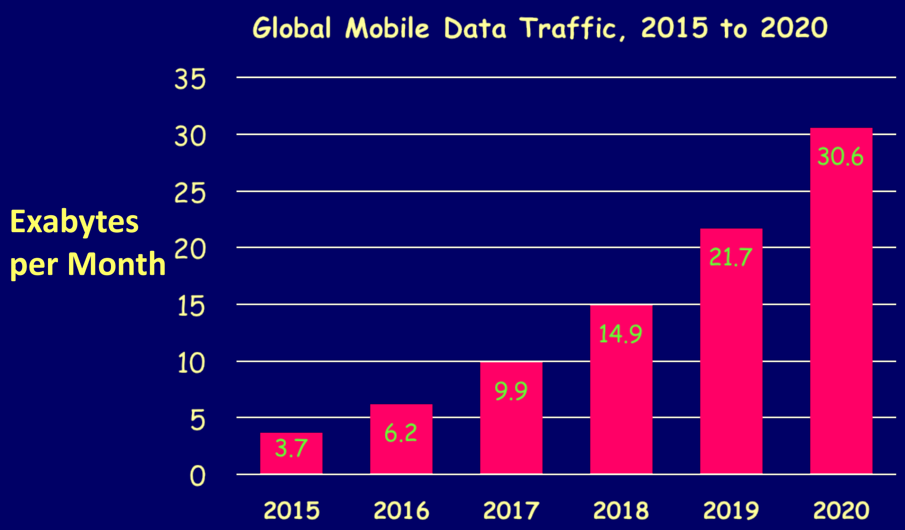
# SoftAir:

# A Software Defined Networking and Network Function Virtualization Architecture for 5G Wireless Systems


## I. F. AKYILDIZ

Ken Byers Chair Professor in Telecommunications
Georgia Institute of Technology
School of Electrical and Computer Engineering
BWN (Broadband Wireless Networking) Lab
Atlanta, GA 30332, USA
http://www.ece.gatech.edu/research/labs/bwn

# EVOLUTION OF WIRELESS SYSTEMS




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

1 Exabyte = $10^{18}$ Bytes


Pictures taken at St. Peter's Square for papal inauguration ceremonies of Pope Benedict (2005) and Pope Francis (2013)
http://www.nydailynews.com/news/world/check-contrasting-pics-st-peter-square-article-1.1288700

# OBJECTIVES OF 5G WIRELESS SYSTEMS

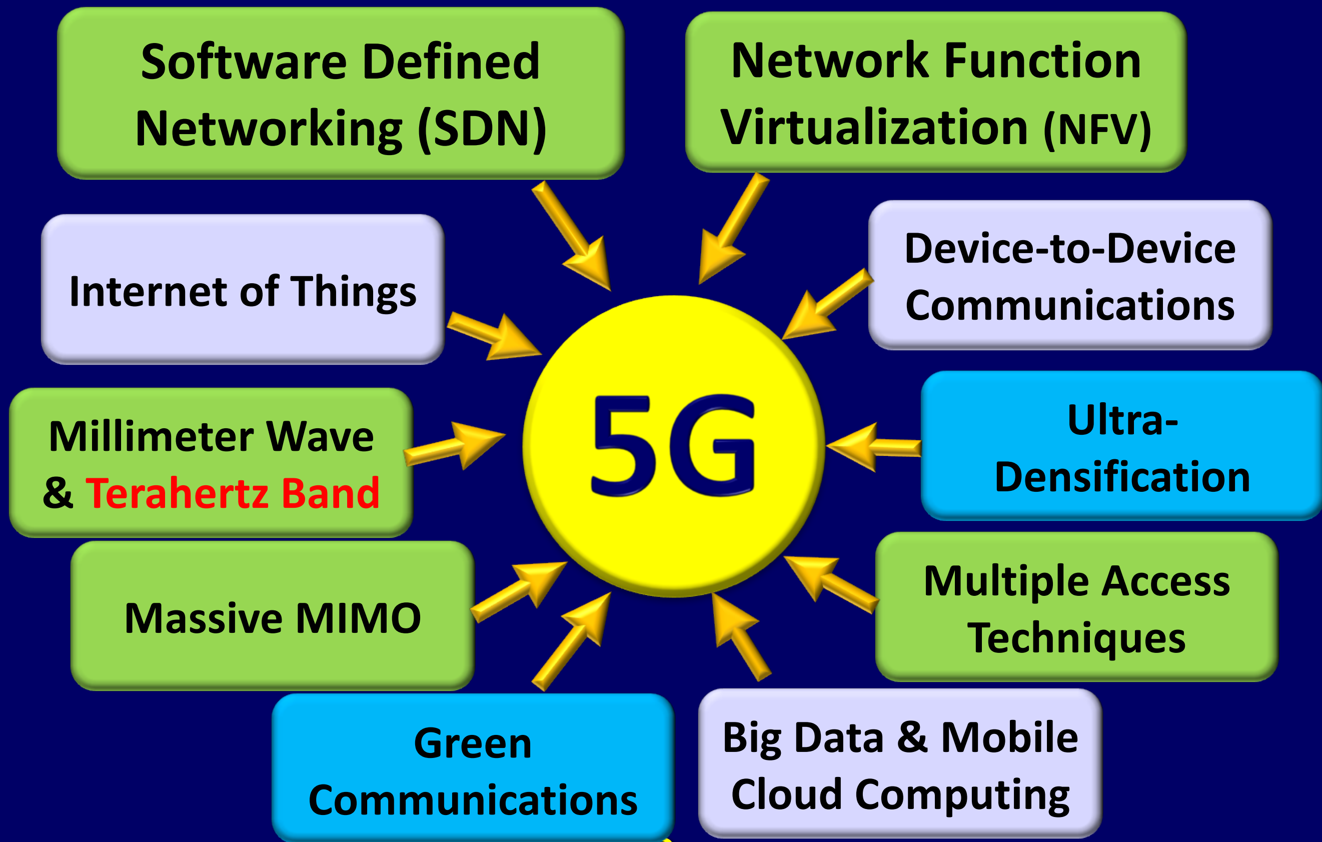
I. F. Akyildiz, S. Nie, C. Han, and M. Chandrasekaran, "5G Roadmap: 10 Key Enabling Technologies," Computer Networks (Elsevier) Journal, Sept. 2016.

**5G**

- Ultra High Capacity
  1000x capacity/km$^2$
- Flexible Network Architectures
- Reduced Latency
  RAN Latency < 1ms
  (Almost Zero Latency)
- Energy Savings (90%) & Cost Reduction
- Always Connected to Best Networks
  Anytime, Anywhere
- Connection of Billions of Things & People
  (7 Billion People
  7 Trillion Things)
  Scalability
- Ultra High Data Rates
  100x
  10 Gbps peak data rate
  100 Mbps cell edge data rate
- Mobile Cybersecurity

# 10 KEY ENABLING TECHNOLOGIES FOR 5G

I. F. Akyildiz, S. Nie, C. Han, and M. Chandrasekaran, "5G Roadmap: 10 Key Enabling Technologies," Computer Networks (Elsevier) Journal, Sept. 2016.



# Current 5G Projects @ BWN LAB

## SoftAir Project

Software Defined Networking (SDN)

Network Function Virtualization (NFV)

## TeraNets Project

Terahertz Band
& Ultra Massive MIMO
(1024 x 1024)

## MetisX

CHANNEL
MODELING &
SIMULATION TOOL

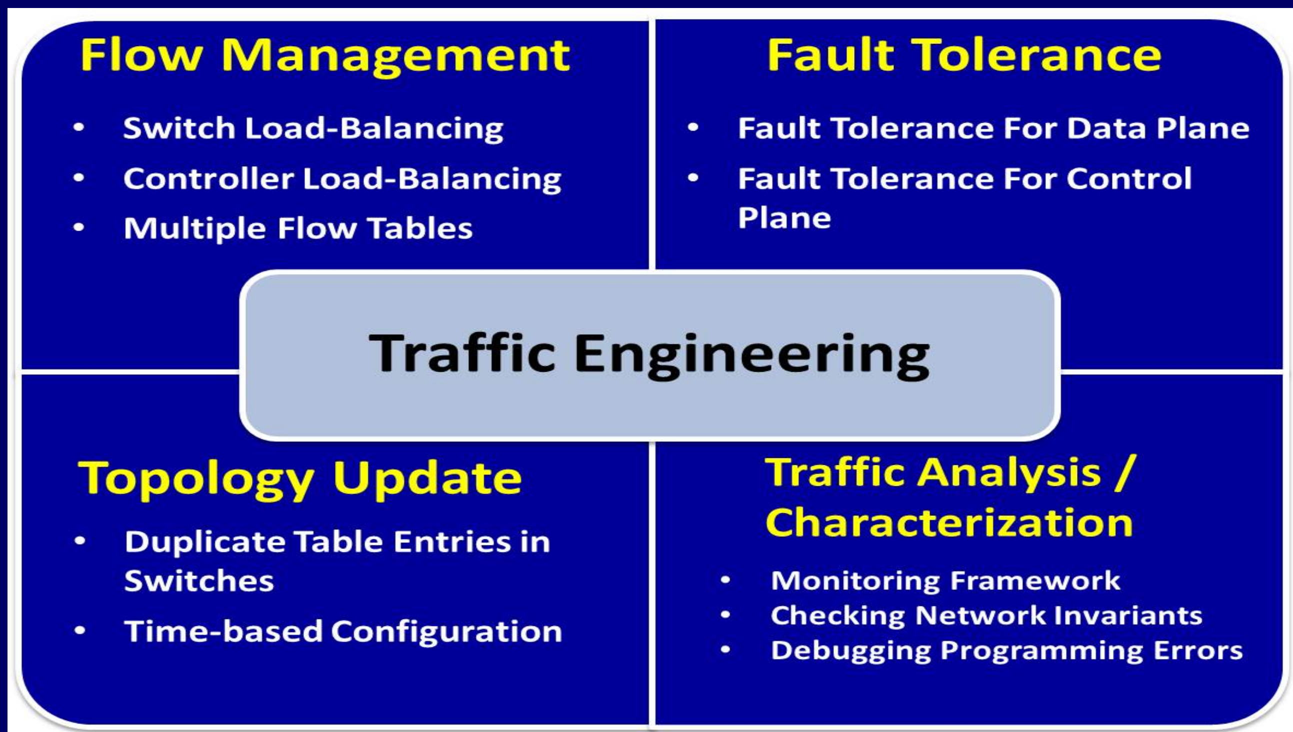
## IoT

* Internet of Things
* Internet of NanoThings
* Internet of BioNanoThings

# TRAFFIC ENGINEERING FOR SOFTWARE DEFINED NETWORKS

I. F. Akyildiz, A. Lee, P. Wang, M. Luo, and W. Chou, "A Roadmap for Traffic Engineering in SDN-OpenFlow Networks," Computer Network (Elsevier) Journal, vol. 71, pp. 1-30, October 2014.

I. F. Akyildiz, A. Lee, P. Wang, M. Luo, and W. Chou, "Research Challenges for Traffic Engineering in Software Defined Networks," IEEE Network, vol. 30, no. 3, pp. 52-58, May-June 2016.



## PATENTS WITH HUAWEI-SHENZEN

## SOFTWARE-DEFINED NETWORKING AND NETWORK FUNCTION VIRTUALIZATION SOLUTIONS: CORE NETWORK

- M. Luo, S.-C. Lin, and I. F. Akyildiz,
  "Apparatus for Self-Regulated LIFO Scheduling in Software Defined Networks with Hybrid Traffic," 2016.
- M. Luo, S.-C. Lin, and I. F. Akyildiz, "Software Defined Networks Traffic Congestion Control," 2016.
- M. Luo, S.-C. Lin, and I. F. Akyildiz, "Apparatus for Control Traffic Balancing with Multi-Controllers in SDNs," 2016.
- M. Luo, S.-C. Lin, and I. F. Akyildiz, "Apparatus for Jointly Optimized Traffic-Driven Controller Placement in SDNs," 2015.
- M. Luo, D. G. Estévez, and S.-C. Lin, "Management for Data Centers with Multi-Resource Schedulable Unit-Network Extension," 2015.
- M. Luo, S.-C. Lin, and I. F. Akyildiz, "Apparatus for Maximum Network Capacity Policy in Generalized Packet-Switched Networks with Heavy-Tailed Traffic," 2015.
- M. Luo, S.-C. Lin, and I. F. Akyildiz, "Apparatus for Control Traffic Balancing in Software Defined Networks," 2014.

# REVIEW OF EXISTING W-SDN ARCHITECTURES

I. F. AKYILDIZ, S.-C. LIN, P. WANG,
"WIRELESS SDNS & NFV FOR 5G CELLULAR SYSTEMS: AN OVERVIEW AND QUALITATIVE EVALUATION,"
COMPUTER NETWORKS (ELSEVIER) JOURNAL, VOL. 93, PART 1, PP. 66-79, DECEMBER 2015.

