SDN for 5G Wireless Networks: Research and Standardization Directions

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Abhay Karandikar
Director
Indian Institute of Technology Kanpur, India
director@iitk.ac.in
karandi@ee.iitb.ac.in

Pranav Jha
Senior Research Scientist
Indian Institute of Technology Bombay, India
pranavjha@ee.iitb.ac.in

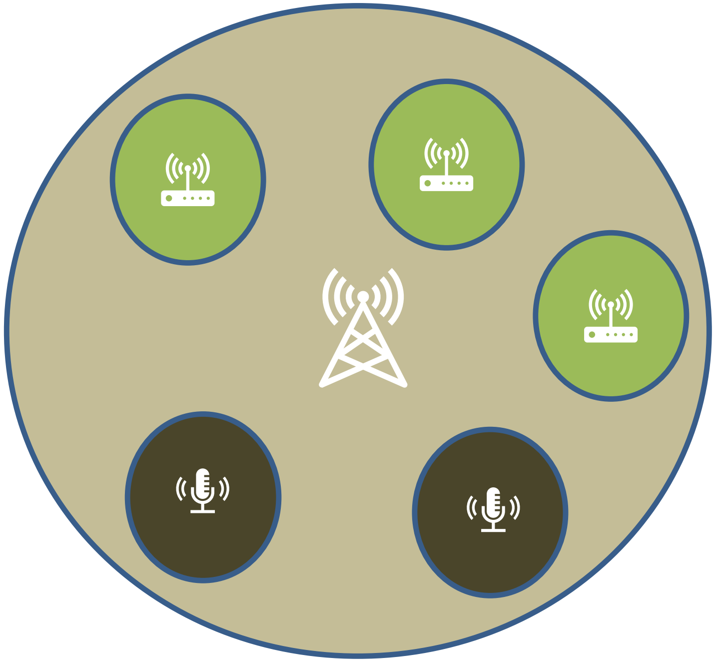
Agenda

- Mobile Networks – Moving towards 5G
  - Issues with existing mobile Networks - LTE and Public Wi-Fi Networks
  - Expectations from 5G Mobile Networks
- Introduction to Software Defined Networking
- SDN Architecture and Protocols
  - ONF, RFC 7426
  - OpenFlow, OF-Config, NETCONF
- Introduction to Network Function Virtualization
- Using SDN in Mobile Networks
  - Research Proposals
- Using NFV in Mobile Networks
  - Research Proposals
- 5G Standards and Protocols
  - 3GPP 5G Architecture and SDN & NFV (RAN and Core network)
  - 3GPP SDN Interfaces and Protocols – F1, E1, PFCP, NGAP
  - IEEE Standards – IEEE P1930.1
- Radio Resource Management and a Few Other Use cases

Mobile Networks – Moving Towards 5G

Mobile Network Landscape

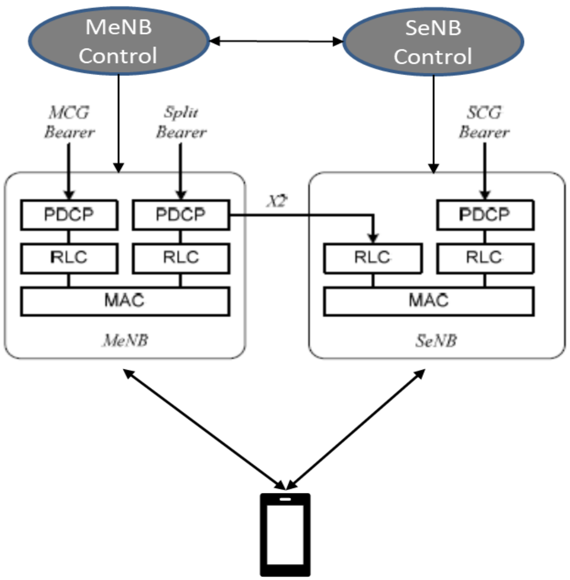
- Increased Network Densification
  - Heterogeneous Networks
  - Coexistence of Small and Large Cells
- Multi-RAT Networks
  - Different Radio Access Technologies exist together
  - LTE, WLAN, and 5G in near future
- RAN - Fragmented Decision Making
  - LTE eNBs, WLAN Access Points and Controllers and gNBs take decisions independently
  - Increased Complexity
    - Dual Connectivity – Complex Procedure
  - Suboptimal Resource Utilization
    - Load Balancing
  - ....

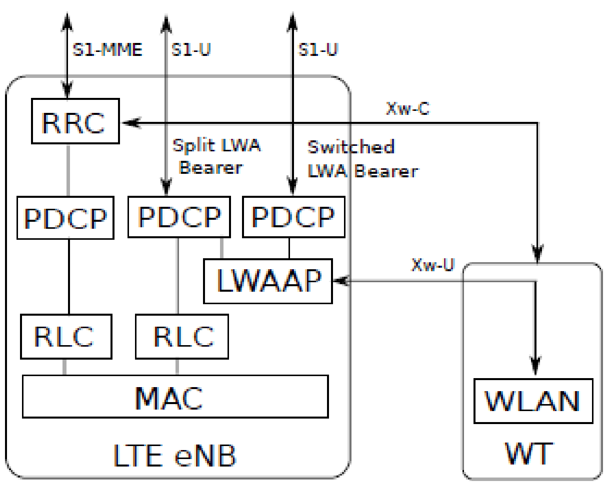


Dual Connectivity – An Example

- Heterogeneous Network (HetNet)
  - Macro cells overlaid with small cells
  - A solution to handle the increasing mobile data traffic
- Large no. of small cells in HetNet
  - Increase in no of handovers and handover failures
- Dual Connectivity
  - UE simultaneously connected to small & macro cells
  - Data transfer over both cells
    - Small as well as Macro cell
  - Control plane communication through Macro cell only
    - Reduces Handover Signaling and Handover Failures in Hetnet
  - Improves per-user throughput and system capacity

LTE Dual Connectivity Architectures



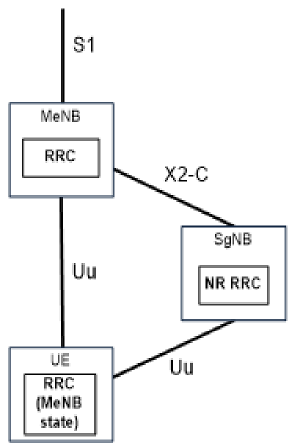


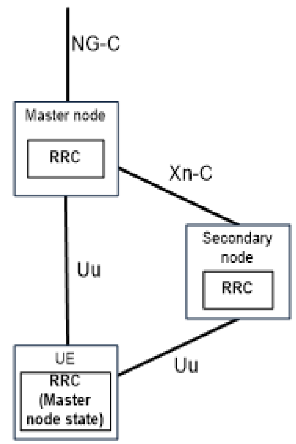
Courtesy : 3GPP TS 36.300 and TR 36.842

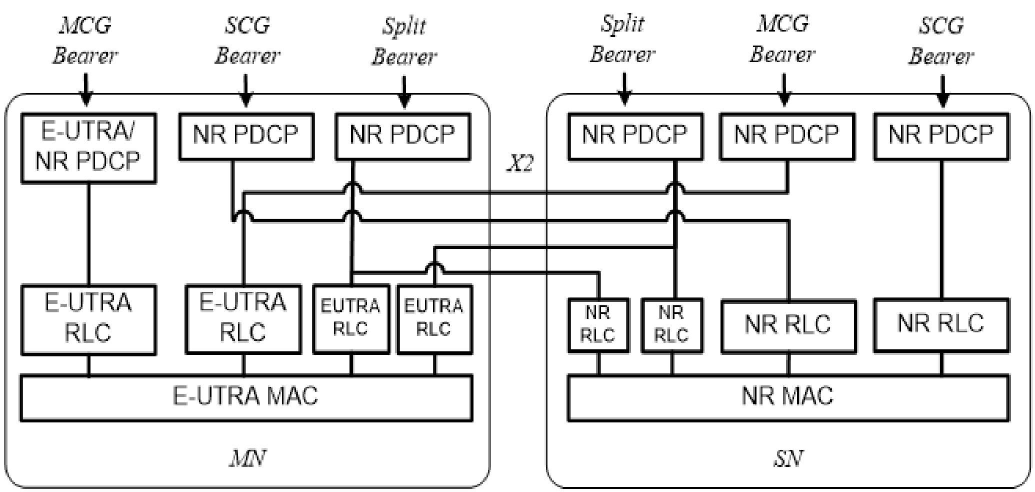
- LTE - LTE Dual Connectivity
  - A UE utilises Radio Resources provided by two eNBs
    - Master and Secondary eNBs
    - eNBs connected via a non-ideal backhaul over the X2 interface
- Control plane Communication
  - Through the Master Node
  - RRC located at MeNB
    - SRBs (SRB1 and SRB2) use the radio resources of the MeNB only
  - S1-MME located at MeNB
- User plane handled by MN, SN or both

