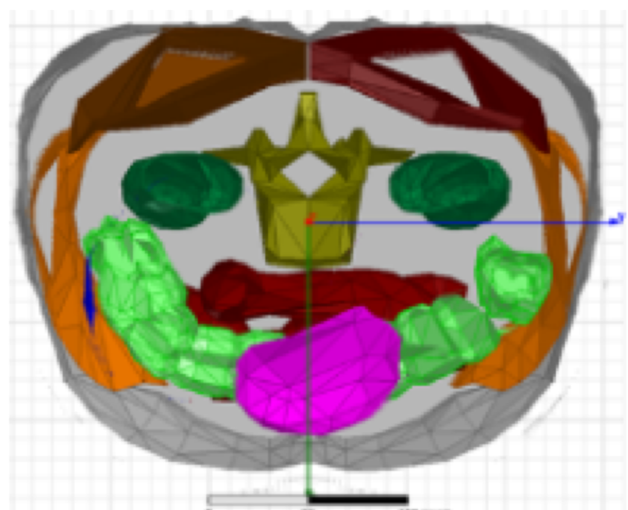
- *IEEE Vehicular Technology*, June 2016
- *Advances in Body-Centric Wireless Communication: Applications and State-of-the-art*, IET, 2016, ISBN: 978-1-84919-989-6

- 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.

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.**

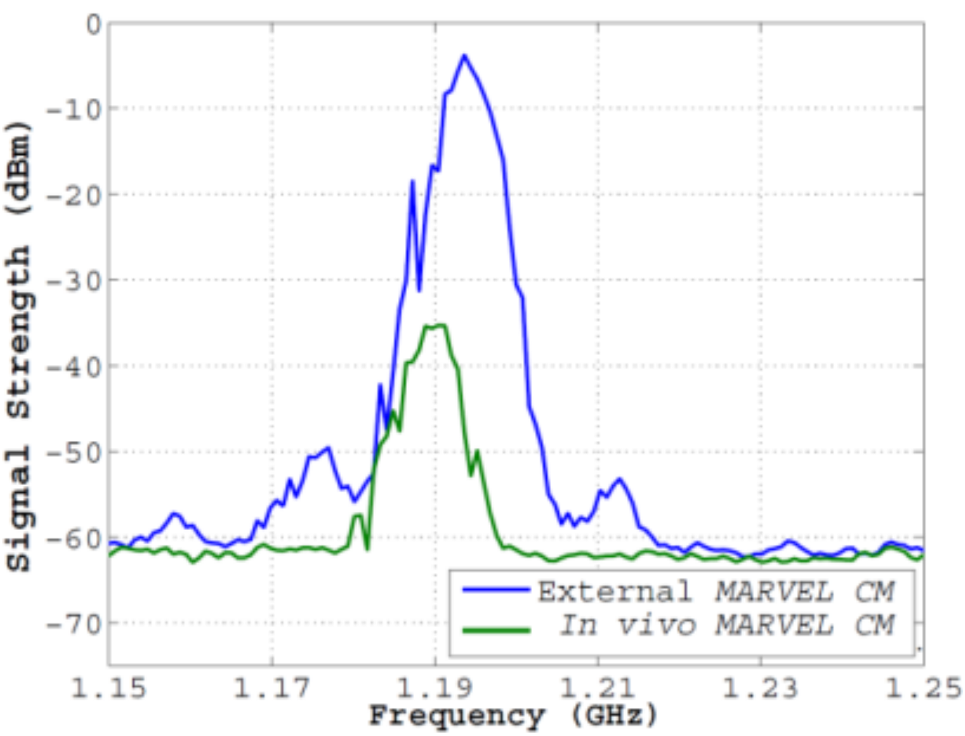


Top-down view of the human body showing locations of internal organs, muscles, and bones