- **CellSDN**
  L. E. Li, Z. M. Mao, and J. Rexford, "Toward Software-Defined Cellular Networks," European Workshop on Software Defined Networking (EWSDN), 2012.
  * SD Cellular Core Network Design

- **C-RAN**
  * SD Radio Access Network Design

  China Mobile Research Institute. (Jun. 2014). *C-RAN White Paper: The Road Towards Green RAN*. Available: http://labs.chinamobile.com/cran

- **DoCoMo W-SDN**
  * Modified C-RAN

  NTT DOCOMO, INC. (Jul. 2014). *DOCOMO 5G White Paper: 5G Radio Access: Requirements, Concept and Technologies*. Available: https://www.nttdocomo.co.jp/corporate/technology/whitepaper_5g/

- **SK Telecom W-SDN**
  SK Telecom (2014). *SK Telecom 5G White Paper: SK Telecom's View on 5G Vision, Architecture, Technology, and Spectrum*. Available: http://www.sktelecom.com/
  * Integrated SD-CN and SD-RAN Architecture

## LIMITATIONS OF C-RAN & NTT DOCOMO & SK TELECOM

* Limited Scalability and Evolvability of RANs:
  Coarse-Grained BS Decoupling
* No NW virtualization functionalities
* Only RAN considered without the CN functionalities
* Traffic Engineering solutions discussed mainly at PHY layer

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## SoftAir Management Tools

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1. Dynamic RRH Formation
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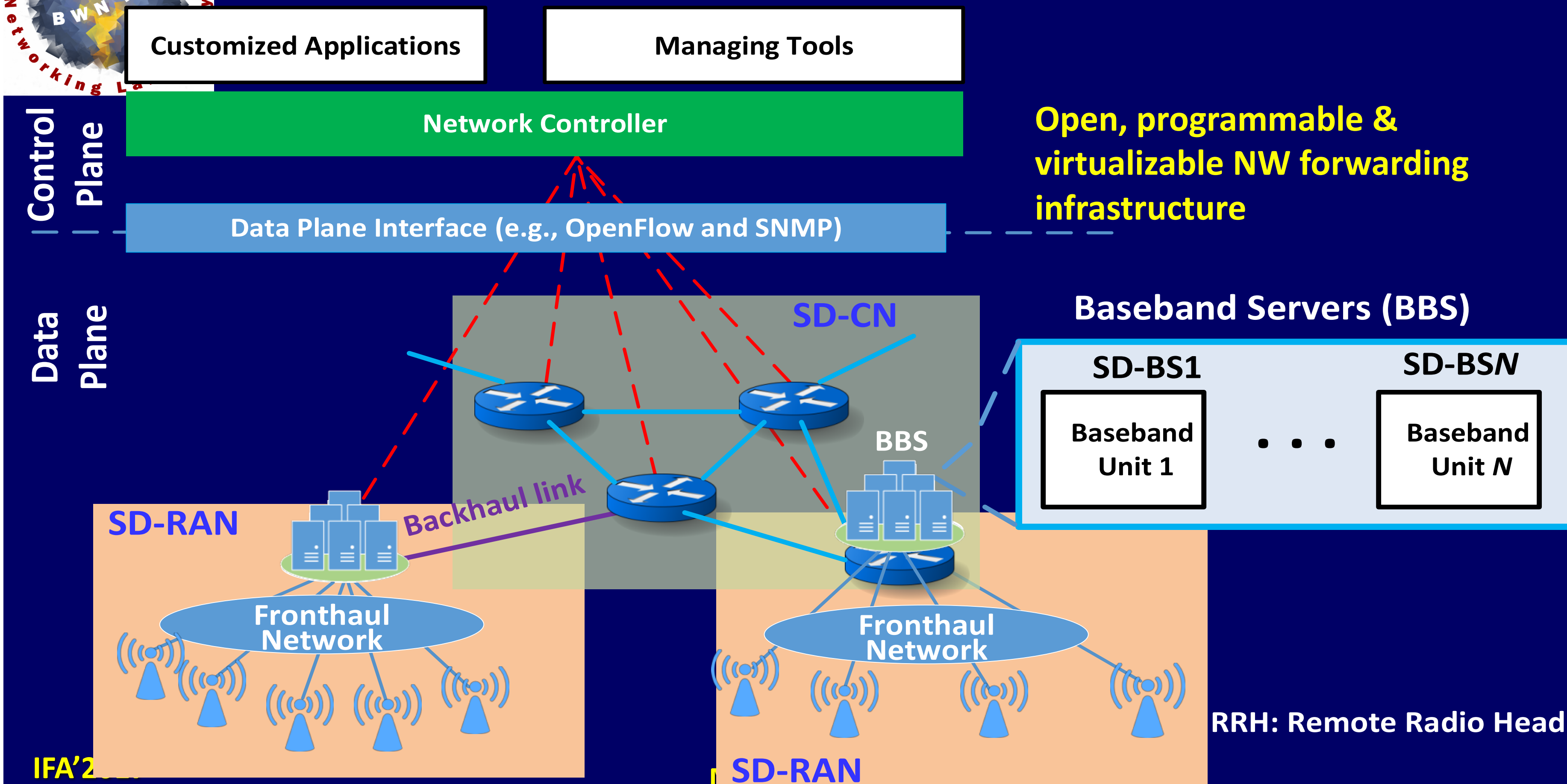
# SOFTAIR ARCHITECTURE: (SCALABLE DECOUPLING PLATFORM)

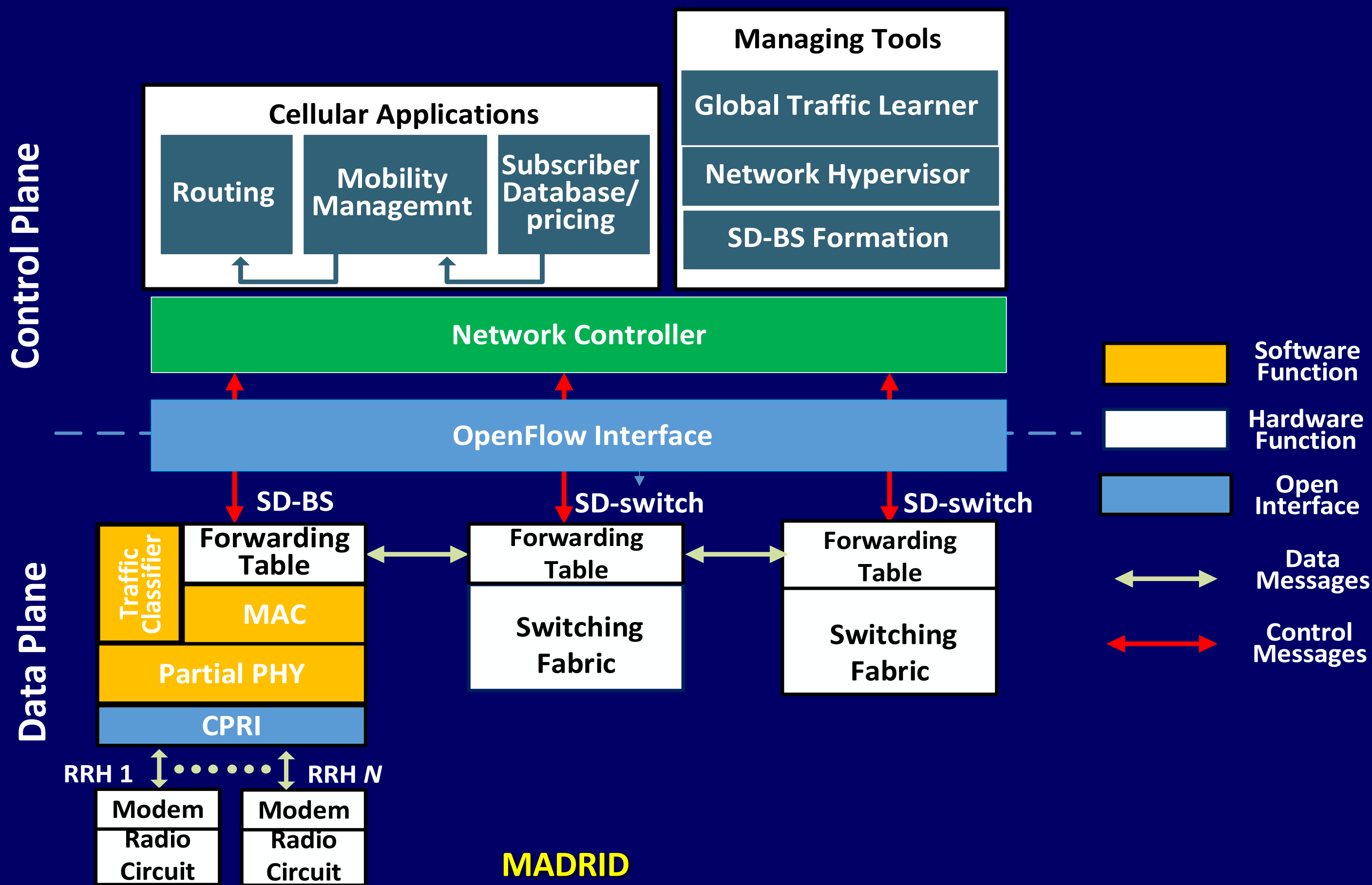



Open, programmable & virtualizable NW forwarding infrastructure

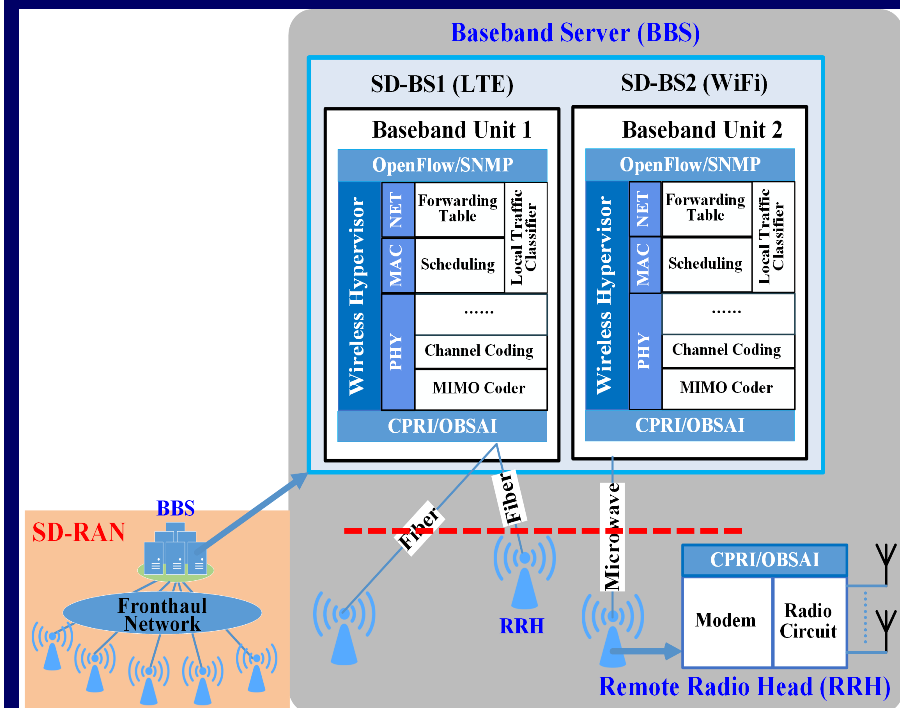
RRH: Remote Radio Head

# NETWORK FUNCTION VIRTUALIZATION:

## SCALABLE FUNCTION CLOUDIFICATION



# QUANTITATIVE EVALUATION OF SOFTAIR



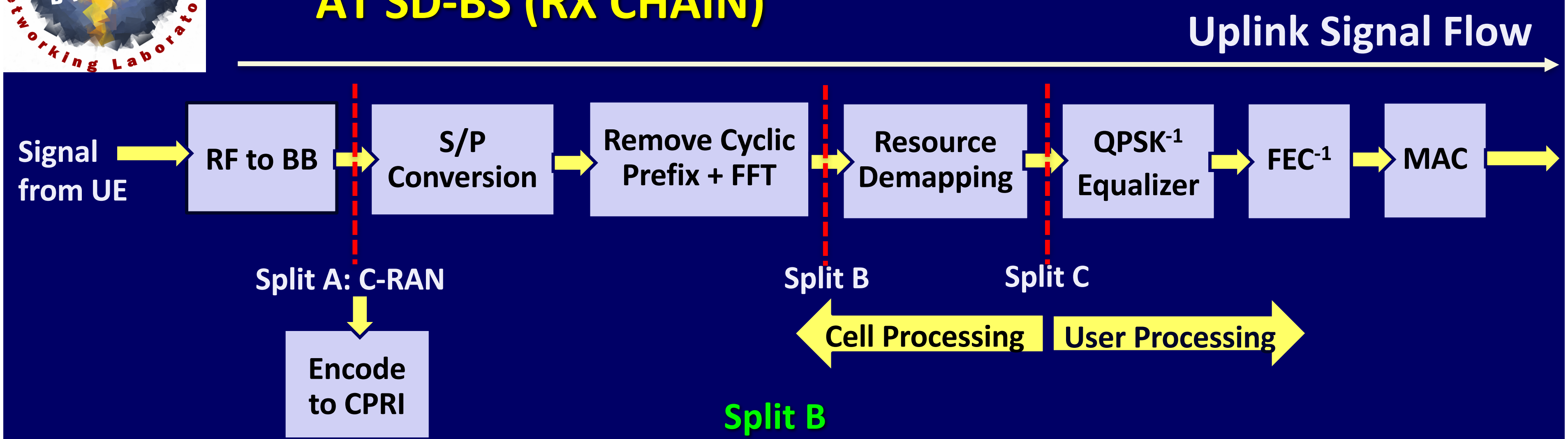

## Cloud-RAN based 5G Systems

- **Centralized Baseband Processing**
  - CPRI: Used to separate HW antenna (RRHs) and SW algorithms (BBS)
  - Bandwidth required I-Q transmissions becomes a bottleneck

## SoftAir: Scalable SD-RANs

- **Partial Baseband Processing at RRHs**
  - MODEM is put on the RRHs
  - → I-Q transmissions are eliminated

# UPLINK PHYSICAL LAYER PROCESSING CHAIN AT SD-BS (RX CHAIN)




## Split A: C-RAN

- Raw I/Q samples are transmitted between RRHs and BBSs (Massive redundancies transmitted over fronthaul links)

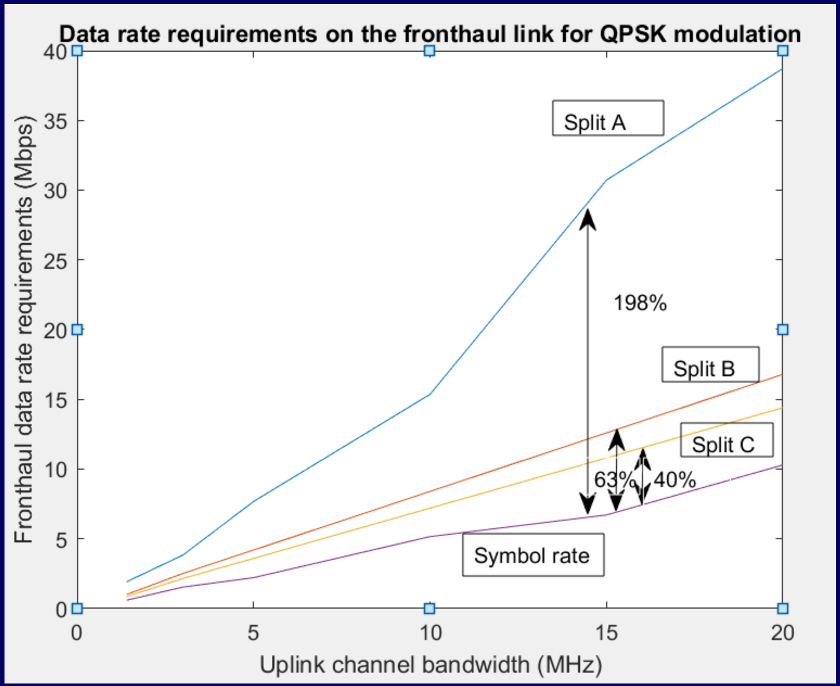
## Split B

- RRHs remove CP, apply DFT to transform samples into frequency domain, and remove guard band subcarriers