- LTE-WLAN aggregation (LWA)
  - A Connected UE can utilize radio resources of LTE & WLAN both
  - configured by the eNB
- Similar to LTE DC
- Control plane Communication through eNB
  - SRBs use the radio resources of the eNB only
  - S1-MME located at the eNB
- User plane handled by eNB and WLAN both
- Two Schemes for data transfer
  - Split Bearer
  - Switched Bearer (similar to SCG bearer in LTE DC)
- One more variant - LWIP

5G Multi-Radio DC Architecture







Courtesy : 3GPP TS 37.340

- Generalization of the LTE DC to Multi-Radio Scenario
- UE utilises resources provided by two different RAN nodes
  - One providing NR access
  - Other one providing either E-UTRA or NR access
  - Connected via ideal/non-ideal backhaul
- Connected to either 4G or 5G Core
  - Through MN
- Three types of SRBs
  - SRB1 and SRB2 can be split across both MN and SN
  - SRB3 is through SN
  - Initial signalling through MN only

Dual Connectivity Issues with the Existing Architecture

- Disparate DC Mechanisms
  - Each DC mechanism is different from the others
    - LTE DC allows for SRB setup between MN and UE only
    - MR-DC allows for an additional SRB between SN and UE
  - Subtle differences in DC mechanism across RATs - Brings higher complexity
- Complex Control Plane Interaction
  - Radio Resources in each BS under the control of RRC at each eNB/gNB
    - Extensive coordination between MN and SN
  - MN and SN exchanges control plane information
    - to be shared with UE/CN
- Not all combinations of DC supported
  - DC between 5G NR and WLAN not yet supported
- Multiple mechanisms for WLAN interworking with 3GPP Network
  - WLAN Interworking with 5G Core through a new interworking function - N3IWF, TNGF
  - LTE WLAN Aggregation – Another mechanism for interworking
  - WLAN Interworking with 4G Core – through evolved Packet Data Gateway (ePDG)

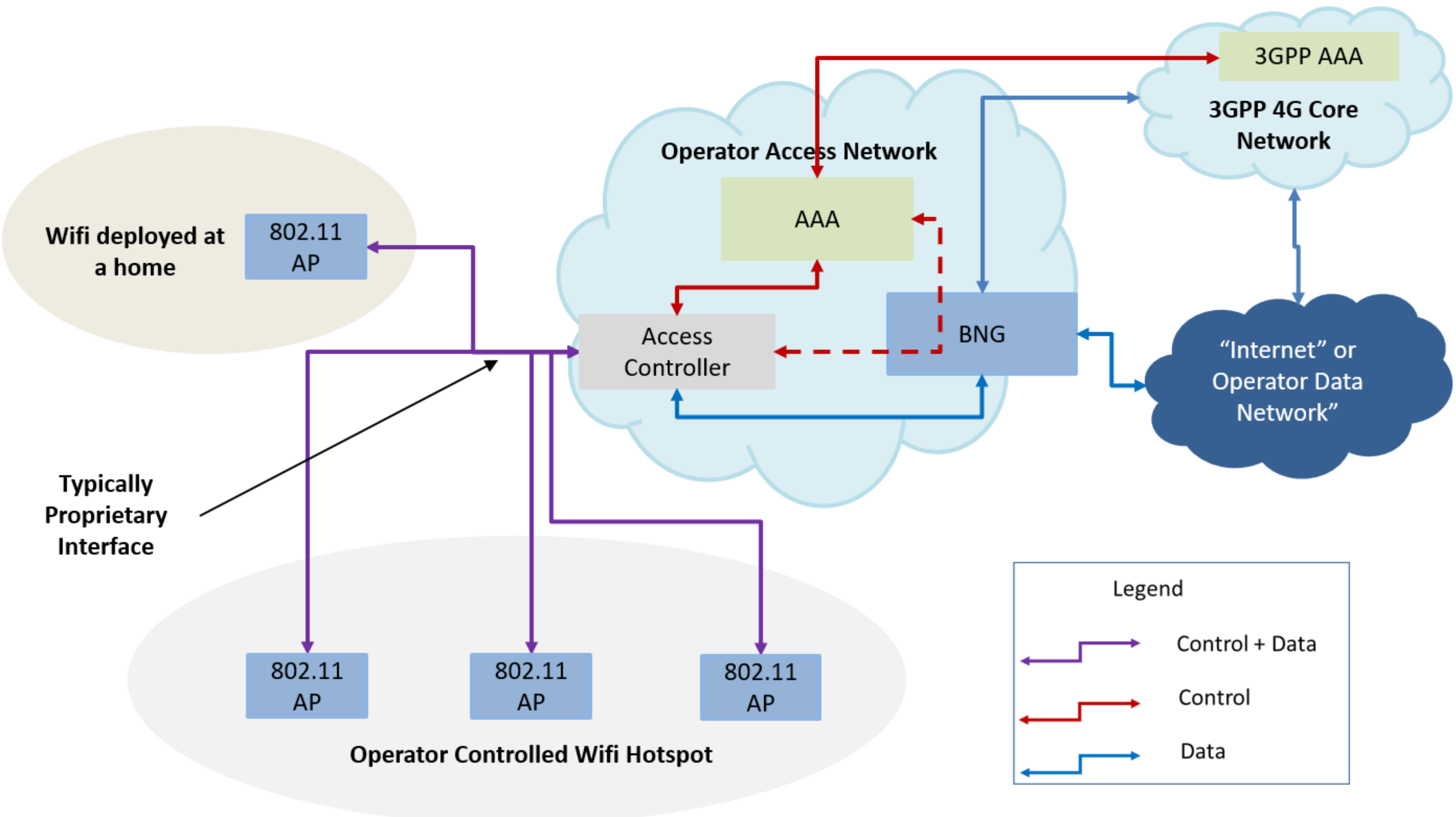
Load Balancing - Suboptimal Utilization of Resources

- Distributed scheme across eNBs (gNBs)
  - Load Information shared over X2/Xn
    - No Load Information in the absence of X2/Xn
  - No entity with a unified/global view of RAN resources
  - Load Balancing may not be very effective
- Load balancing across RATs even more difficult
  - Wi-Fi and eNB/gNB
  - (Though 3GPP is trying to build some mechanism)

WLAN Deployments Today

- Significant change in WLAN Deployment Landscape
  - Earlier WLAN deployments catered to enterprise networks
    - A single vendor enough to provide access to all users
  - Now large scale deployment of IEEE WLANs
    - Public Wi-Fi Networks being deployed by Operators
    - Typically Multi-vendor Networks
- Centralized architectures for Public Wi-Fi Networks
  - Most commonly used architecture
  - Centralized Controller, typically called Access Controller (AC)
  - Wireless nodes, Access Points (APs)
  - APs together with the AC support the IEEE 802.11 functions
  - Offers better manageability and control of the underlying RAN

Public Wi-Fi Network Architecture



Public Wi-Fi Network Architecture

- ACs manage, control, and configure the APs
  - Typically terminates the control and management traffic received from APs
- AC may also be an aggregation point for the data plane
  - AC may lie in the data path between the UE/AP and the external data networks, e.g., Internet
  - All types of traffic, i.e., control, management and data traffic from different APs may be aggregated at the AC
- AC could be connected to the AP
  - Over Layer 3 (Internet Protocol) or Layer 2 (Ethernet) interface
- Multiple ACs may be present in a network to support
  - Redundancy
  - Load balancing
- The distribution of functions/services across AP and AC may vary
- AC and AP Communication
  - Typically based on the CAPWAP or other similar protocols
  - CAPWAP - Control And Provisioning of Wireless Access Points Protocol
  - IETF RFC 5415 and RFC 5416