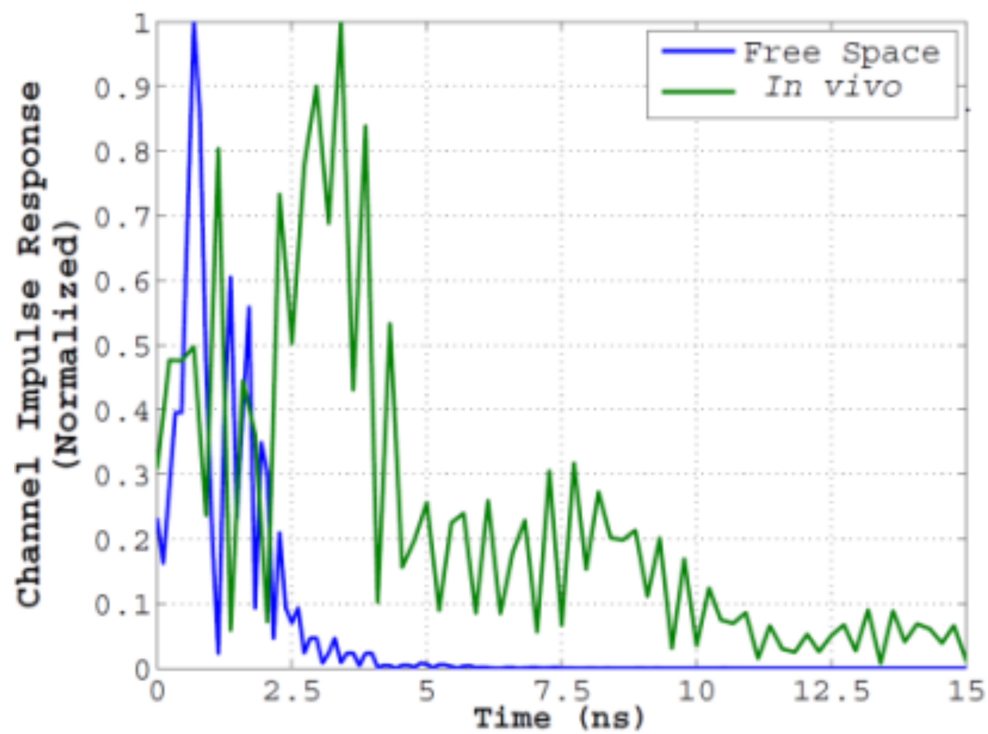
Human Body Model

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

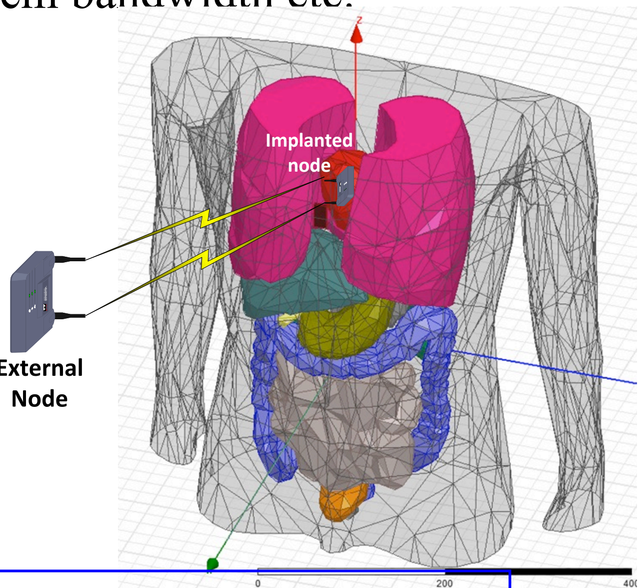


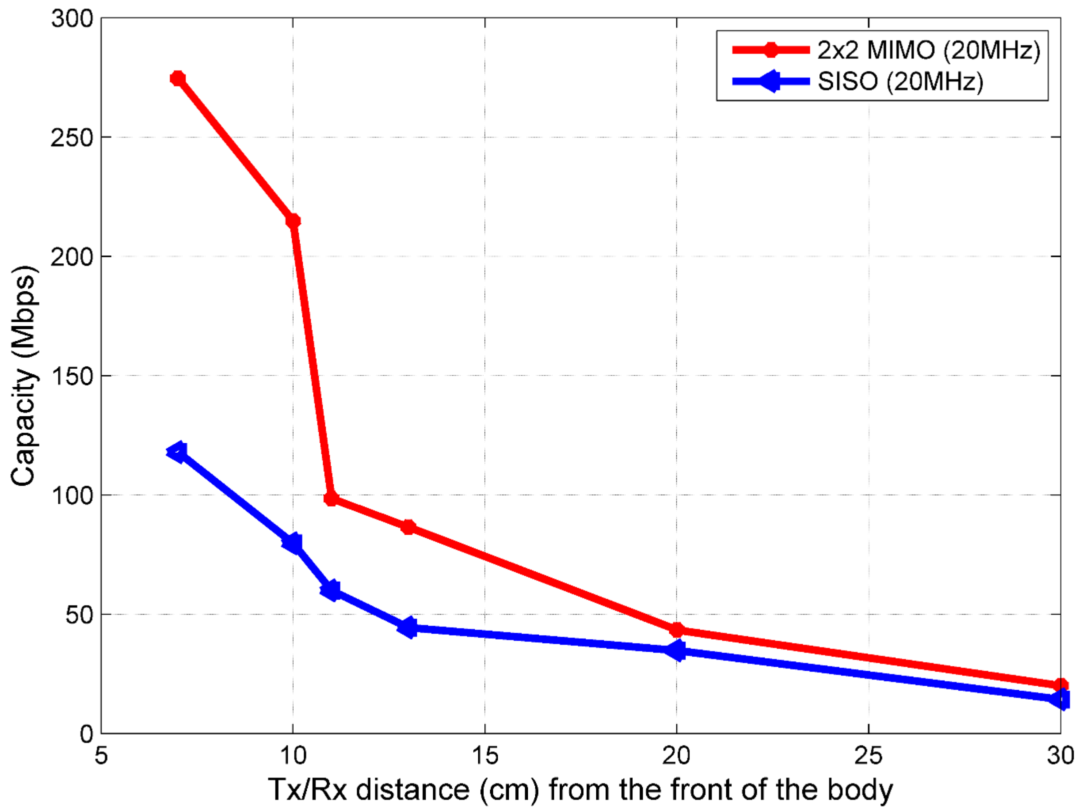
Normalized channel impulse response for free space and the porcine abdomen environments