## Split C

- Further include resource element (RE) demapper in RRHs, which categorizes REs with respect to served UEs
- Per-cell processing in RRHs; per-user processing in BBSs

# UPLINK PHYSICAL LAYER PROCESSING CHAIN AT SD-BS (RX CHAIN)




| Parameters | |
|---|---|
| **Bandwidth (MHz)** | **1.4, 3, 5, 10, 15, 20** |
| # of UE transmit antennas | 4 |
| # of RRH receive antennas | 4 |
| Modulation | QPSK |
| Cyclic prefix | Normal |
| Cyclic shift | 0 |
| Duplex mode | FDD |

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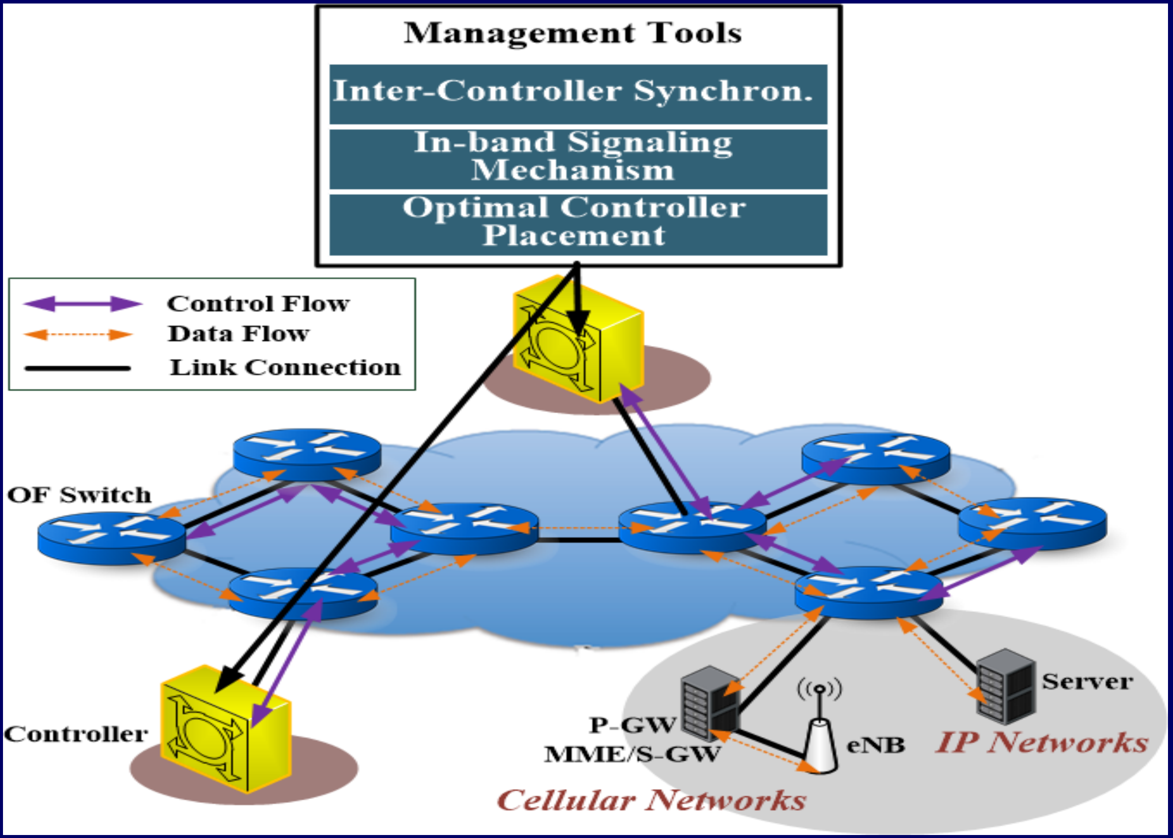
# CONTROL TRAFFIC MANAGEMENT



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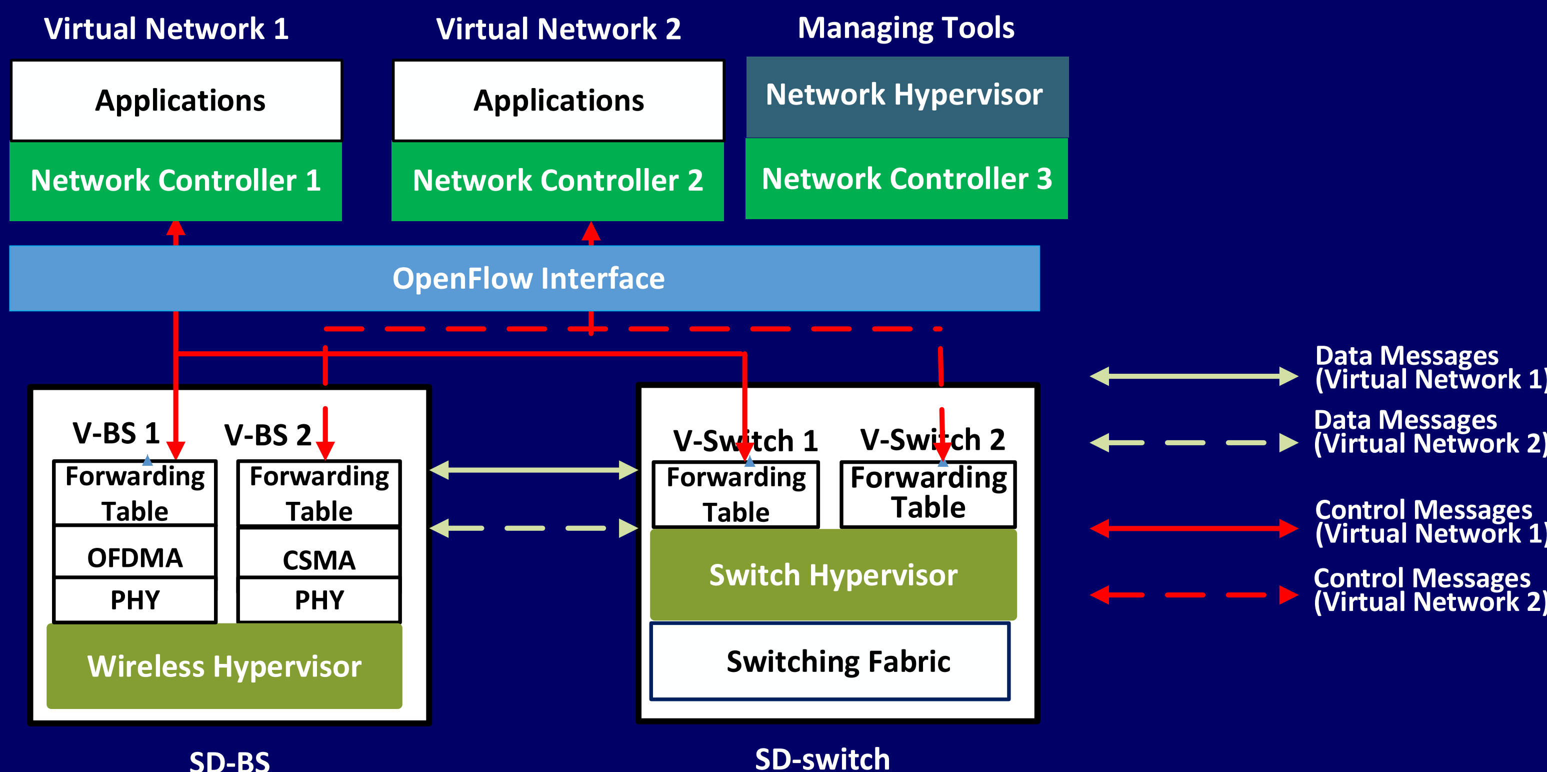
# NETWORK VIRTUALIZATION IN SOFTAIR

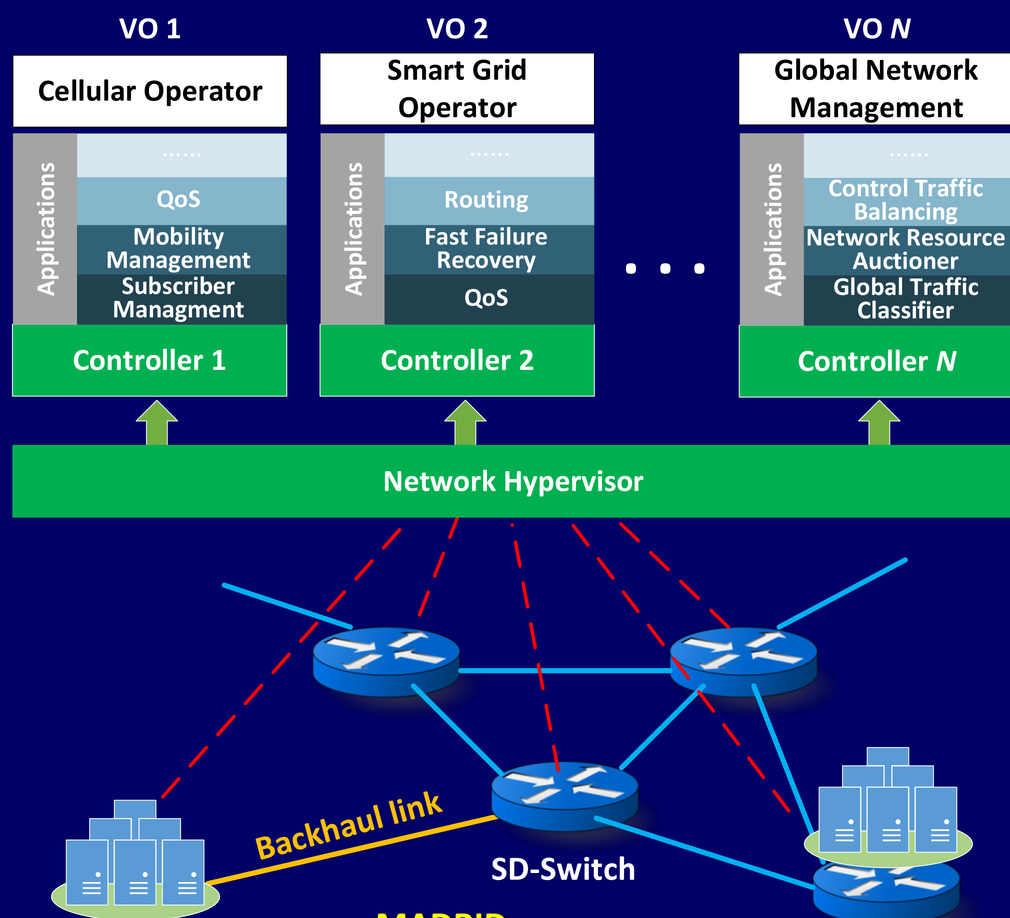
S. C. Lin, P. Wang, and M. Luo,

"Jointly Optimized QoS-aware Virtualization and Routing in SDNs,"

Computer Networks (Elsevier) Journal, vol. 96, pp. 69-78, 2016.



# NETWORK VIRTUALIZATION: NETWORK HYPERVISOR



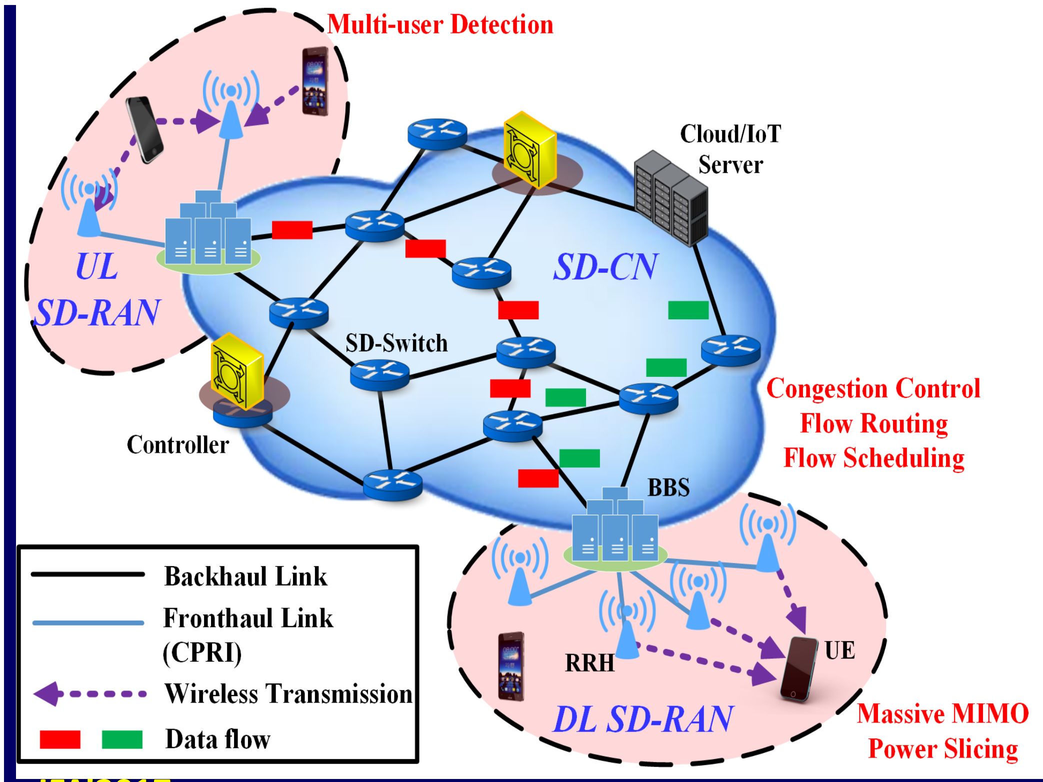

MADRID

## NETWORK VIRTUALIZATION: WIRELESS & SWITCH HYPERVISOR

S.-C. Lin, P. Wang, I. F. Akyildiz, and M. Luo,
"Delay-Based Maximum Power-Weight Scheduling in Queueing Networks with Heavy-Tailed Traffic,"
filed U.S. Patent, 2015.
to appear in IEEE/ACM Transactions on Networking, Fall 2017.