Public Wi-Fi Network Architecture

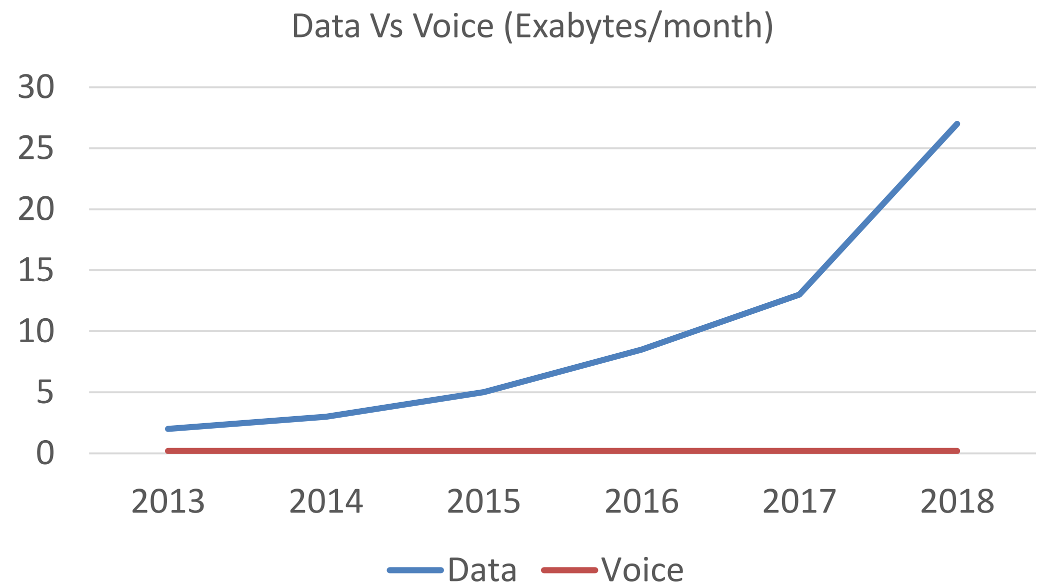
- AC forwards the UL data (from the UE) to Broadband Network Gateway
  - Further sent by BNG towards Internet/External Data Network
- DL data destined for a UE is received by the AC from the BNG
  - Forwarded towards the UE via the associated AP
- AC can be collocated with BNG
- AC communicates with AAA for subscriber authentication
  - Either directly or via the BNG
- Public Wi-Fi network may be connected to the cellular core networks
  - BNG connected to the existing 4G Core Network
    - Via the evolved Packet Data Gateway (ePDG)
  - AAA server in Public Wi-Fi network connected to 4G Core AAA server
    - For 3GPP based authentication of the subscribers
- Wi-Fi Network may be integrated with 3GPP 5G Core Network too
  - Non-3GPP Interworking Function
  - Trusted non-3GPP Gateway Function
  - Being defined as part of 3GPP's 5G specifications

Public W-Fi Network Architecture – Issues/Challenges

- Vendor Interoperability
  - No universally acceptable interface between AC and AP
    - or at least acceptable to a majority of the vendors
  - APs and ACs from different vendors do not interwork
- Non-interoperability of equipment slows down
  - Network Deployment
  - Network Upgrades
  - Introduction of new services
- No clear separation between control plane and data plane
  - Another Key Issue
  - AC not only a control plane entity, an aggregation point for data plane as well
    - Increased complexity of the Node
    - Independent evolution of Data Plane and Control Plane not possible
    - Throttles innovation, delays introduction of new services
- Such Centralized Architectures also RAT specific
  - Typically catering to IEEE 802.11 based networks only
  - No centralized RAN controller for, e.g., 3GPP LTE
    - RAN control functionality is embedded in individual eNBs
    - Though Management function may be centralized in an EMS/NMS System
- No unified architectural framework to describe Multi-RAT RAN
  - comprising of different RATs, e.g., IEEE 802.11, IEEE 802.22, 3GPP 4G-LTE, 3GPP-5G

Mobile Networks – Where is it headed?

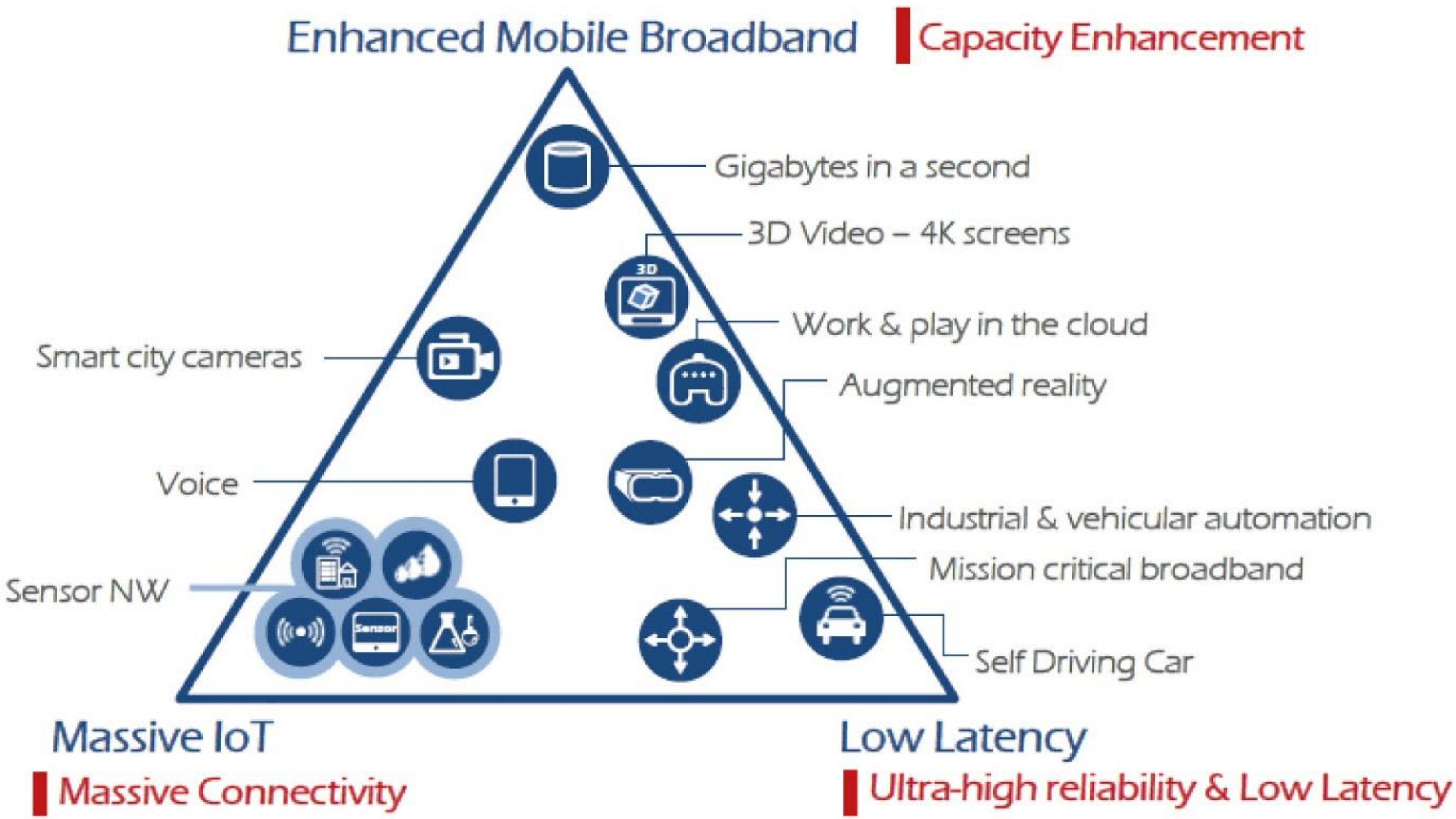
- Huge Growth in Mobile Usage
- 7.9 billion mobile subscriptions world-wide
- 6 billion mobile broadband subscriptions
  - Year-on-year growth of 15%
- Growth primarily in data traffic
- Lower ARPU



Mobile Network Evolution – From Voice to Data

Courtesy : Ericsson Mobility Report June 2019

What does growth in data traffic mean?