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.





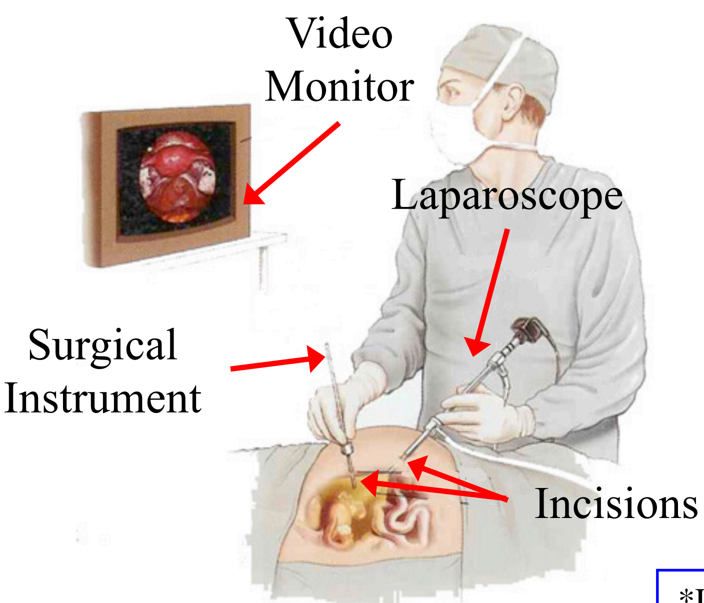
- Capacity decreases rapidly with the distance between the TX and RX antennas.
- For the required ***MARVEL*** data rate of ~100 Mbps, the distance must be ≤11cm.

*MIMO *In Vivo*, *IEEE WAMICON*, 2014.

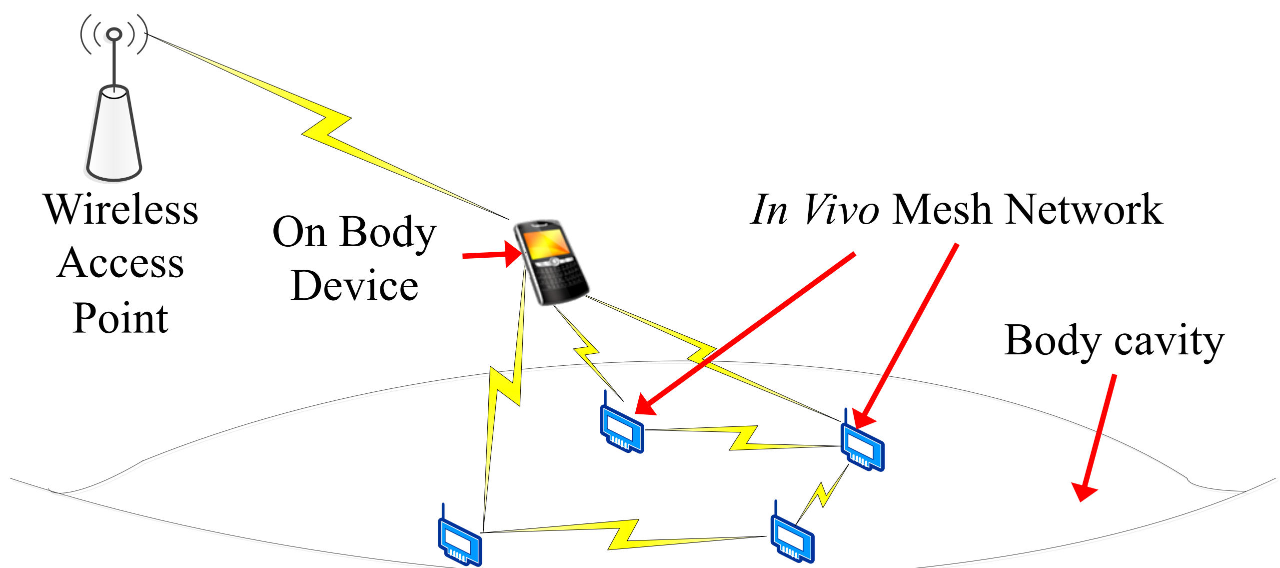
Advancing Minimally Invasive Surgery (MIS) via Wirelessly Networked Devices*
A paradigm shift in MIS surgery by eliminating the laparoscope