- **Execute the resource sharing polices determined by the NETWORK HYPERVISOR**
- **Wireless Hypervisor:**
  **Uses a scheduling algorithm in the BBSs to realize the resource sharing determined by the NW Hypervisor.**
- **Switch Hypervisor:**
  **Uses a scheduling algorithm in the core SD-switches, e.g., FlowVisor**

# DESIGN PRINCIPLE: NETWORK VIRTUALIZATION




- "Horizontal": Optimal resource allocation along the way

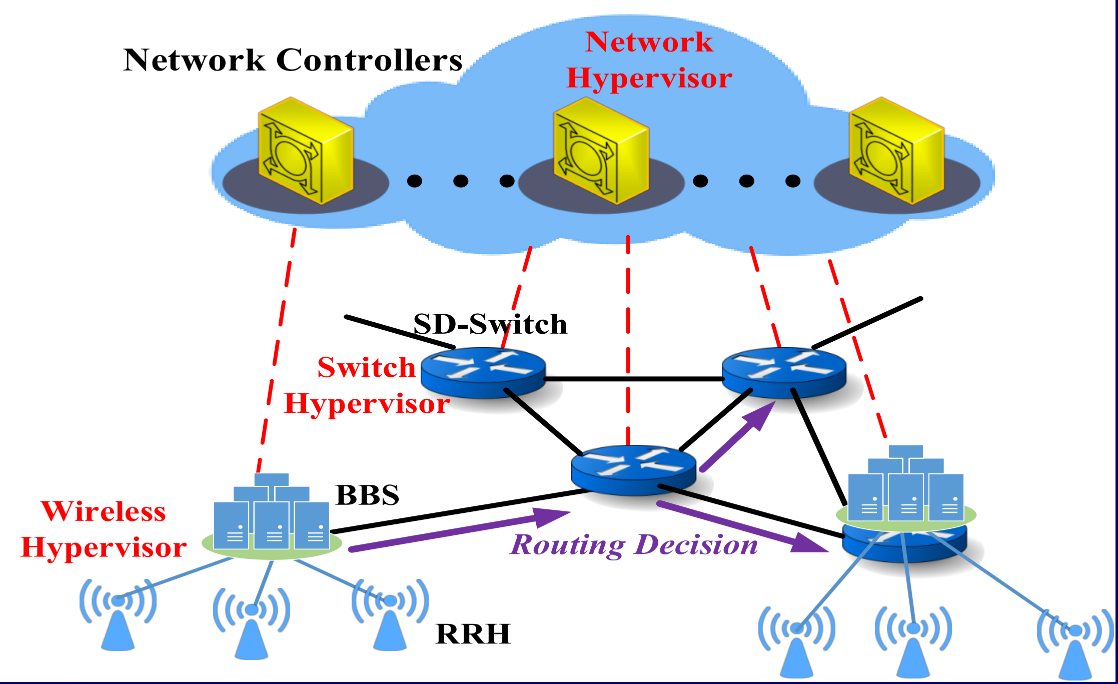
  UL SD-RAN → SD-CN → DL SD-RAN

  1. UL SD-RAN: Multi-user detection
  2. DL SD-RAN: Massive MIMO & Power slicing
  3. Entire network: Congestion control & Flow routing & Flow scheduling

- "Vertical": Joint optimization for congestion control, flow routing, and power slicing

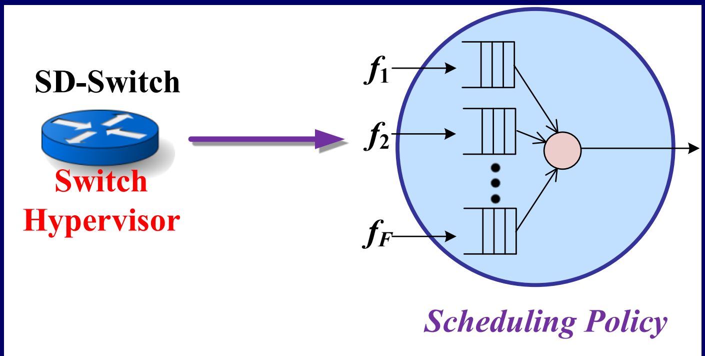
# DESIGN PRINCIPLE: NETWORK VIRTUALIZATION

## Joint Optimization for Network & Wireless & Switch Hypervisors



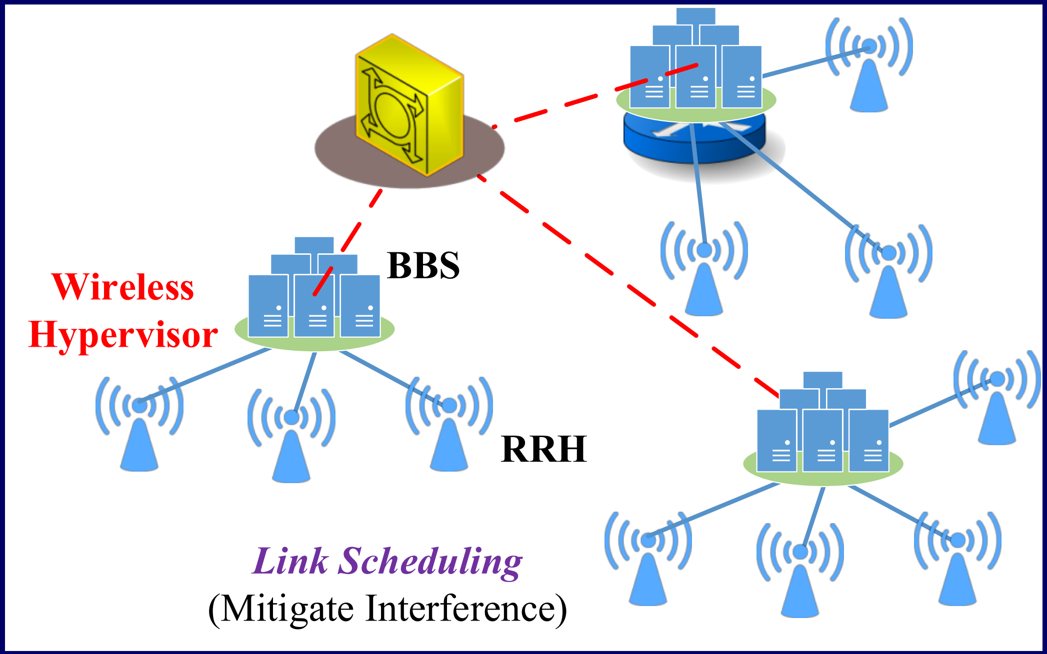

- NW-Hypervisor level: Routing Policies (Resource Sharing Policies)
- WIRELESS/SWITCH HV-level: Scheduling Policies

⇒ Optimally determine at the same time



# DESIGN PRINCIPLE: WIRELESS HYPERVISOR

**Wireless Link Scheduling:** Find non-conflict set of RRHs by avoiding interference between them



# JOINT OPTIMIZATION PROBLEM FOR NETWORK VIRTUALIZATION

- Network Utility Maximization (NUM) Problem
  - * **Flow Routing**: NW layer - Network Hypervisor
  - * **Link Scheduling**: MAC/PHY layer - Wireless/Switch Hypervisors

**Objective**: Maximize total supportable traffic arrival rate from all VOs

**Subject to** Flow conservation constraint for routing ← NW HV

Bandwidth constraint in the core NW ← SWITCH HV

RAN capacity constraint characterizing the interference for wireless channels ← WIRELESS HV

## OPTIMAL SYSTEM DECOUPLING FOR NP-HARD JOINT OPTIMIZATION

- **WIRELESS/SWITCH HV-level**
  - → Scheduling Policies

*OPTIMAL non-conflict set of RRHs*
*OPTIMAL bandwidth scheduling in core SD-switches*

⬇

- **NW-Hypervisor level**
  - → Routing Policies (Resource Sharing Policies)

**Iteratively (Adaptively) Decide Optimal Policies for 3 Hypervisors**

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# DYNAMIC RRH FORMATION

- **WHY?**
  * To maximize the Cooperation Gain

- **PROPOSED SOLUTION:** Optimal Clustering of RRHs

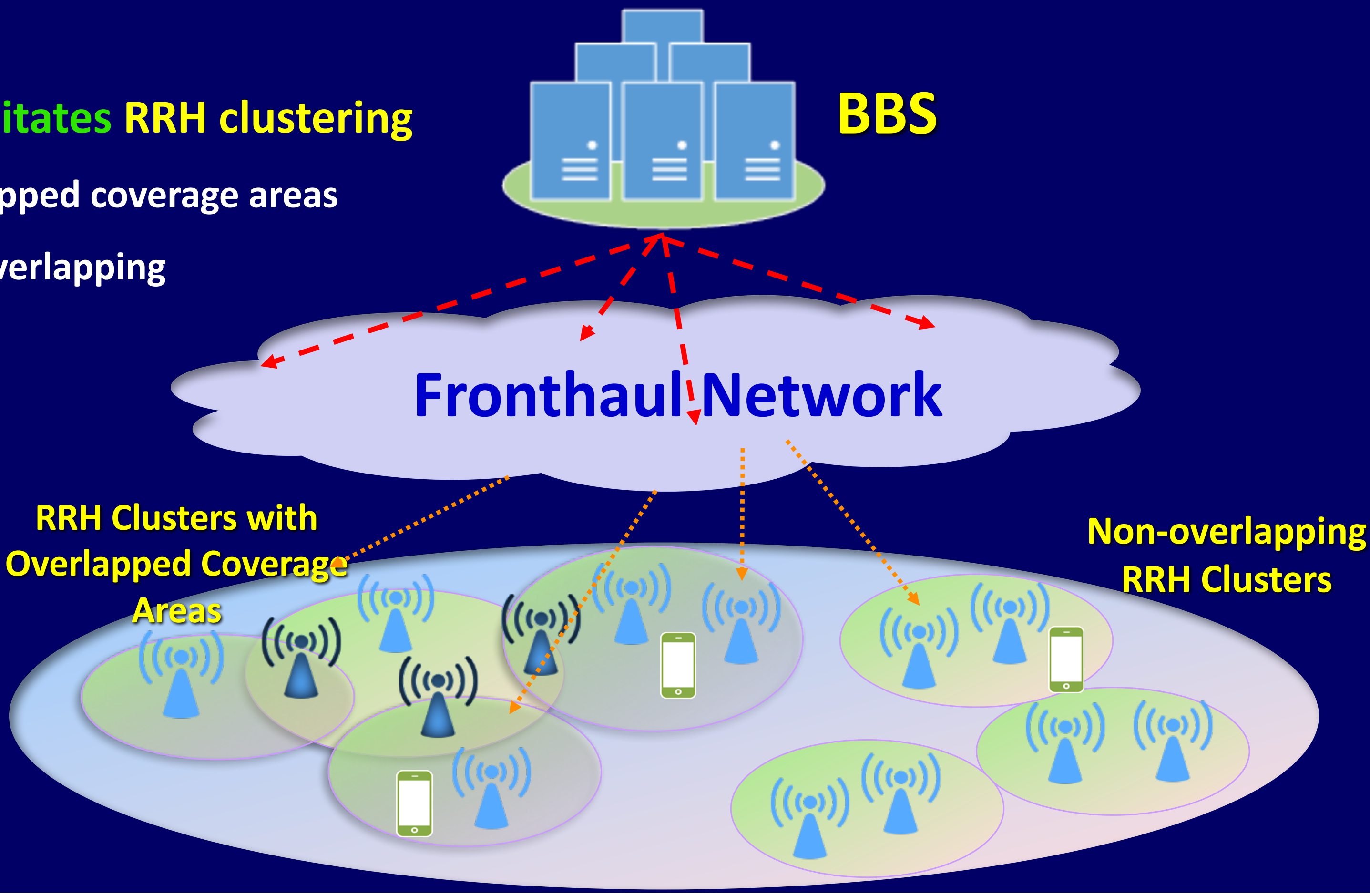
  → Maximize the spectral efficiency while considering specific cooperation costs