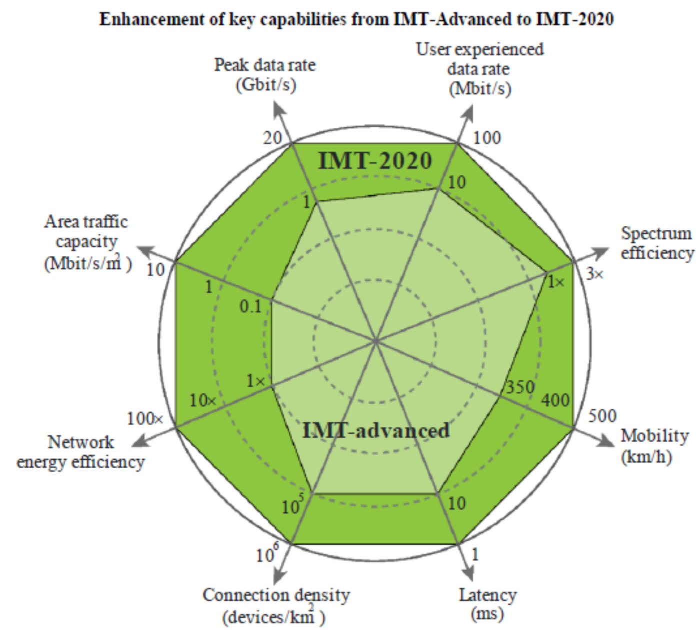


Application/Usage Diversity – A key need for 5G

Courtesy –ITU/IEEE

Usage Diversity and Network Capabilities

- Application/Usage Diversity
  - Variety of Business Customers - Automotive, Manufacturing, Public Safety, e-Commerce, Healthcare…
  - Flexibility
- Enhanced Network Capability over 4G
  - Higher throughput (peak as well as user experienced)
  - Lower Latency
  - High Connection Density
  - Enhanced Mobility
- Efficiency and Cost Reduction
  - Provide enhanced capabilities w/o increasing
    - Energy Consumption, Network Equipment Cost, Deployment Cost
  - Efficient Control and Management
  - Improved Performance



Courtesy –ITU

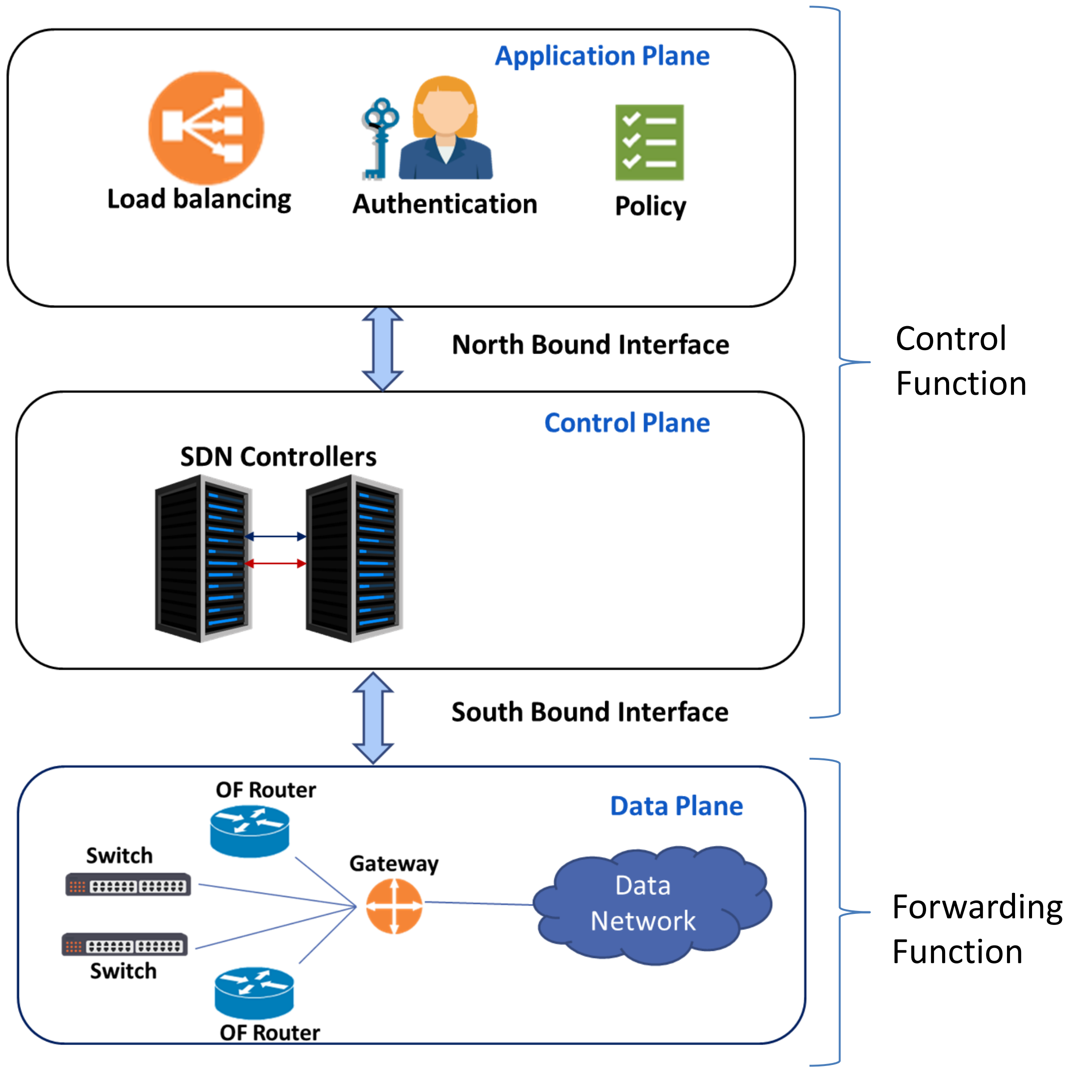
How do you address these Challenges?

A Short Detour

Software Defined Networking and Network Function Virtualization

Software Defined Networking (SDN)

- Network divided into two set of functions
  - Control Function
    - Programs forwarding elements
  - Forwarding Function
    - Responsible for Data Forwarding
- Functions separated through an open programmable Interface

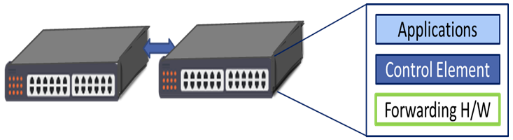


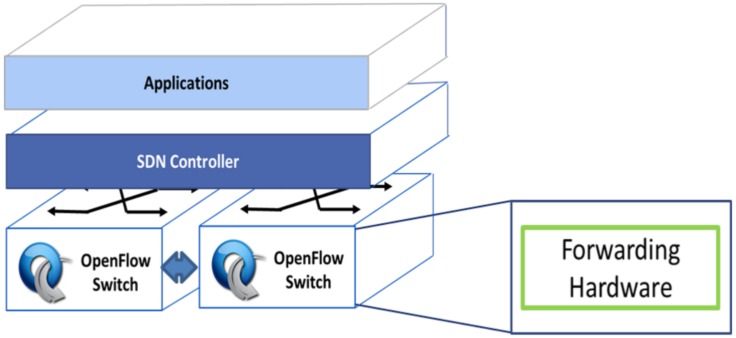
SDN Architecture

Traditional Networks vs Software Defined Networks

- Traditional Networks
  - Tightly coupled control and forwarding function
    - Proprietary Interfaces
    - Vendor Monopoly and Lack of Interoperability
    - Throttles Innovation
    - Independent innovation at constituent planes not possible
  - Distributed intelligence and state
    - Suboptimal decisions due to fragmented view
- Software Defined Network
  - Separation of control & data planes
  - Open, Standardized interfaces for the Controller to control/manage the data plane
  - Distributed Data Plane
  - Logically Centralized Control plane
    - Unified Control