- 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



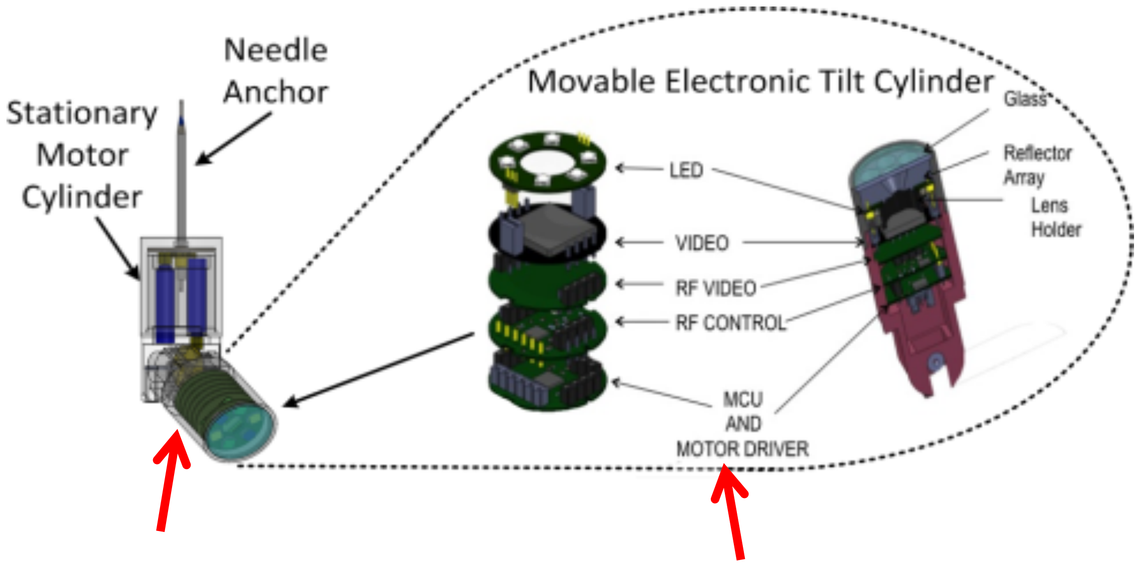
*US Patent No. 8,358,981, *Minimally Invasive Networked Surgical System*
A Wireless Miniature Robot for Networked Expedited Laparoscopy, *IEEE Transactions on Biomedical Engineering (TBME), April 2013*.

MARVEL: Research Challenges Included

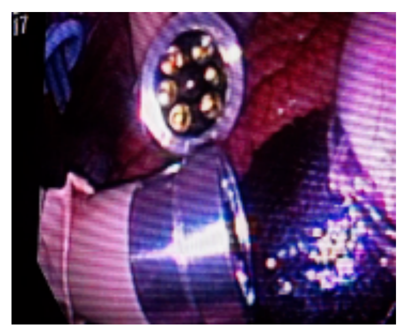
- Reliable, high-throughput and low-latency intra-body wireless communications.
- New networking paradigms for devices which are very limited from a communication and computing standpoint.
- Sensing, actuation, privacy, and security for such devices of limited complexity.
- Electronic, optical and mechanical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

<u>Experimental Results</u>

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



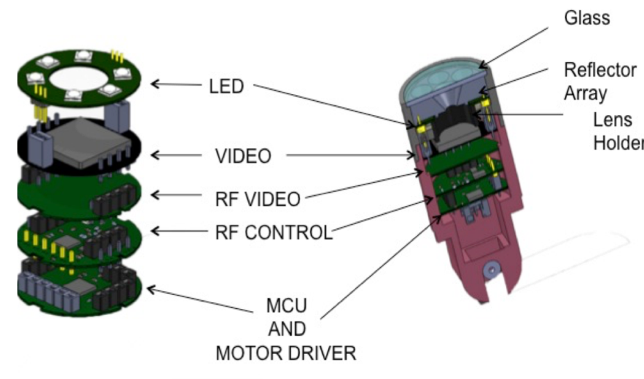
***MARVE*L CAD model and exploded circuit board stack**