  → Can enable COMP & NW MU-MIMO & Phantom Cell, Massive MIMO & mmWaves

# OPTIMAL CLUSTERING OF RRHS

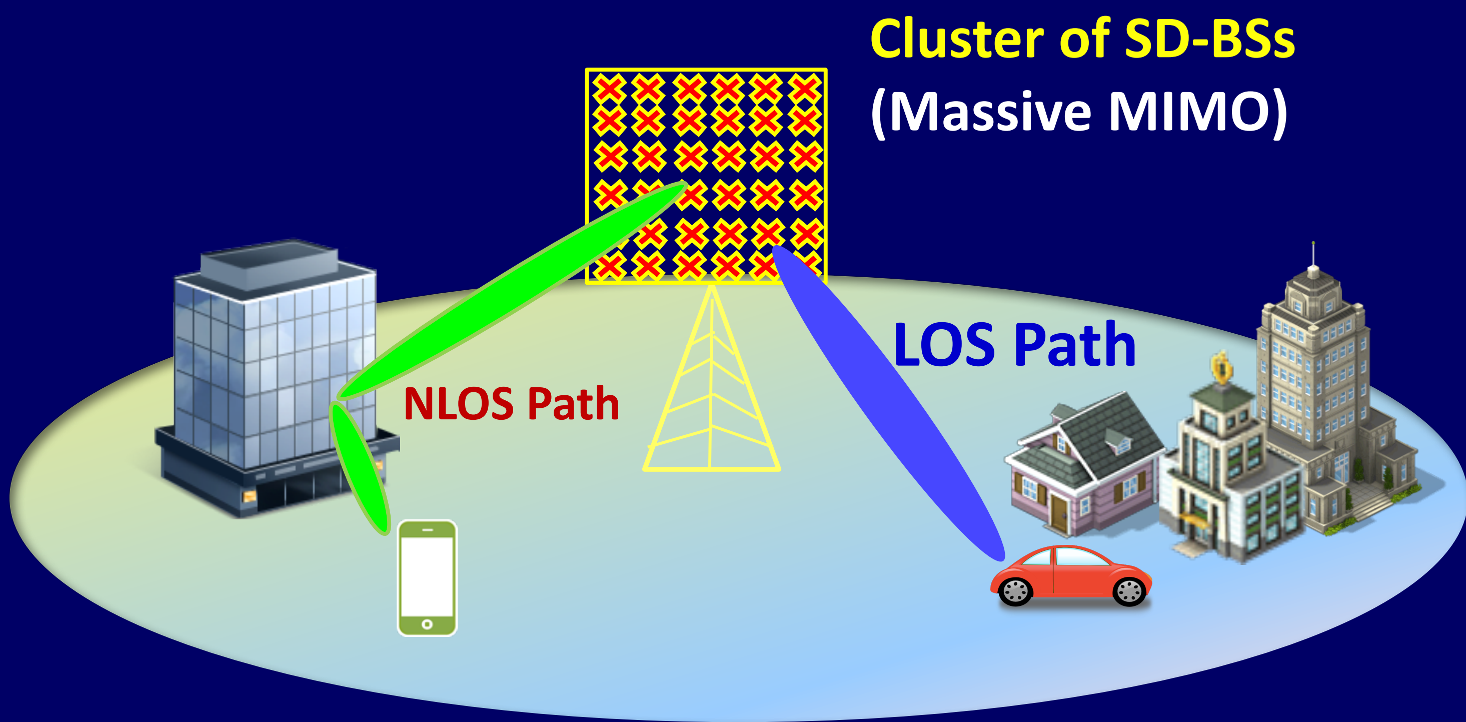
**BBS facilitates RRH clustering**

- Overlapped coverage areas
- Non-overlapping

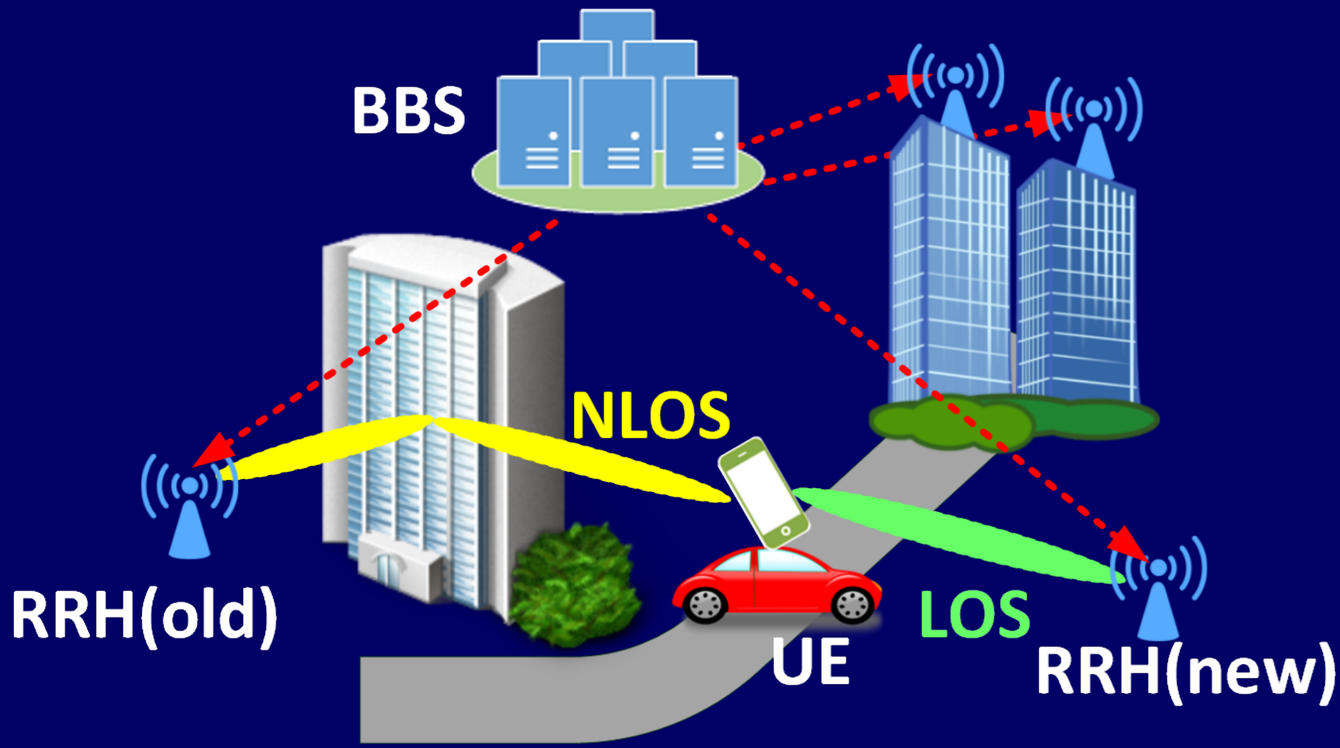


# A CLUSTER CAN ACT AS A MASSIVE MIMO

BBS forms a cluster of SD-BSs with multiple RRHs



## CLUSTERING
### NLOS SOLUTION FOR MM-WAVE SYSTEMS



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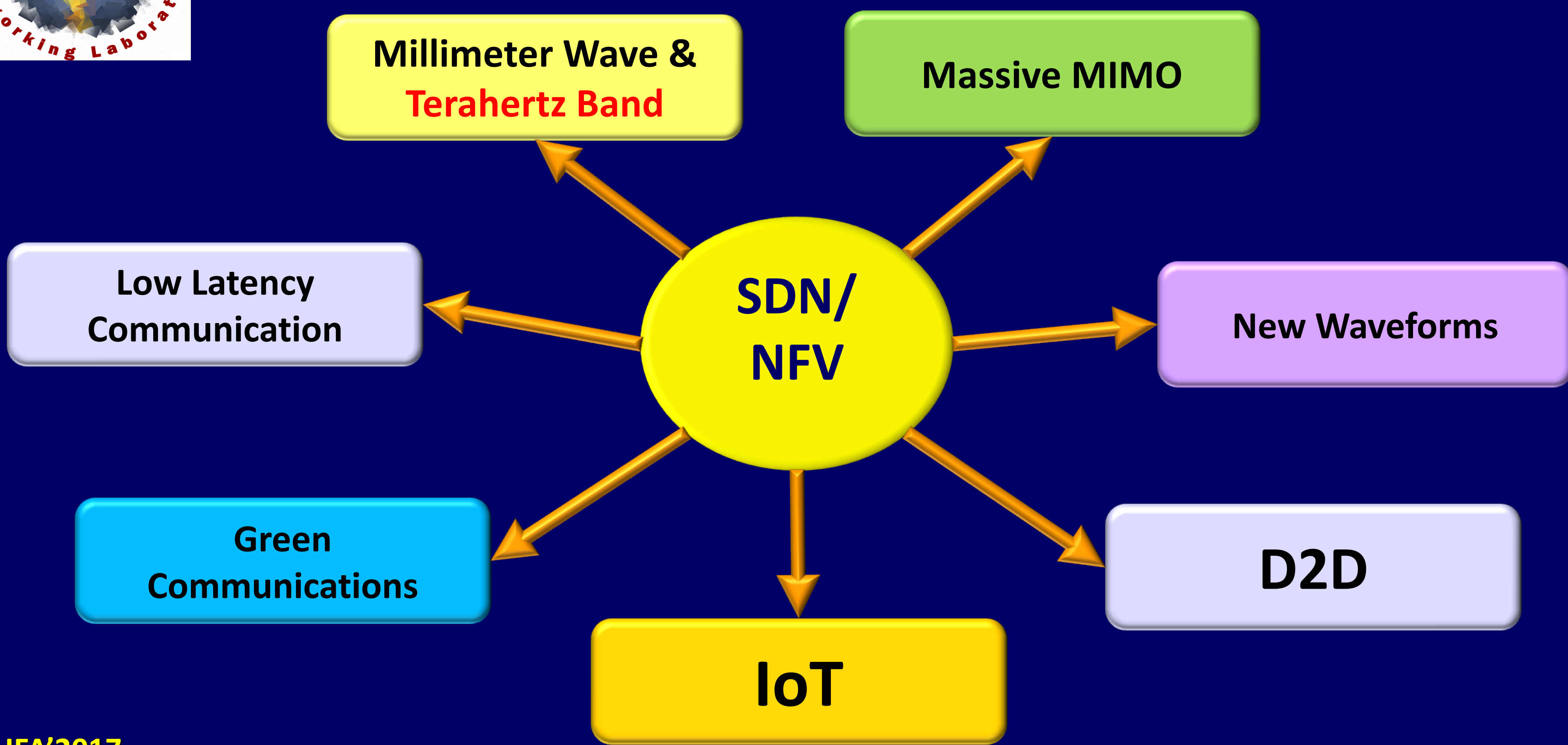
## CAN SDN/NFV BE USED AS THE FUNDAMENT FOR 5G WIRELESS SYSTEMS ??



# Challenges for mm-WAVE COMMUNICATION

- mm-Waves suffer from high spreading loss
  - Path-loss increases with the square of the frequency
- Transmission Distance
- Sparse-scattering radio patterns
- Blockage effect
- NLOS → path loss is too high for a reliable communication
  - Cannot continuously support good qualities at UEs via mm-Wave

## Challenges for mm-WAVE COMMUNICATION

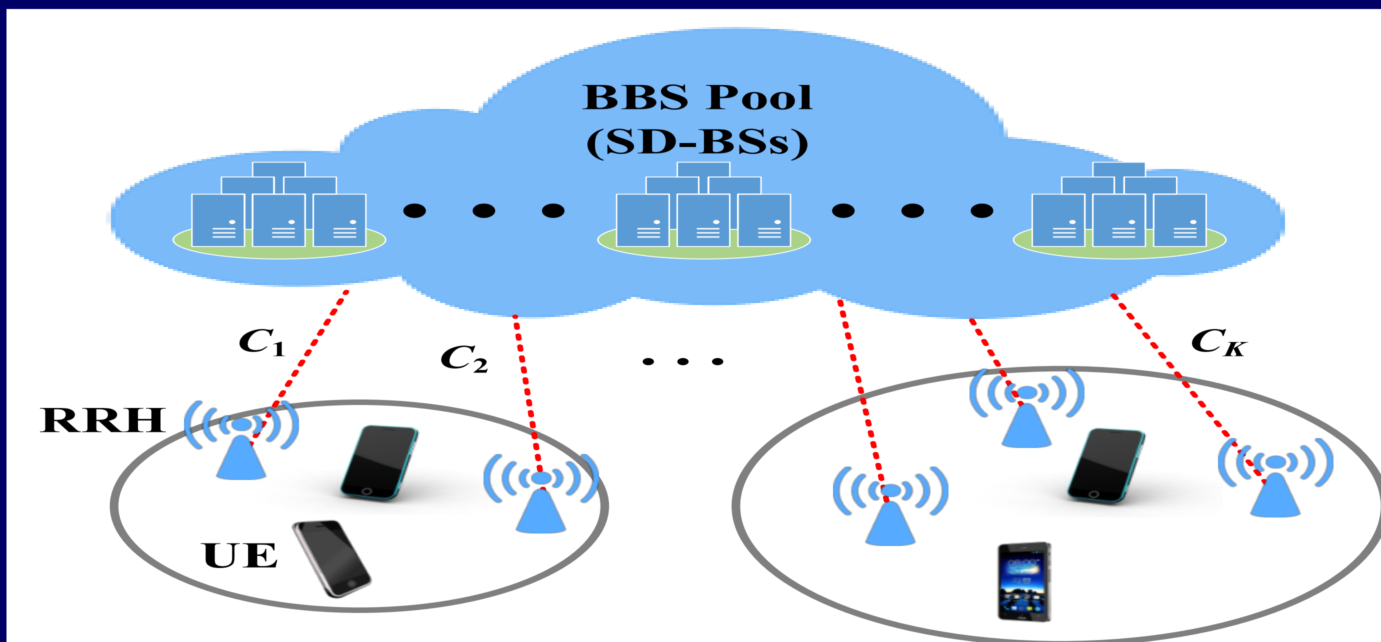
- **Dynamic Power Control Algorithm**
  - Channel condition varies largely
  - Signal strengths drop 15~40 dB from LOS to NLOS
- **Cell Search**
  - mm-Wave BS utilizes directional propagation for higher channel gain
- **User Scheduling and Congestion Control**
  - Multiple users in same cell
  - Collision avoidance

# mm-Wave: Softwarization

S.C. Lin and I. F. Akyildiz

Dynamic Base Station Formation for Solving NLOS Problem in 5G mm-Wave Communication

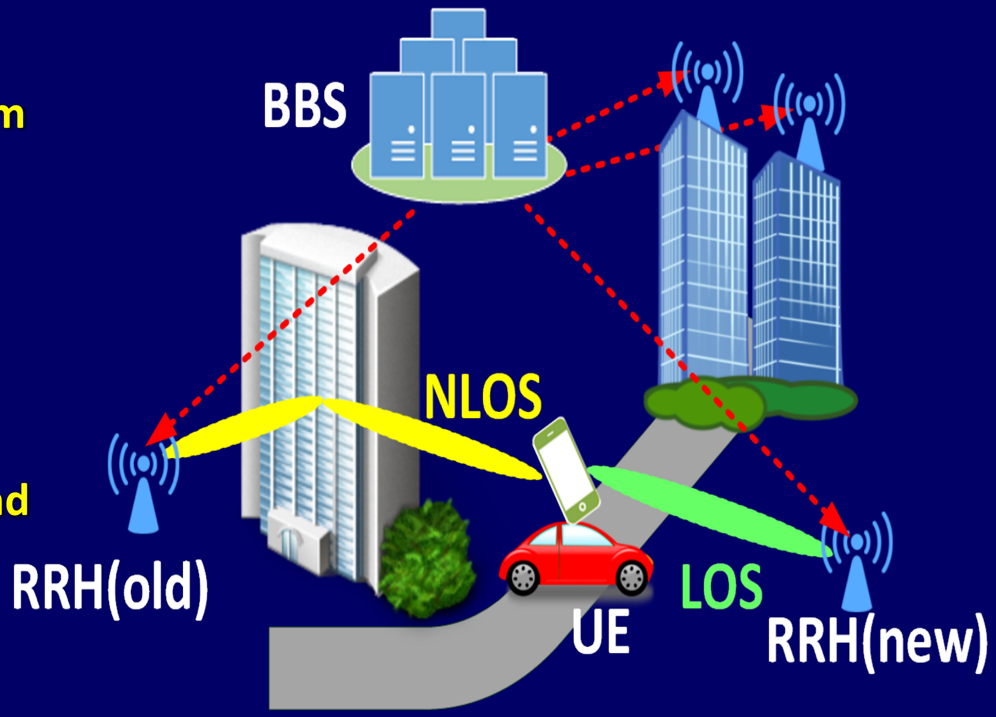
IEEE INFOCOM, May 2017.