Traditional Network





SDN based Network

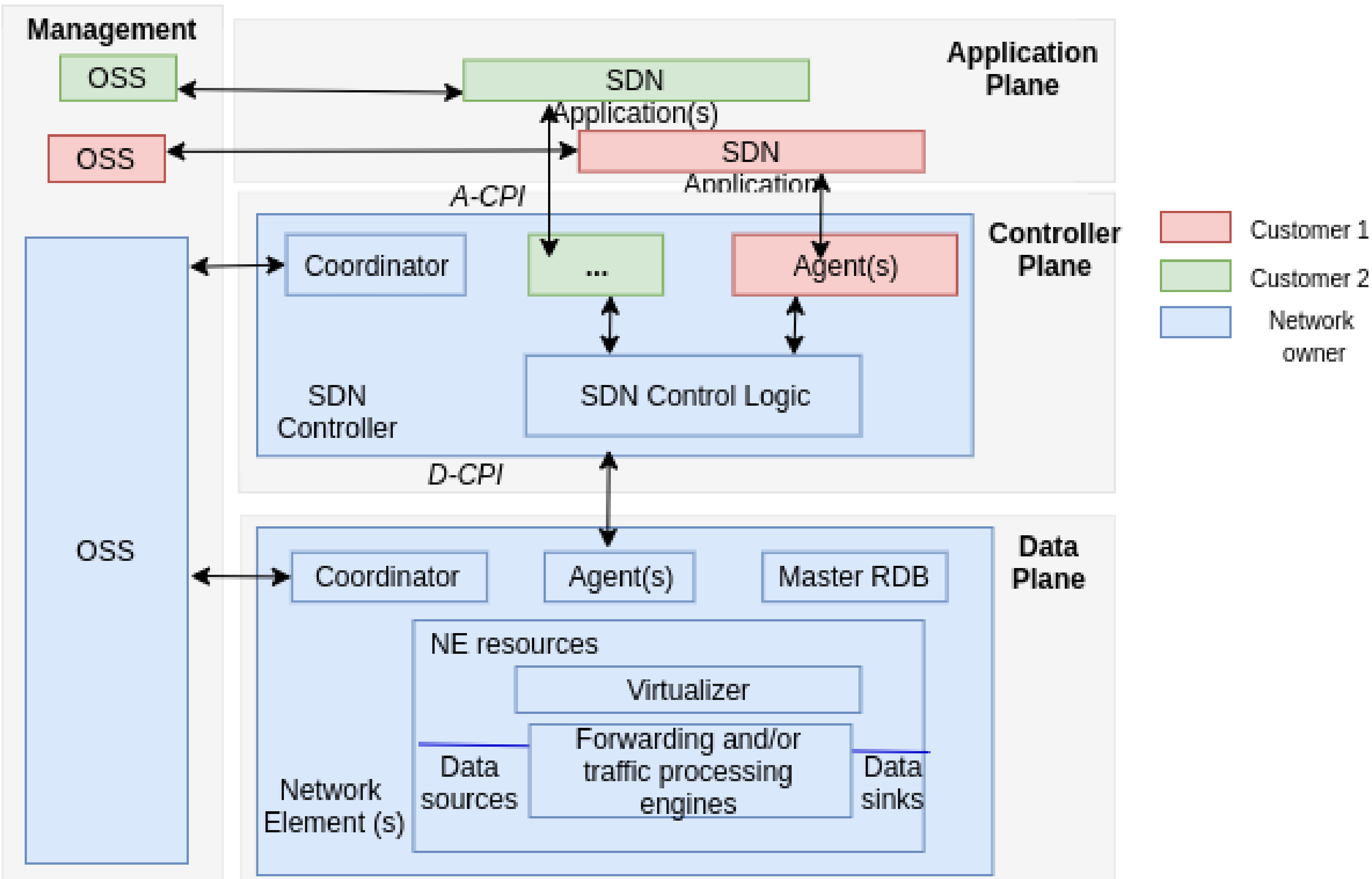
How does SDN help?

- Programmable Network
  - Application Provides policies, decisions to the Controller
    - Through North bound interface
      - e.g., REST based interface
  - Controller configures Forwarding Elements
    - Through South bound interface
      - e.g., OpenFlow, NETCONF
- Better utilization of network resources due to a unified global view of the network
  - Intelligence - logically centralized
- Easy introduction of new services, e.g., Dual Connectivity
- Independent evolution of all three planes
- Reduced cost of the network elements

SDN Architecture – ONF

- Architectural frameworks for SDN defined on similar lines by
  - Open Networking Foundation (ONF) and Internet Engineering Task Force (IETF)
- ONF Architecture
  - Management Plane
    - Responsible for allocating resources and configuring the policy decisions for a particular client or application
  - Application Plane
    - Consists of SDN applications that request certain services from the controller plane
  - Controller or Control Plane
    - A Group of SDN controllers
    - Configures the data forwarding and processing rules
  - Data Plane
    - Responsible for the actual data processing and forwarding of data/packets
- Two sets of APIs are defined
  - Using the controller plane as the reference
- The Interface between Application and Controller Plane
  - A-CPI or North Bound Interface (NBI)
- The Interface between the Controller and the Data plane
  - D-CPI or South Bound Interface (SBI)
- OpenFlow - A widely used protocol for the D-CPI

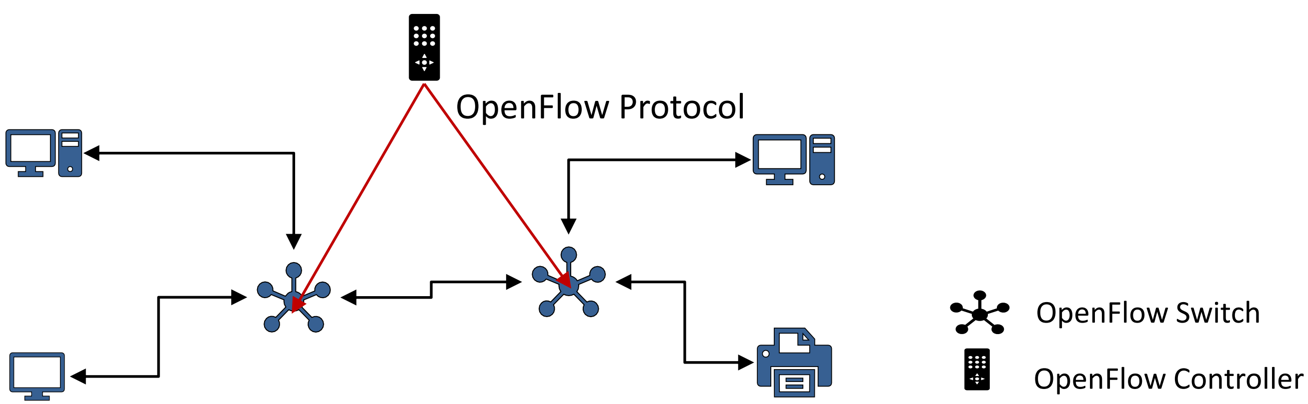
SDN Architecture - ONF

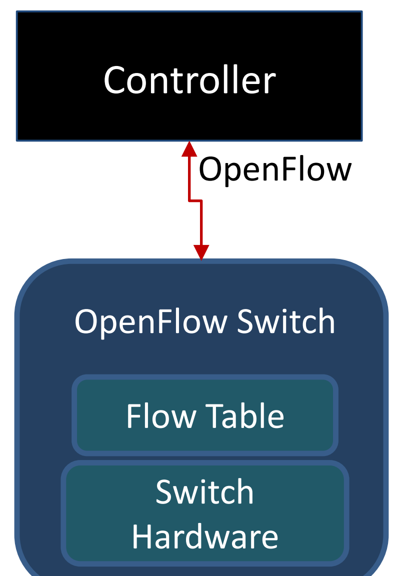


Courtesy –ONF

Some SDN Protocols - OpenFlow

- Goal
  - Creation of Virtualized Programmable Networks
  - Facilitate research and experimentation in campus networks
- Flow-tables
  - Most forwarding entities in Networks (switches/routers) has a flow-table
  - Identifies individual traffic flows
  - Helps in Routing, NATing, QoS, Firewall, Statistics Collection
- OpenFlow
  - A protocol between the Controller and the Forwarding Elements (Switches) in the Network
  - Enables a Controller to manipulate the flow-table in the switch





Courtesy: *Nick McKeown et al. "OpenFlow: Enabling Innovation in Campus Networks", Open Networking Foundation "OpenFlow Switch Specification"*

OpenFlow Switch

- The Switch performs actions, e.g.,
  - Forward the packets through a port
  - Drop packets
  - Forward Packets to the Controller for analysis and flow table configuration
- Supports OpenFlow Protocol
  - Enables exchange of commands and packets between a controller and the switch
  - an open and standard way for a controller to communicate with a switch
  - Uses a secure communication channel
- Has a Flow Table
  - Identifies individual flows with an action associated with each flow
  - Tells the switch how to process a particular flow