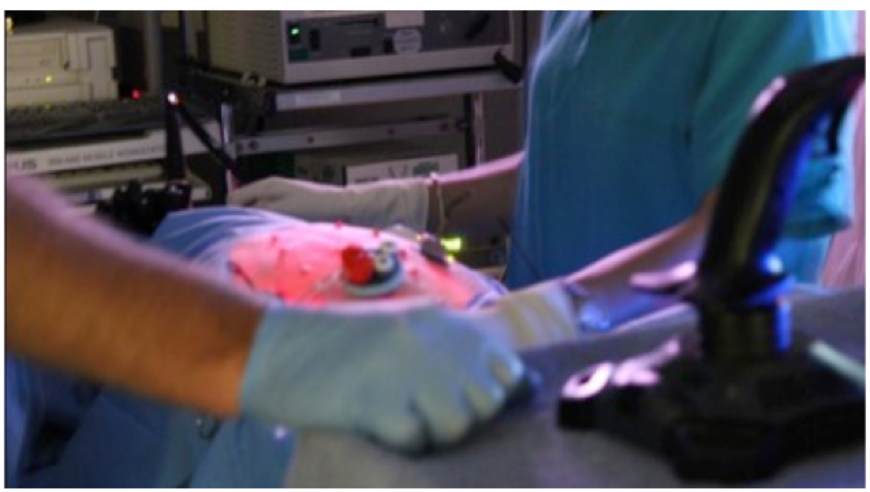
MARVEL units in a porcine abdominal cavity

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

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

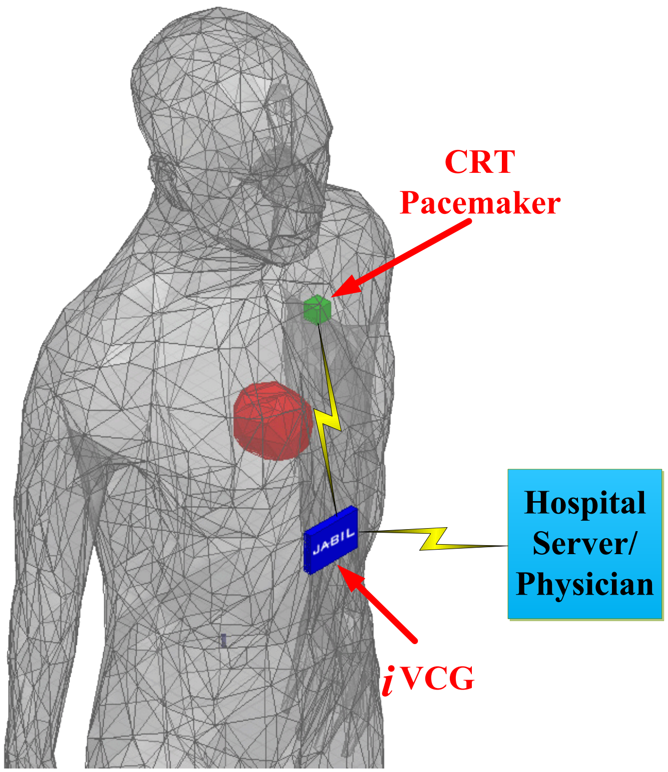


Two MARVEL CMs are shown. The surgeons have independent control of each Camera Module.

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

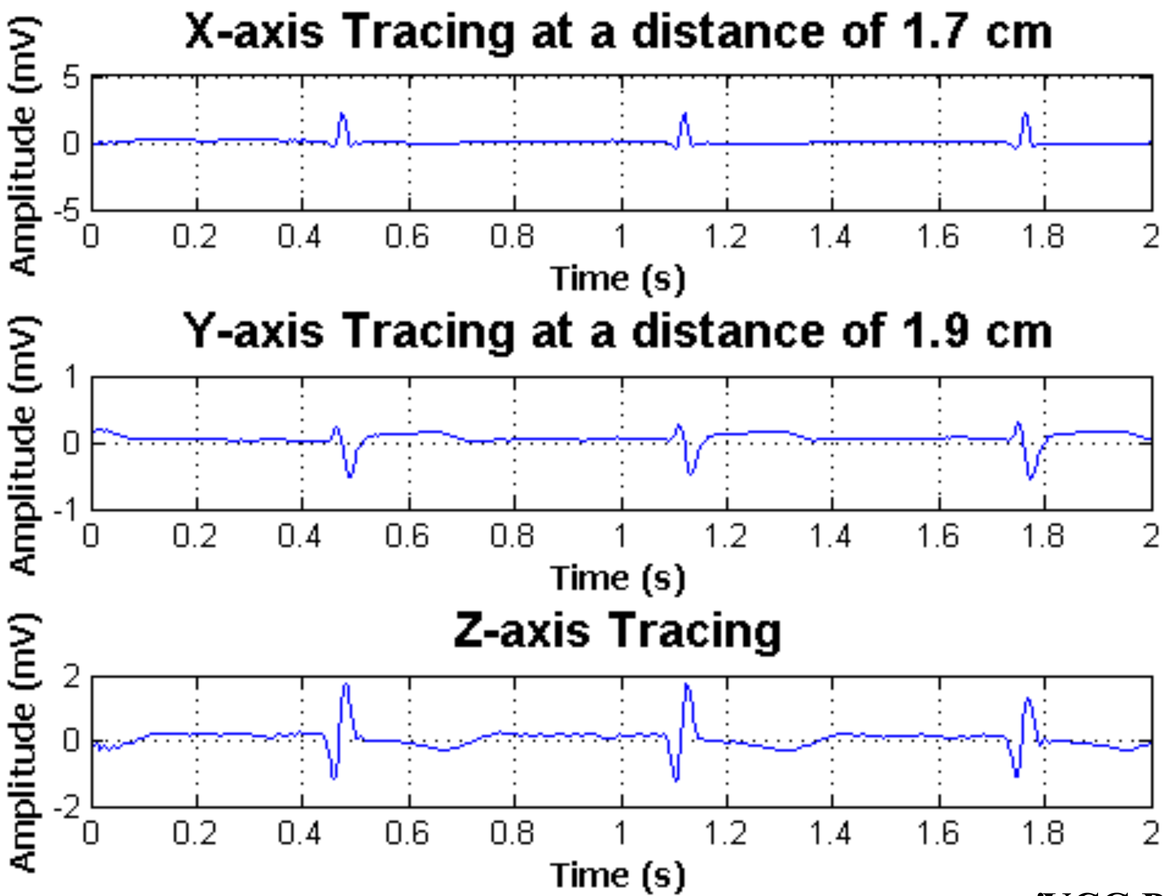
Personalized 24x7 Diagnostic-Quality Cardiac Monitoring System