# mm-Wave: NLOS Solution

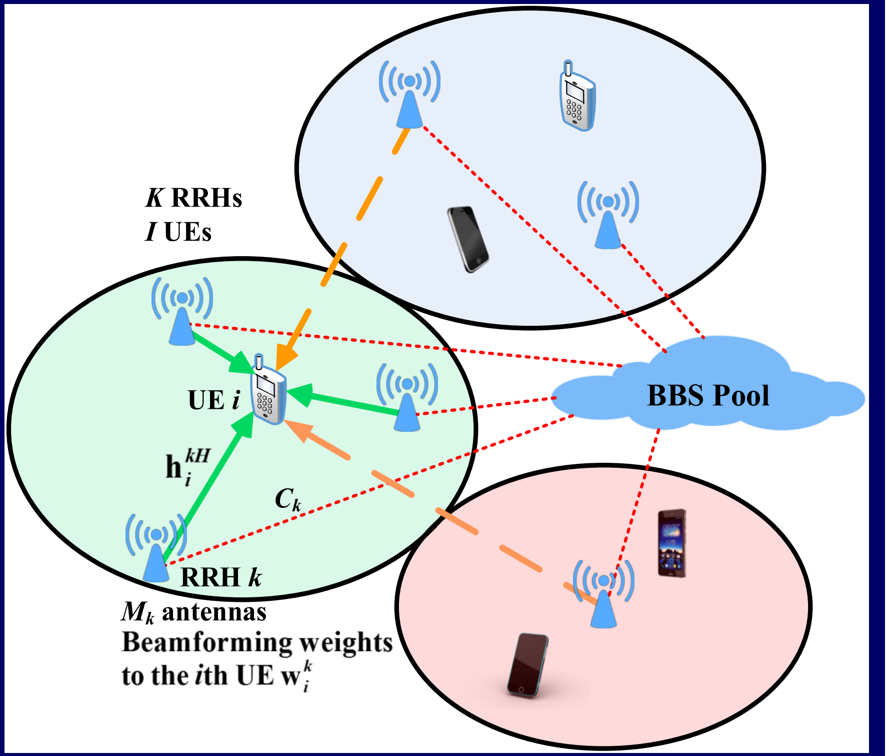
S.C. Lin and I. F. Akyildiz
"Dynamic Base Station Formation for Solving NLOS Problem in 5G mm-Wave Communication"
IEEE INFOCOM, May 2017.

- Softwarization can solve NLOS problem through efficient coordination of RRHs/antennas
- Form dynamic mm-wave BS
- Dynamic power control, scheduling and congestion control can be easily performed by the central controller



# CHALLENGES: DL mm-wave RRHs Transmissions

- **LOS:** No blockage between RRH and UE
  - Assume no beamforming alignment errors
- **NLOS:** RRH-to-UE link is blocked
  - Covariance matrix for small-scale fading: Similar to microwave case
- **Outage:** No link can be established as path loss between RRH and UE is so high
  - In practice, the outage implies the case when the path-loss in either a LOS or a NLOS state is sufficiently large (A more accurate model at mm-wave frequency)



# DYNAMIC BS FORMATION

S.-C. Lin and I. F. Akyildiz,
"Dynamic Base Station Formation for Solving NLOS Problem in 5G mm-wave Communication,"
IEEE INFOCOM conference, May 2017.

- **Ubiquitous mm-wave Coverage for UE mobility:**

  Support good channel quality in an entire geographic area

  SD-BSs (BBS pool) dynamically adapt hosting schemes of RRHs to always satisfy UEs' QoS requirements

**Objective**: Maximize the achievable user sum-rate

**Subject to**

- Users' QoS requirements
- RRH-user association constraints
- Fronthaul capacity constraints
- RRHs' beamforming weight constraints

System-level constraints

## OPTIMIZATION PROBLEM

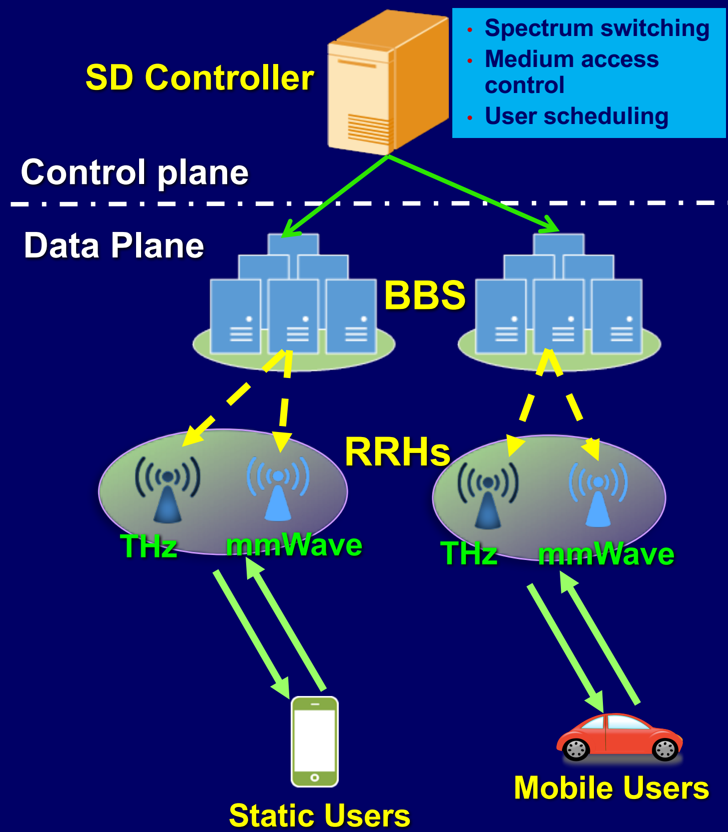
- NP-hard: Mixed-integer non-linear programming (MINLP)
  - Very difficult to compute global optimal solutions; even if possible, (little practical use)
- Conduct problem transformation => Successive Convex Approximation (SCA)
  - Propose SCA-based dynamic BS formation
- Evaluate in MetisX
- Results: Always support each UE with at least 500 [Mbps]

# THZ BAND COMMUNICATION

- mm-Wave bandwidth is still limited to 7 GHz
- Why not move to higher frequencies ?
- THz band: 100 GHz – 10 THz
- Provides incredibly huge bandwidths for short range
  - Can support 1 Tbps link over a distance of 1 m
- Channel has strong dependence on molecular composition
  - Presence of water vapor molecules

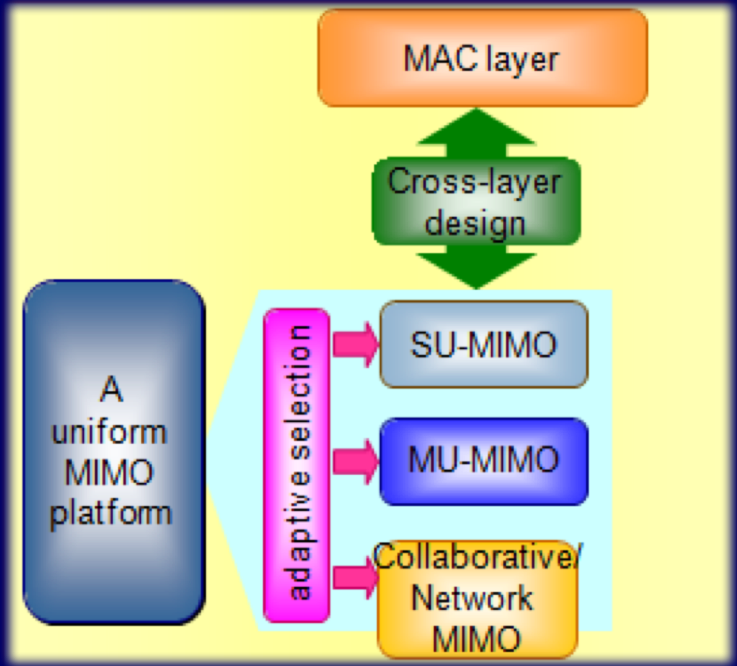
# THZ BAND: SOFTWARIZATION

- SD Controller for mmWave and THz
  - Dynamic spectrum switching between mmWave and THz for different throughput needs
  - Accommodate multiple users with different motions
  - Enhancement on overall throughput and channel gain



# MULTIMODE ADAPTIVE MIMO: RESEARCH CHALLENGES

- SU-MIMO for high peak rates
- MU-MIMO for average rate enhancement
- Collaborative MIMO for cell-edge user data rate boost

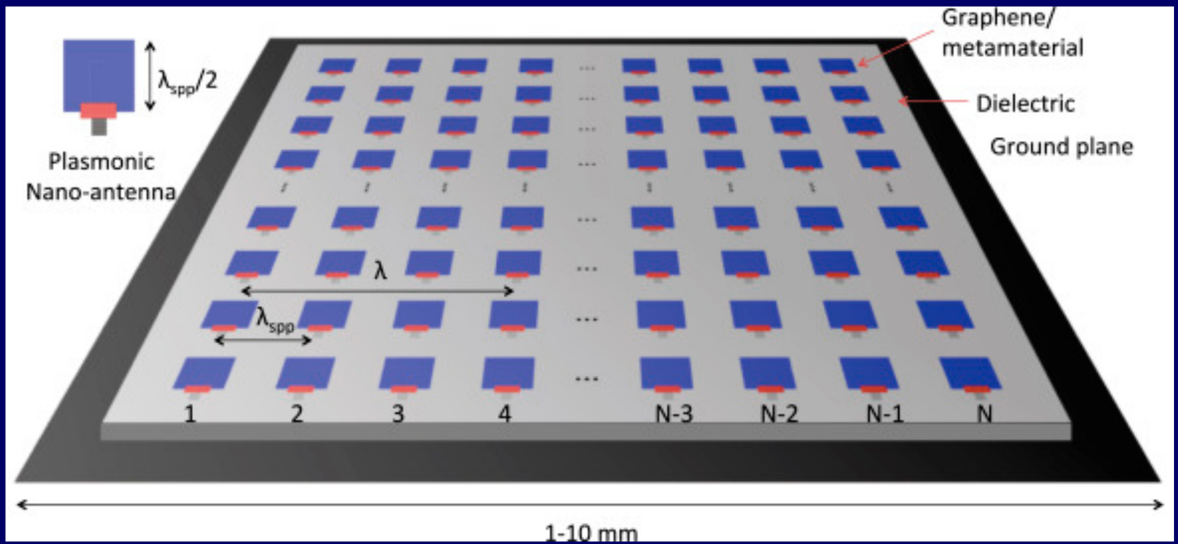


# ULTRA-MASSIVE MIMO

I. F. Akyildiz and J. M. Jornet

Realizing Ultra-Massive MIMO Communication in the (0.06–10) Terahertz Band
Nano Communication Networks, (Elsevier) Journal, available online March 2016;
Patent applied in February 2016; revised in July 2017.

- 1024X1024 Antenna Element Array
- Based on Graphene Nanomaterial



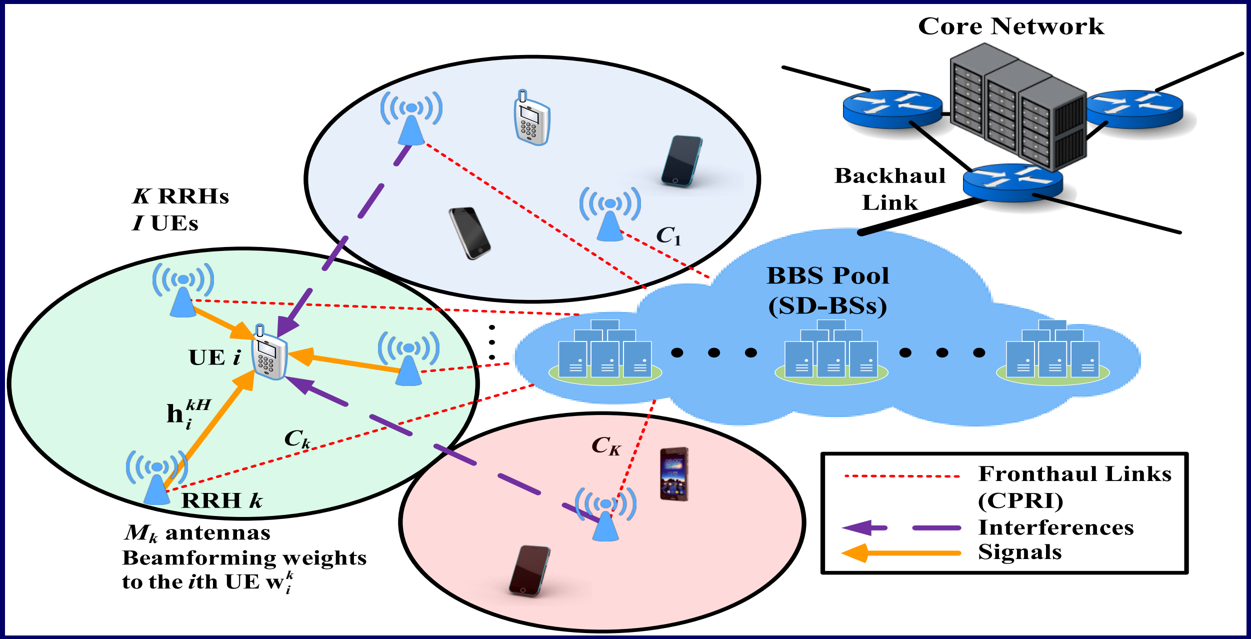

A square uniform plasmonic nano-antenna array

# MASSIVE MIMO: SOFTWARIZATION

S.C. Lin and I. F. Akyildiz

**Dynamic Base Station Formation for Solving NLOS Problem in 5G Millimeter-wave Communication**

IEEE INFOCOM, May 2017.