OpenFlow Switch

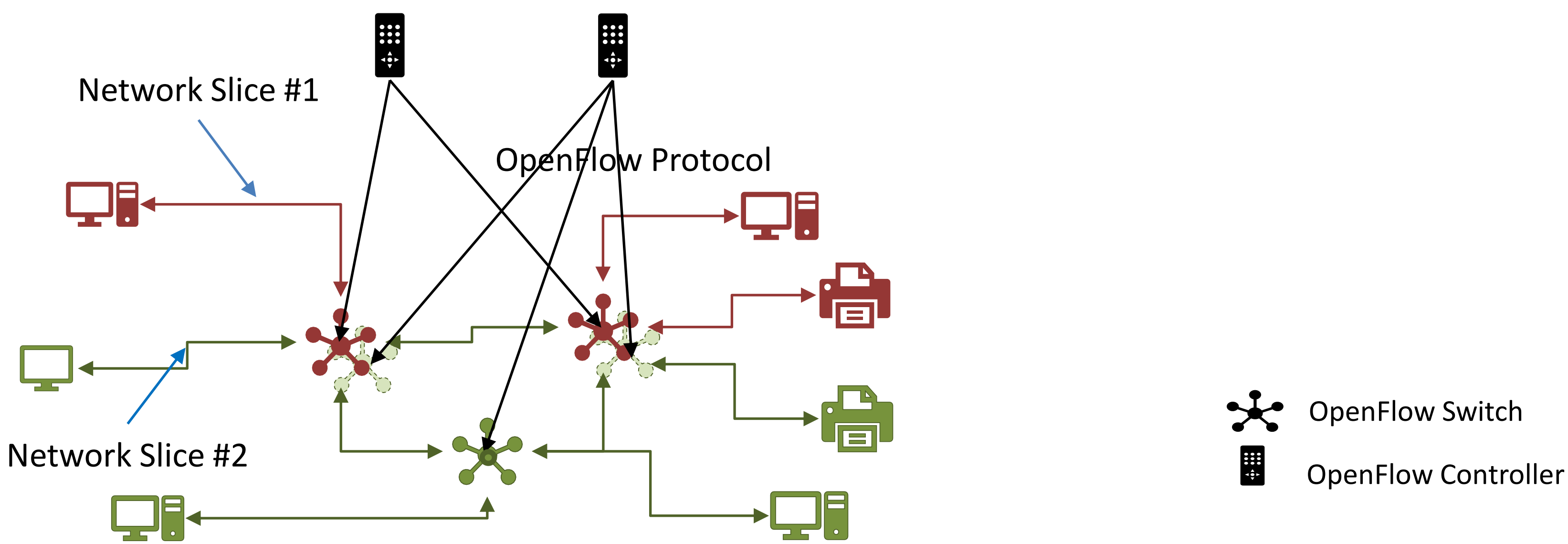
- A Flow Table entry has three fields
- A packet header that defines the flow, e.g.,
  - Packets belonging to a TCP connection
  - Packets for a particular MAC address or IP address
  - Packets matching a specific header
- An associated action, i.e., how the switch should process the flow packets
  - Output Action
    - Forward a packet to a specified OpenFlow port for egress processing
  - Group
    - Process the packet through the specified group
    - The exact interpretation depends on the type of group
  - Drop
    - Packets whose action sets have no output/group action are dropped
- Counters/Statistics
  - No of Bytes/Packets exchanged for the flow
  - Time since the flow is active/not active

OpenFlow Controller

- An entity interacting with the switch using the OpenFlow protocol
- Typically controls many OpenFlow Switches
- Adds, Modifies, and Deletes flow entries in flow tables of Switches
- Both Reactive and Proactive Establishment of Flows
  - Reactive Flow Establishment
    - A Switch forwards packets of a new flow to the Controller encapsulated in an OpenFlow message
    - Controller analyses the packets and decides to setup a new flow entry in the flow tables of the switches
  - Proactive Flow Establishment
    - Controller adds flow entries in the flow tables before the packets of a flow are received by the switches
- Static as well as Dynamic Flow Establishment
- May also configure the switch ports and other switch resources
  - Possibly through OpenFlow Management And Configuration Protocol
  - One can also use a protocol like NETCONF

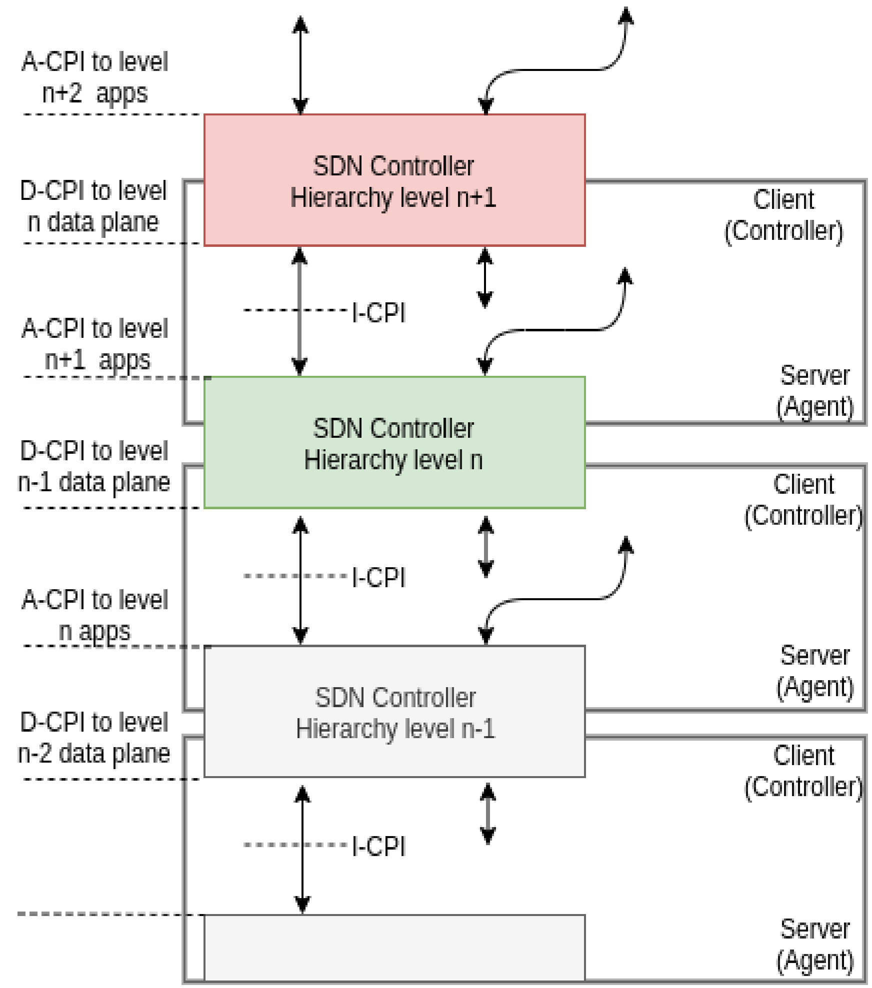
SDN and OpenFlow - Network Slicing

- Usage of flow-space as the network resource
  - Facilitates virtualization of the network
- Virtualization over Flow Space
  - Can be divided into sub-spaces with each sub-space representing a virtual network
  - The Switch can support virtualization through flow space splitting
  - Partition traffic into different sets of flows
    - Each set of flows - A separate Logical Network (Network Slice)
- Network Slice
  - Different Treatment, e.g., QoS
- Each Network Slice can be controlled separately



SDN and OpenFlow - Recursive Architecture

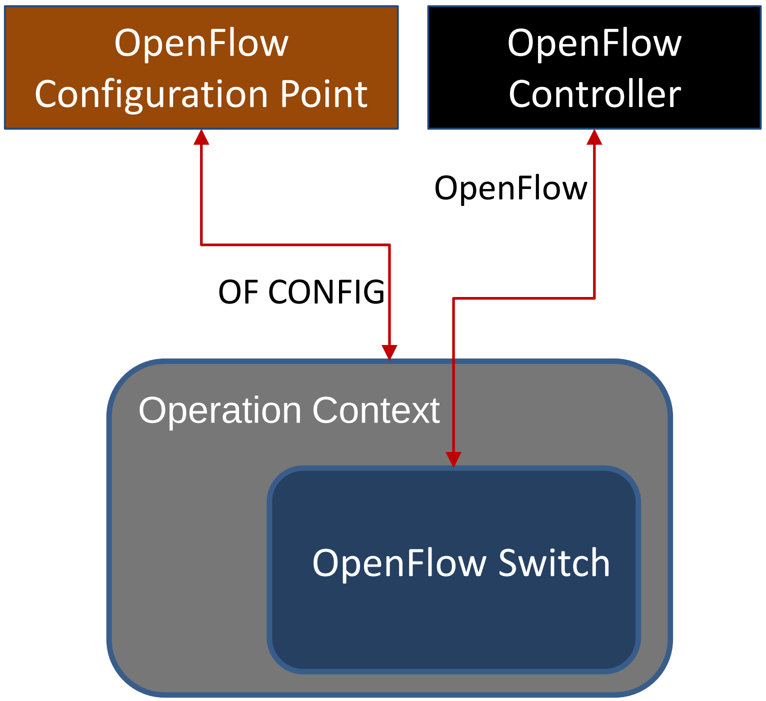
- SDN Controllers may be placed
  - In a recursive fashion for better scalability
- Recursion allows for
  - Applications to provide finer-grained services by combining multiple applications
- Higher level controller, e.g., at level “n + 1” appears to the lower level controller “n” as an Application
- The controller at level “n – 1” appears as Data Plane to Controller at level “n”
- Open Flow and Recursion
  - Division of flow-space into smaller sub-spaces can also lead to Recursive Network Architecture
- A Lower-level Controller
  - Divides the flow-space into sub-spaces
  - Maps these individual sub-spaces to independent virtual networks
- These virtual networks (sub-spaces) may be controlled by separate higher-level controllers
- Virtual network controllers can manipulate the corresponding virtual networks through OpenFlow protocol