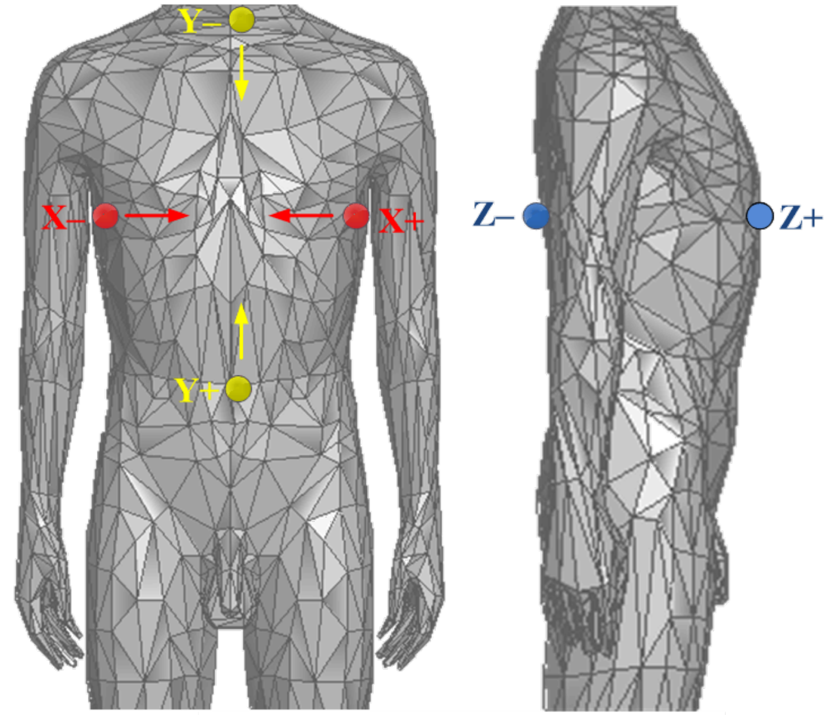
- The 3-lead diagnostic quality Vectorcardiogram (VCG) was invented in the 1950s and provides ≥ information than the 12-lead ECG.
- The VCG uses three orthogonal systems of leads to obtain the 3D electrical representation of the heart. To date, the VCG has only been a pedagogical tool.
- A system may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

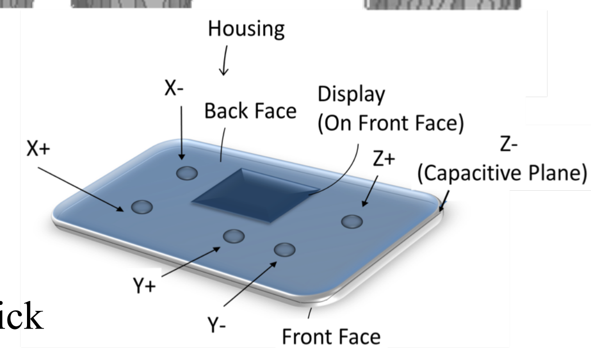


*G. E. Arrobo, C. A. Perumalla, Y. Liu, T. P. Ketterl, R. D. Gitlin, P. J. Fabri, "A Novel Vectorcardiogram System," 2014 *IEEE Healthcom*.
*D. S. Wickramasuriya, C. A. Perumalla, and R. D. Gitlin, "Predicting Episodes of Atrial Fibrillation using RR-Intervals and Ectopic Beats," *IEEE/EMB International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