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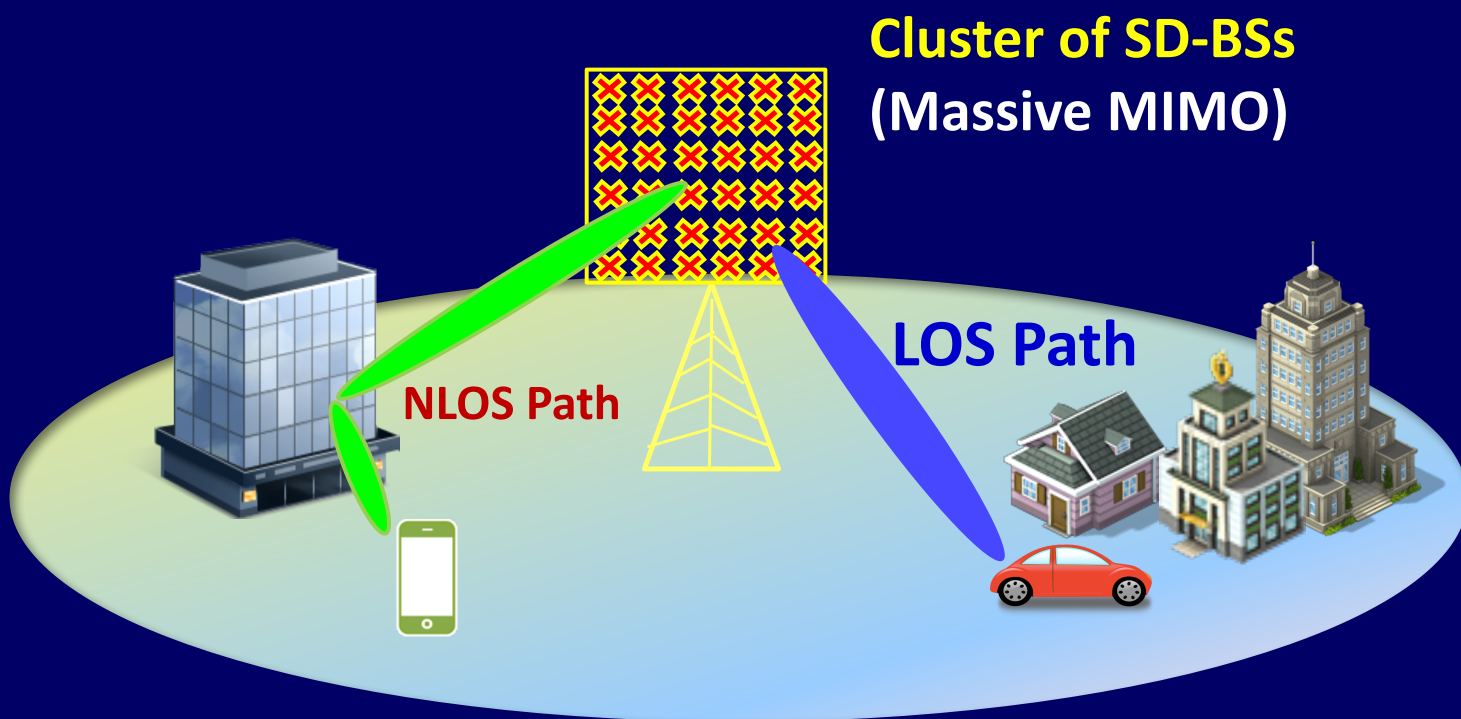


# NEW WAVEFORMS

- **Requirements:**
  - Low latency
  - High data rate
  - Compatibility with MIMO
  - Less Interference
    - Low out-of-band emissions
    - Less interference to other sub-bands
  - Loose or no synchronization
  - Power constraints
  - Support varying requirements of all devices
    - Ranging from IoT devices to UHD video streaming and tactile internet

# NEW WAVEFORMS PROPOSED

- Filtered OFDM
  - Incremental improvement over OFDM
- Filter Bank Multi-Carrier
- Non Orthogonal Multiple Access
  - Can be used in conjugation with any waveform
- Generalized Frequency Division Multiplexing
  - Widely studied
- Universal Filtered Multi-Carrier

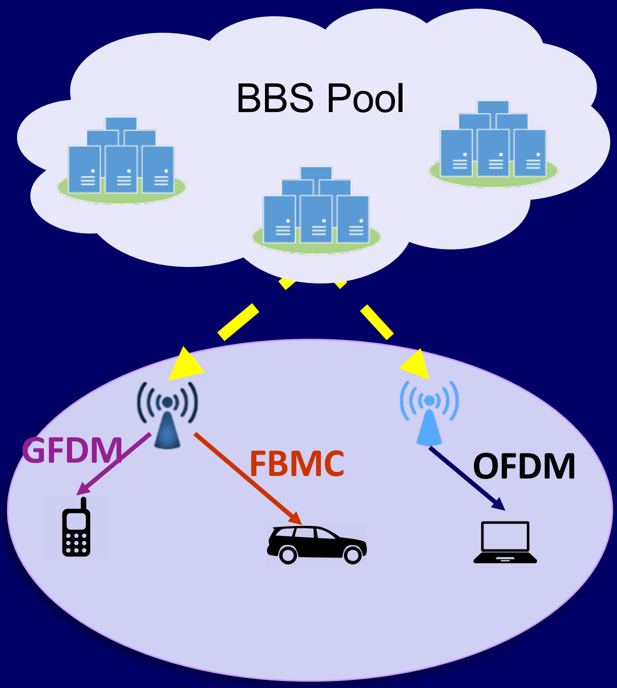
# PROPOSED WAVEFORMS: DRAWBACKS

- None of them meet all requirements of 5G
- Each has drawbacks in terms of interference, decoding complexity, robustness, etc.
- Further, they cannot support devices with varying requirements simultaneously

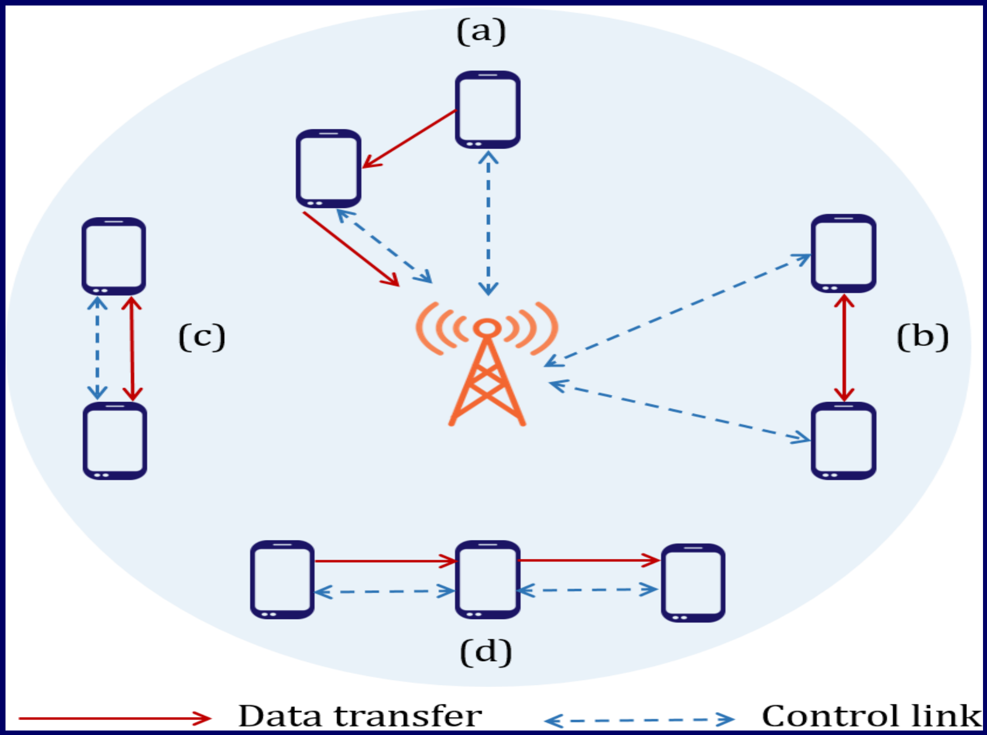
# WAVEFORMS: SOFTWARIZATION

- Requirements for 5G will be met by using a combination of multiple waveforms
  - Adaptively switching waveforms depending on requirements

- Easier to implement in SDN
  - Since demodulation is carried out in BBS, RRHs can easily adopt to new waveforms easily

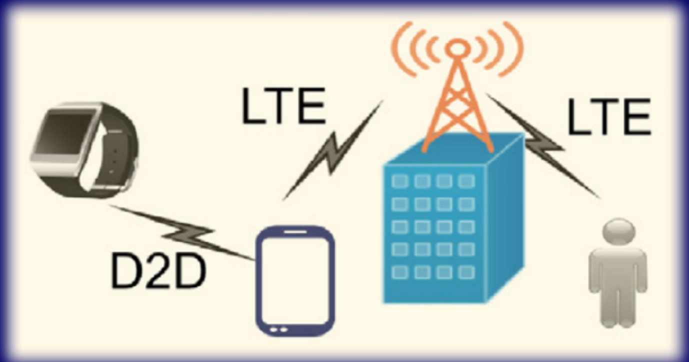


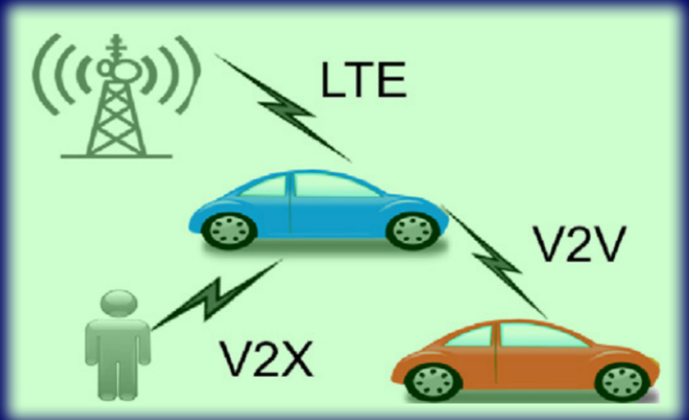
# D2D COMMUNICATIONS



# D2D: USE CASES

- Public Safety and Security
- Cellular Offloading
- Disaster Rescue and Relief Operations
- Vehicular Communications (V2V, V2X)
- Social Networking Applications
- Content Distribution
- Smart City



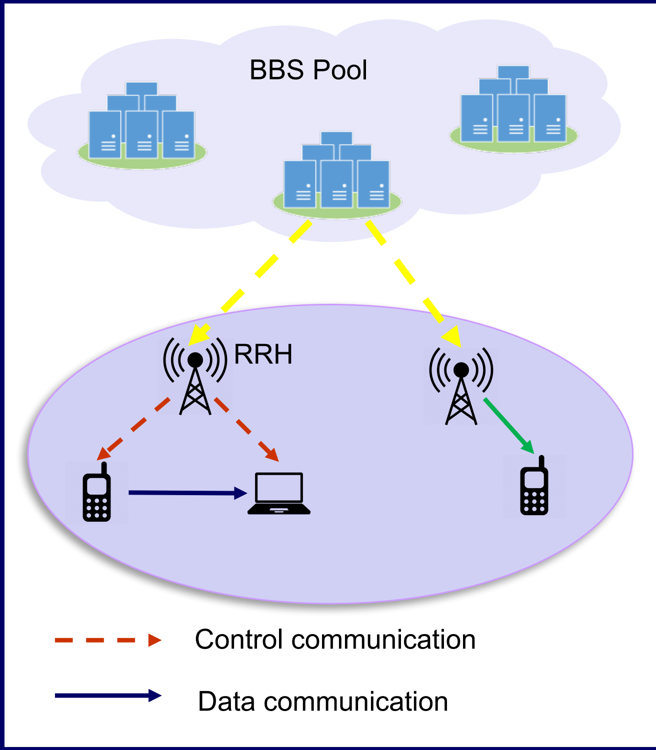



# D2D: OPEN PROBLEMS

- Resource management solutions (admission control, power allocation) for autonomous operation mode with no network/eNB intervention
- Spectrum sharing between D2D and cellular communications
  - Improve operation on licensed and unlicensed spectrum bands
- Challenge on interference management
  - Dynamic power control scheme is needed
- Distributed Device Discovery and Link Setups
- Security and privacy
  - Create “trusted” set of devices for relaying
- Pricing/Charging (Who will get charged?)
- Need global standardization on 5G D2D

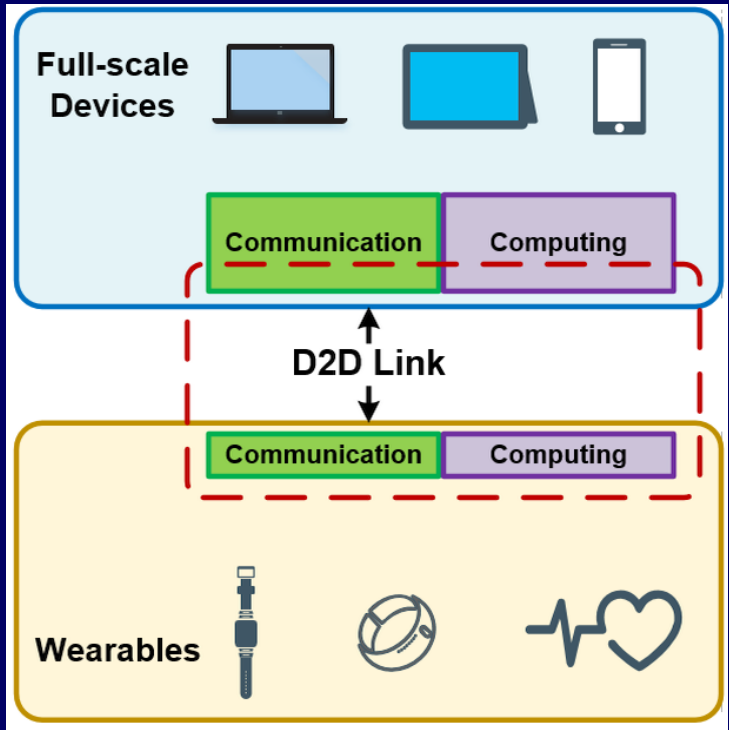
# D2D: SOFTWARIZATION

- SDN/NFV enabled V2X applications
  - Remote sensing and control
  - Cooperative collision management
  - Efficient vehicular traffic management
- Network slicing to support application-specific QoS requirements.
- Flow classification prioritizing emergency services
- Flow optimization and usage coordination of multi-link and multi-RAT
- V2X network planning augmented with big data analytics



# D2D: SOFTWARIZATION

- **Softwarization also enables the horizontal slicing paradigm**
  - Low power devices (e.g. wearables) establish direct link with full-scale wireless devices (e.g. cell phones, tablets, laptops, etc.)
  - Full-scale device slices out a portion of its computational resources, and reserves it for low power devices
  - Computational offloading occurs as low power device can now use resources of full-scale devices over the established link
  - End result: enhanced user experience with efficient resource utilization