Courtesy –ONF

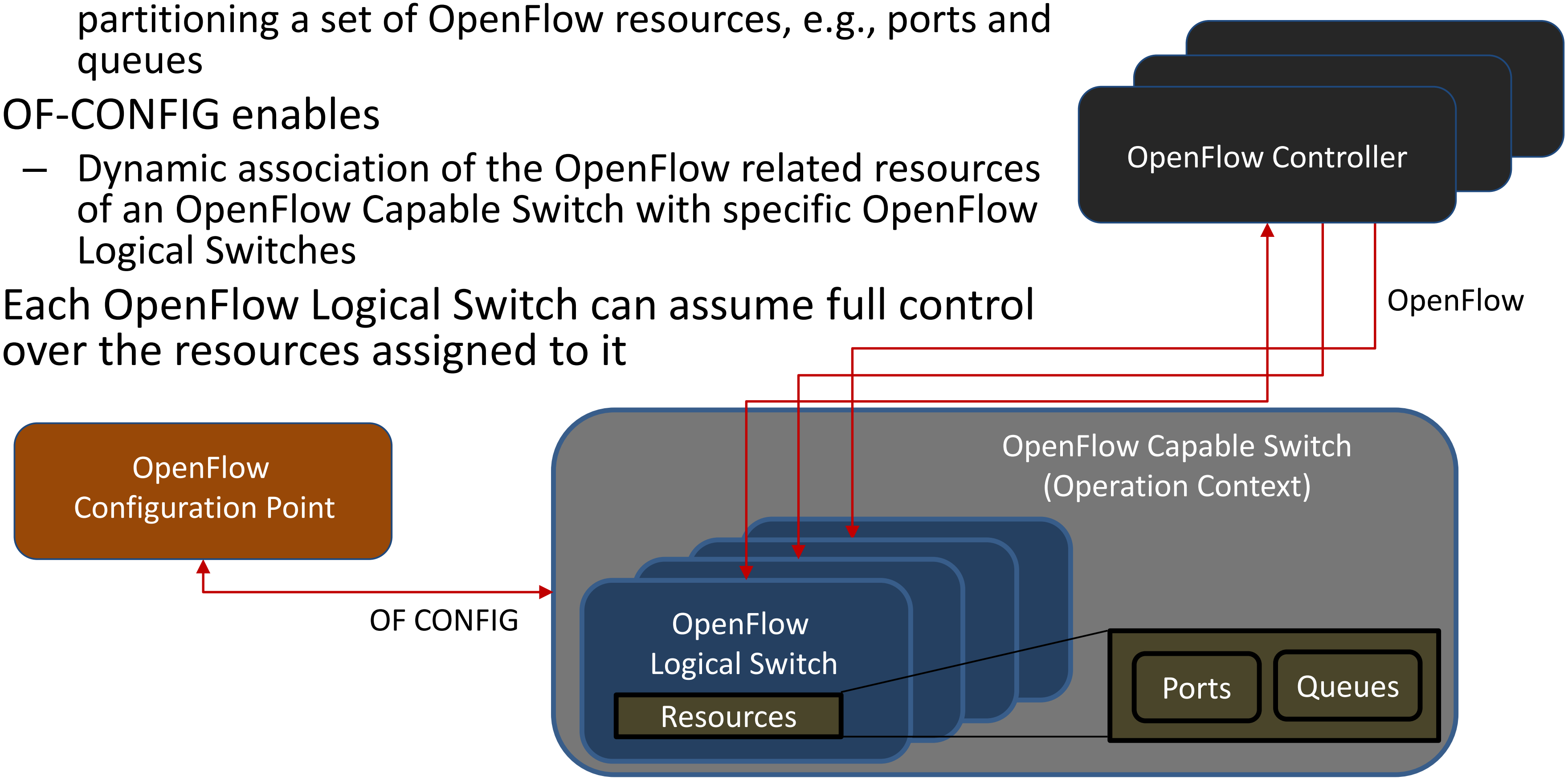
OF-CONFIG and NETCONF

- A Companion Protocol to OpenFlow
- OpenFlow Protocol assumes
  - OpenFlow switch already configured with relevant parameters
- OF-CONFIG - Configuration and Management Protocol of
  - An Operational context containing an OpenFlow Logical Switch
  - OpenFlow Logical Switch - An abstract OpenFlow Switch
- OF-CONFIG Configures an OpenFlow Logical Switch
  - Enables control of the OpenFlow Logical switch by a Controller thru OpenFlow protocol
  - Typically operates on a slower time scale than OpenFlow - Being a Configuration protocol
  - Uses Yang



OF-CONFIG and NETCONF

- OpenFlow Capable Switch
  - An Operating Context for one or more OpenFlow Logical Switches
  - Equivalent to an actual physical or virtual network element (e.g. an Ethernet switch)
  - Hosts one or more OpenFlow Logical Switches by partitioning a set of OpenFlow resources, e.g., ports and queues
- OF-CONFIG enables
  - Dynamic association of the OpenFlow related resources of an OpenFlow Capable Switch with specific OpenFlow Logical Switches
- Each OpenFlow Logical Switch can assume full control over the resources assigned to it