VCG Electrodes at Minimum Distances Maintain Diagnostic Quality





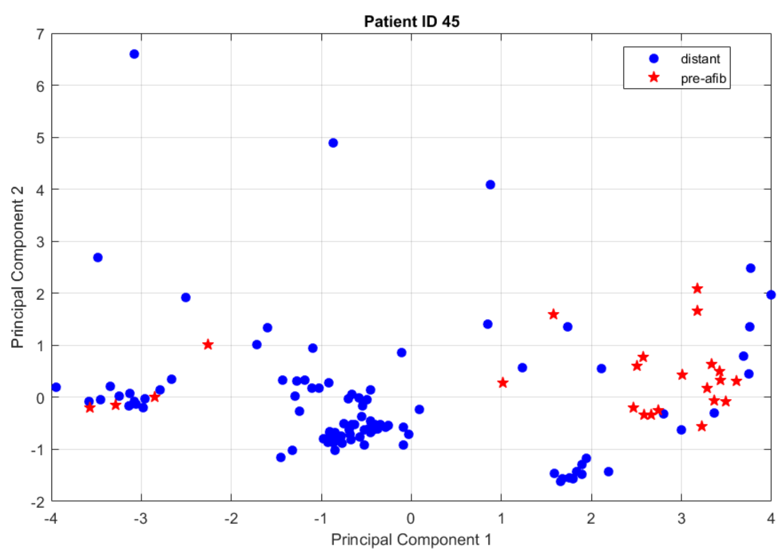


***i*VCG Prototype**
Target Dimensions:
4x4 cm and 1 cm thick

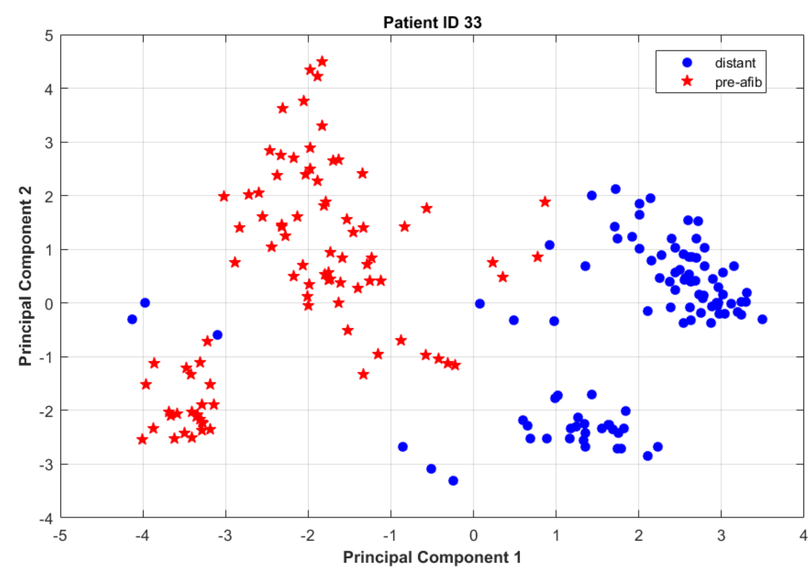
- As the proximity between the leads is decreased, the signals suffer a loss of amplitude and distortion (orthogonality) and are degraded relative to that of a 12-lead ECG.
- Compensate for proximity effects via post-reception signal processing techniques.
- **Diagnostic quality VCG signals at <2cm distances → 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 – <u>Patient-specific Support Vector Machine (SVM) classification</u>
  - 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



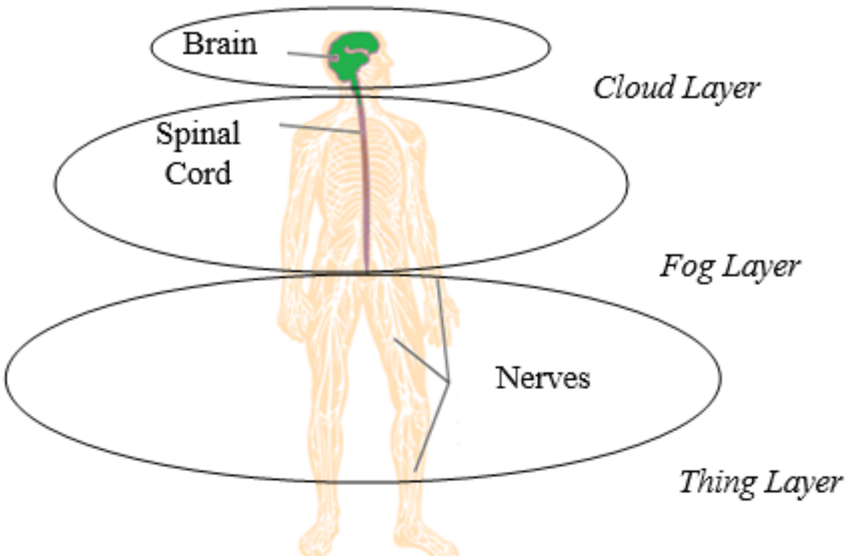
One minute before onset



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.