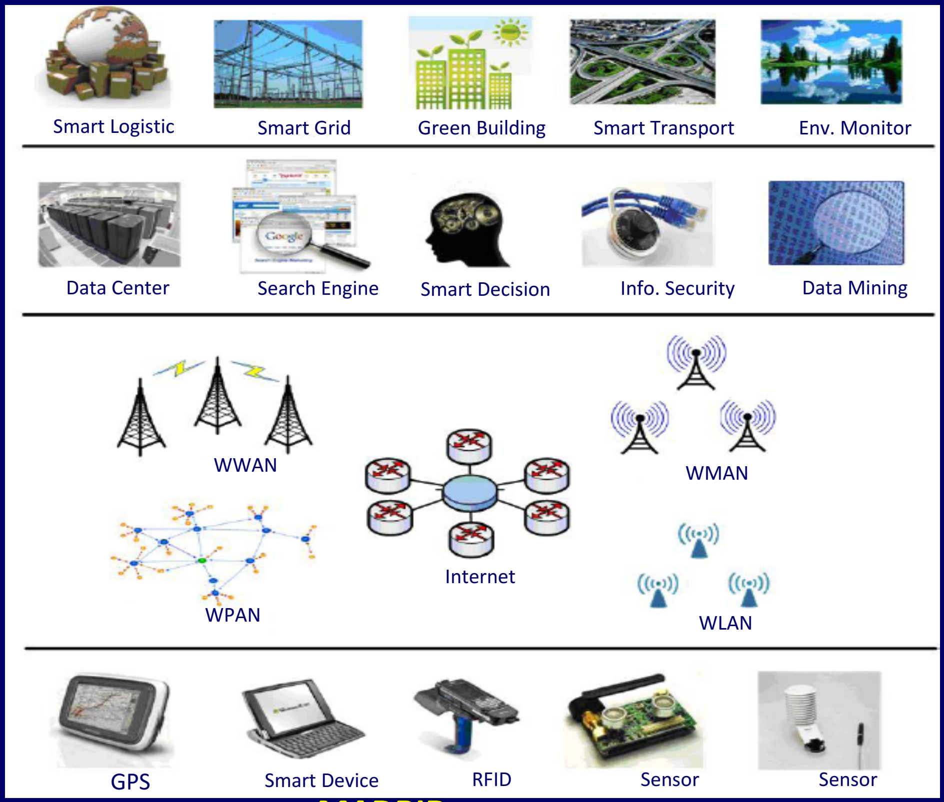
# IoT: 4 LAYERS MODEL

Integrated Application

Information Processing

Network Construction

Sensing and Identification



# IoT PLATFORMS ON THE MARKET

- GE Predix
- Cisco IoT Cloud
- IBM Watson IoT
- PTC ThingWorx

# GE PREDIX

- **Uses a platform as a service (PaaS) model and is a  cloud-based OS**

- **Built on Cloud Foundry, an open-source platform, and is optimized for secure connectivity and analytics at scale,**

  **both in the cloud and on the edge**

# IBM WATSON IoT

Cloud Foundry, Docker®, OpenStack®, Watson IoT Platform development

**Platform connects sensors to cloud applications using IBM Bluemix®**

# PTC® THINGWORX®

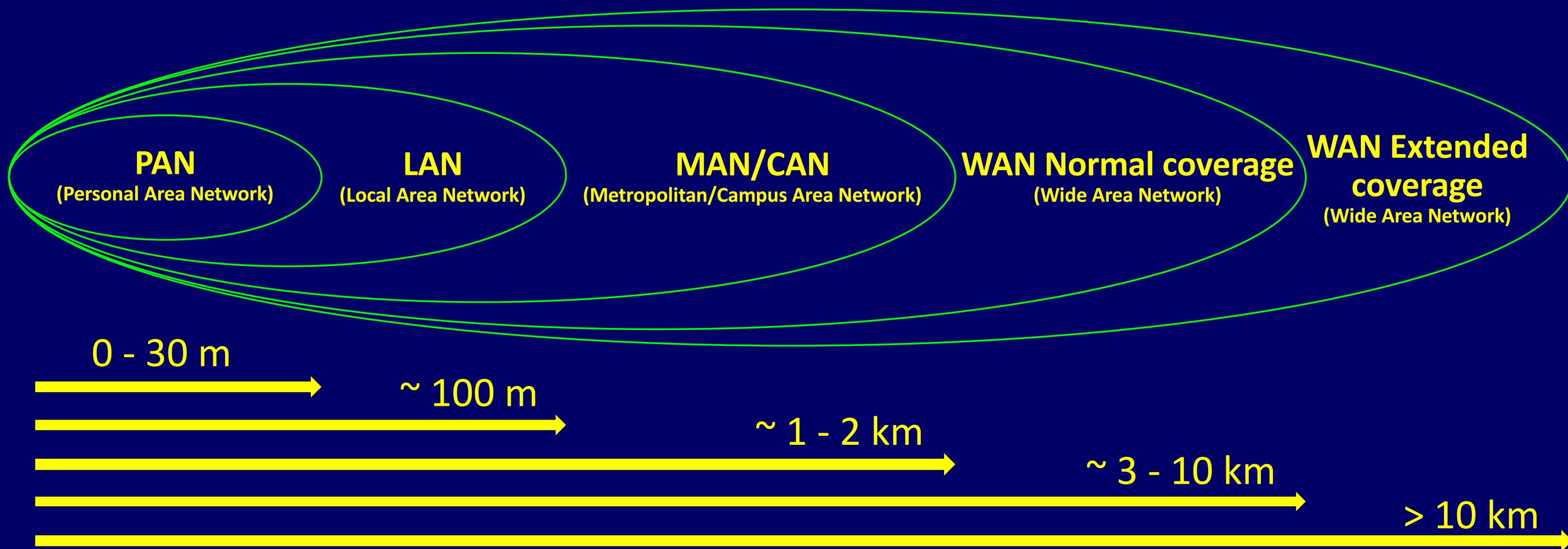
- **Three pillars of technology:**
  - **Core application enablement**
  - **Connection services with device and cloud adopters, and**
  - **Edge connectivity using the Edge MicroServer and Edge “Always On” devices**

**(27% market share)**

# IoT: CURRENT SOLUTIONS

LPWA Segment

| ZigBee, BLE, FeD2D | Ingenu, 802.11 ah | Cat 1, Cat 1 1RX | (F)eMTC, (e)NB-IOT Lora, Sigfox |
|---|---|---|---|

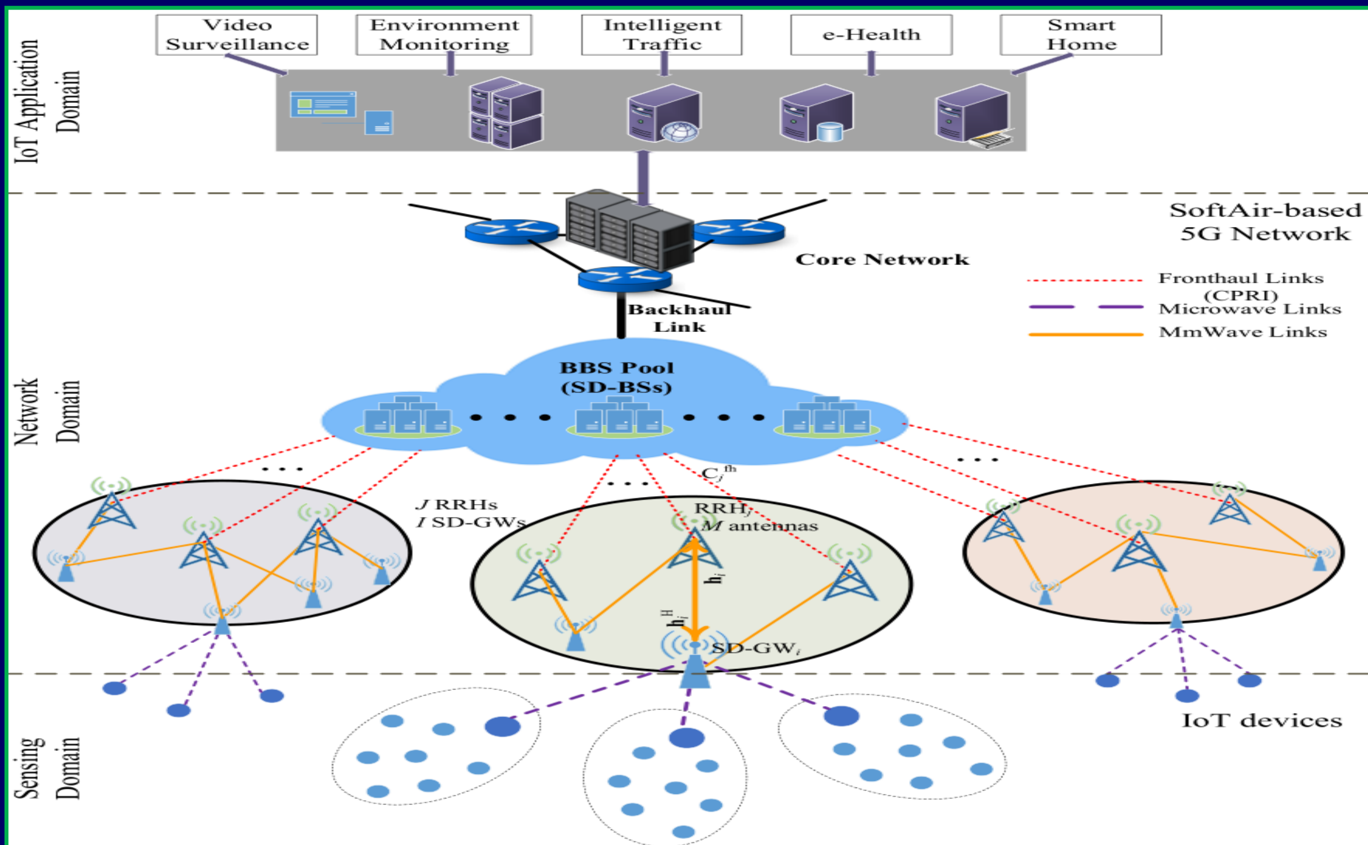



Disclaimer: the ranges are provided as a matter of example and depend on frequency, channel mode, line of sight etc.

# IoT CHALLENGES

- Scalability
- PROCESSING AND STORAGE (Big Data, Fog Computing, Aggregation)
- SIGNALING AND CONTROL OVERHEAD
- STANDARDIZATION
- Security, Privacy and Authentication
- Interoperability
- Power Consumption Problem

# SDN/NFV Based IoT



# SoftIoT: Framework

| SoftIoT Architecture | Distributed SoftIoT Controllers | SD Mgmt. & Orchestration |
|---|---|---|

**SoftIoT Architecture**

1. Scalability
2. Channel Characterization
3. NFV
4. Energy Efficiency
5. Low Latency
6. Security

**Distributed SoftIoT Controllers**

1. Optimal Mobile Controller Placement
2. Task-Resource Matching
3. Service Specification
4. Inter-controller Comm. & Sync
5. Flow Scheduling

**SD Mgmt. & Orchestration**

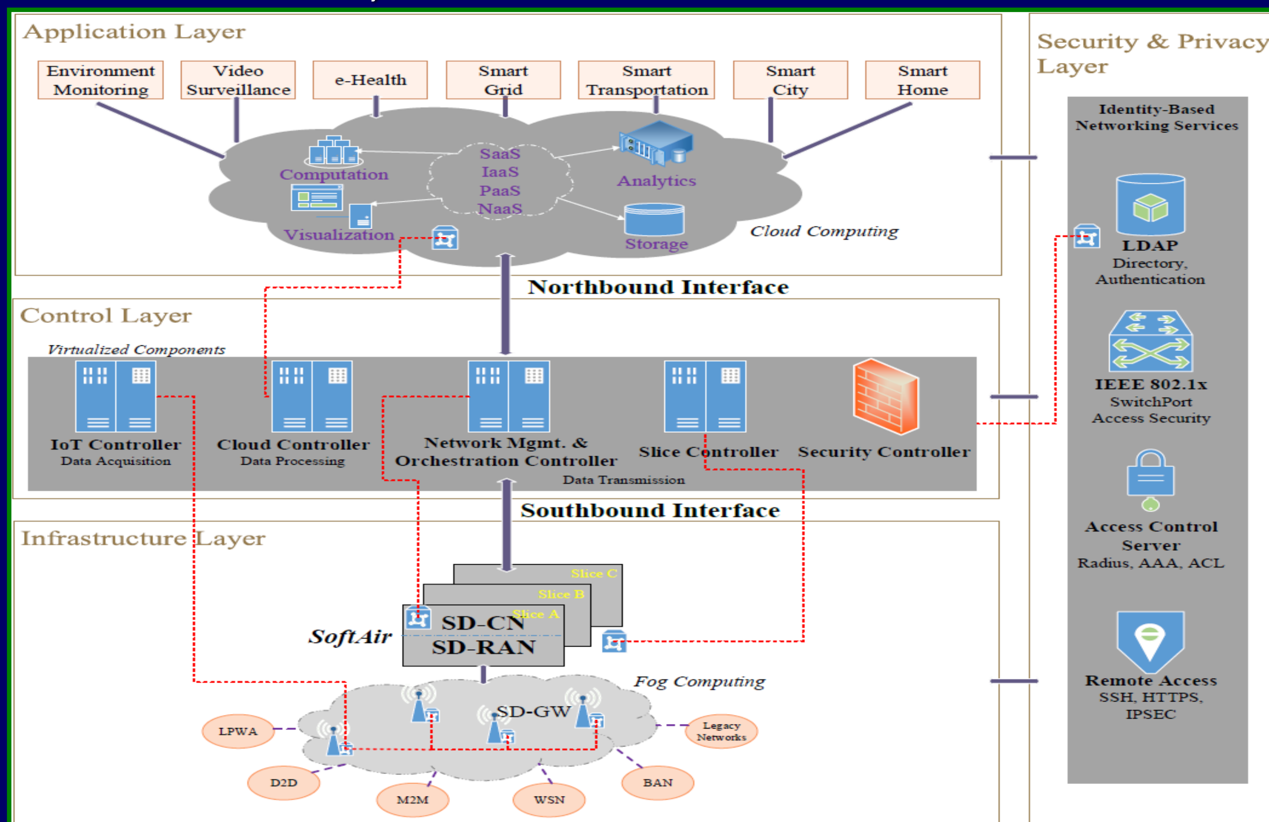
1. QoS Management
2. Traffic Engineering
3. Resource Management
4. Service Centric Analytics
5. Handover Mgmt. between controllers

# SOFTIoT: ARCHITECTURE

L. TELLO, S.C.LIN, I.F. AKYILDIZ AND V. PLA,

"SUM RATE ANALYSIS FOR IOT WITH 5G SOFTAIR ARCHITECTURE",

SUBMITTED FOR PUBLICATION, MAY 2017.



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