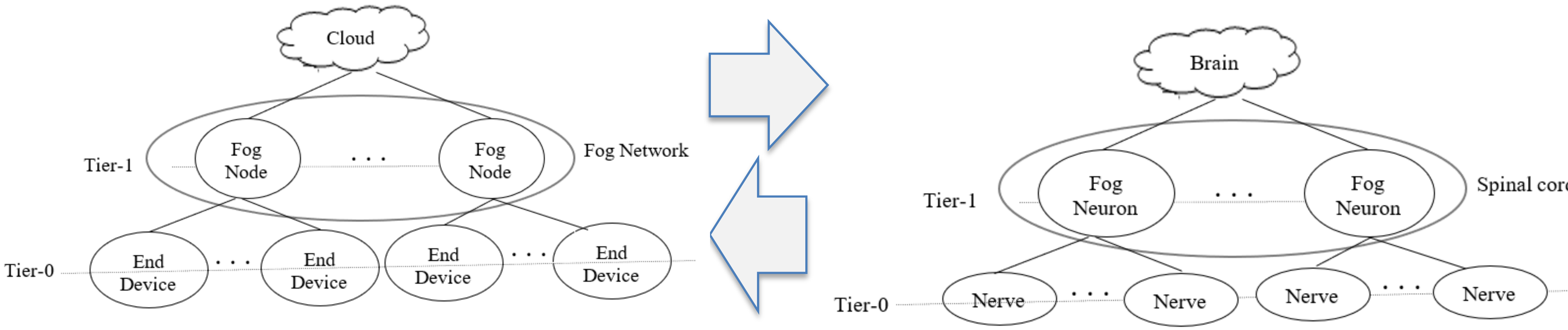
* Eren Balevi and R. D. Gitlin, "An Inherent Fog Network Brain-Spinal Cord-Nerve Networks," IEEE Access, Dec 2018
Eren Balevi and R. D. Gitlin, "Synergies between Cloud-Fog-Thing and Brain-Spinal Cord-Nerve Networks," ITA 2018

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

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

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

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*

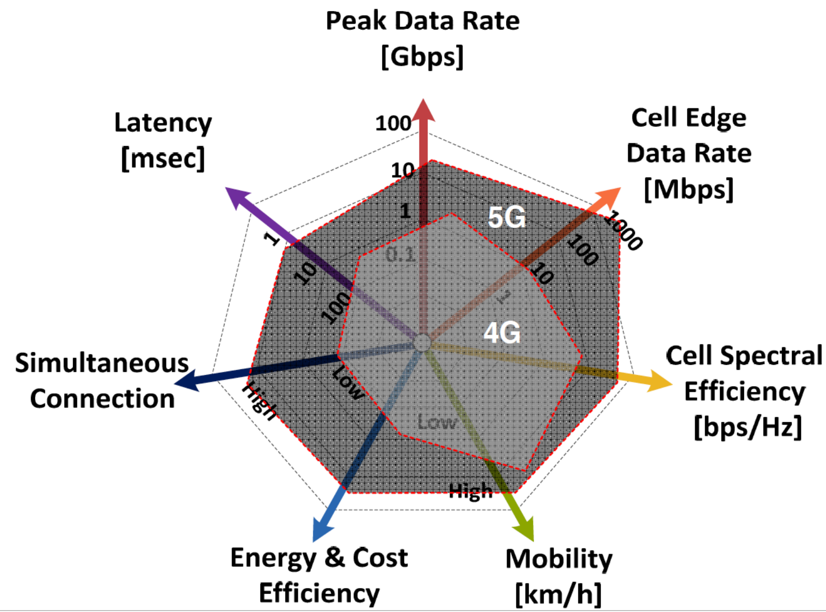
> - Can the central nervous system be better modeled considering the duality with the cloud and fog nodes?
> - The analysis for fog networking that specifies
>   - The optimum number of fog nodes
>   - The location of fog nodes
>
> may be used to localize the causes of disorders in the central nervous 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 = 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 network(s) must be flexible, exceptionally capable, 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.
- This is expected to be extended in 6G both in technology and range of applications (*in vivo*).
- Together their impact will be transformational and will be central to everything we do, forever alter how people access and use information, and will ultimately create …

The Internet of Tomorrow!