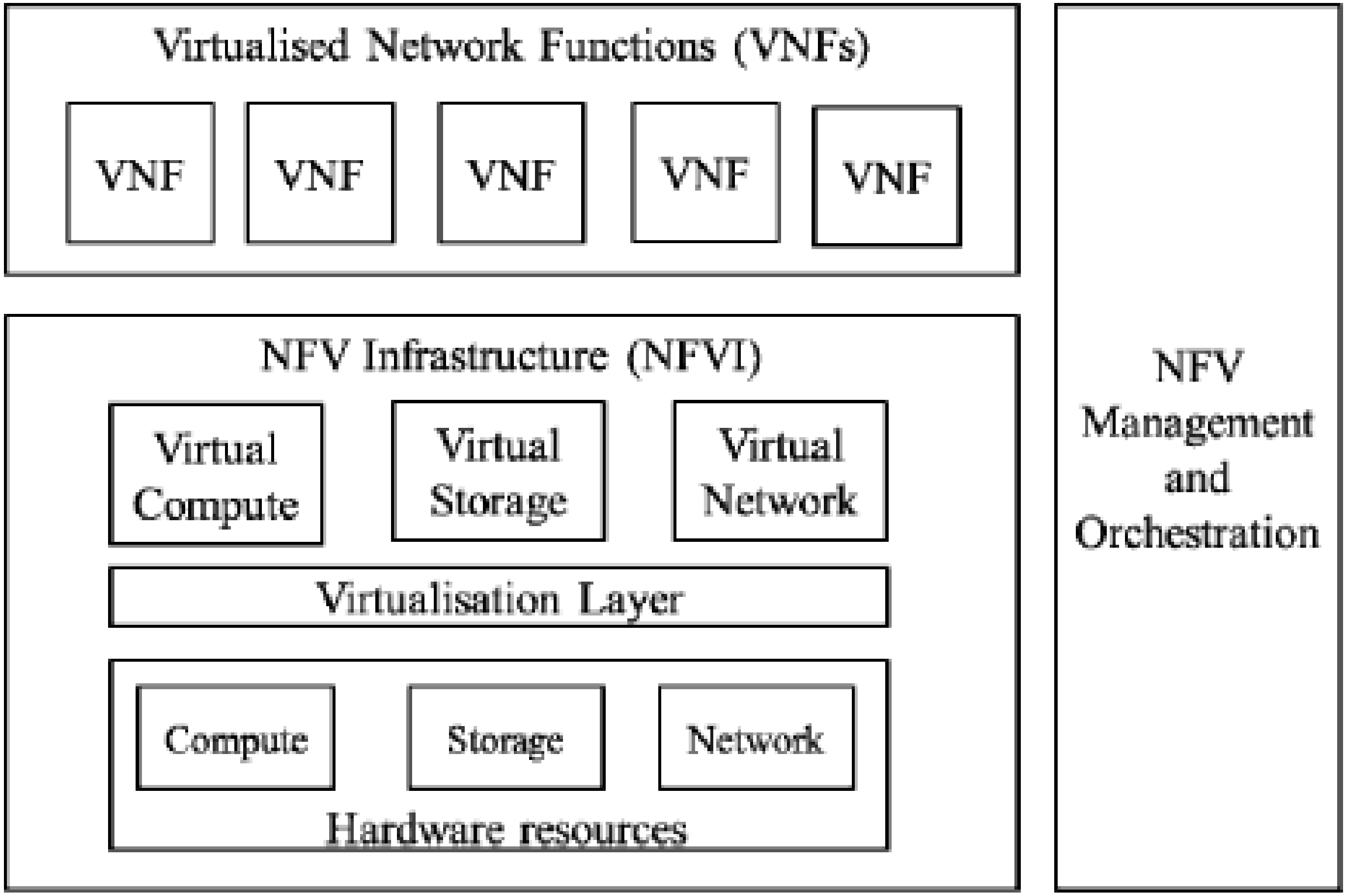
OF-CONFIG and NETCONF

- OF-CONFIG uses NETCONF as the underlying Transport
- NETCONF
  - IETF RFC 6241
  - Provides mechanism to Install, Manipulate, and Delete the configuration of network devices
- Uses an XML-based data encoding for the configuration data as well as the protocol messages
- YANG Modelling Language
  - IETF RFC 6020
  - For specifying NETCONF data models and protocol operations
- Operates on top of Remote Procedure Call based messaging layer

Network Functions Virtualisation

- Network Function (NF)
  - A Functional block within a network infrastructure
    - well-defined external interfaces
    - well-defined functional behaviour
  - Typically a network node or a physical appliance : eNB/gNB, MME/AMF, SMF, UPF/PGW
- What is Network Functions Virtualisation (NFV)?
  - Separation of Network Functions from the Hardware
    - Through virtual hardware abstraction
  - Network Functions are typically implemented using software
    - Few actual hardware dependencies
  - Decouples Network Functions from the underlying Hardware
    - Decouples software implementations of Network Functions from the computation, storage, and networking resources
  - Virtualisation insulates the Network Functions from those resources through a virtualisation layer

Network Functions Virtualisation



Courtesy : ETSI

Why NFV?

- Today's Operator Networks - Issues
  - Networks contain a variety of proprietary hardware equipment
    - Launch of a new service may require a new type of hardware - leading to an undesirable situation
      - Finding the space and power to accommodate these hardware
      - Increasing cost of energy, capital investment
      - Lack of skills to design, integrate and operate the complex equipment set
  - Hardware-based equipment reach end of life in a few years
    - Repeat Procure-design-integrate-deploy cycle

NFV - Management and Orchestration

- Orchestration of Resources (Physical and/or Software) supporting
  - Infrastructure Virtualisation
- Lifecycle Management of VNFs
- Why do you need this?
  - Network functions are decoupled from the Infrastructure
  - You need an infrastructure manager to manage and assign resources to the Network Functions
- Similar to the job of Operating System (Linux) on a Machine
- Focuses on all virtualisation-specific management tasks
- Not responsible for regular Network Management functions
  - Responsibility of NMS, EMS

Why NFV? - Benefits

- Reduced Equipment Cost
- Reduced Cost of Development
- Reduced Power Consumption
- Reduced Time to Market through minimisation of the development cycle
- Multi-tenancy support
  - Usage of a single platform for different applications and users
  - Operators to share resources across services and different customer bases
- Rapid scaling up/down of services and targeted delivery
  - Based on geography or customer groups
- Brings openness, encourages innovation
  - Easy to introduce new services at much lower risk
- Opens the virtual appliance/equipment market
  - Pure Software companies, Small Players, Academic Institutions

SDN and NFV – Relationship

- What do you think?

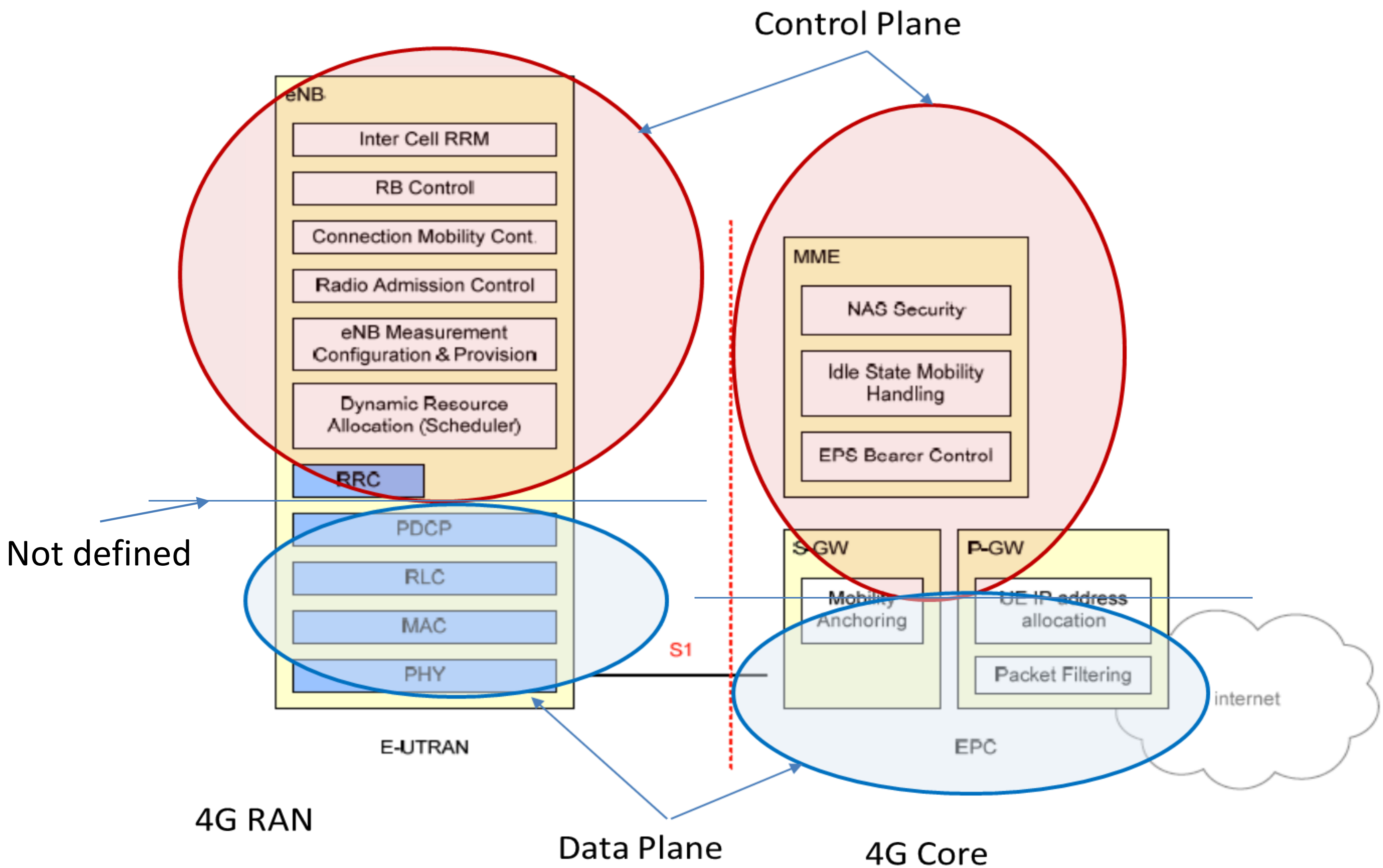
- Typically complementary and not dependent
- Network Functions can be virtualised and deployed without SDN being required and vice-versa, though
  - SDN can facilitate NFV - through virtualization of networks
  - NFV can facilitate SDN by, say, running SDN Controller as a VNF
- Combining them together may lead to development of some interesting use cases
  - These use cases can be supported w/o SDN & NFV also
  - But SDN & NFV provides a more elegant/easier approach towards their implementation

Applying SDN and NFV to Mobile Networks

The Need for SDN in Mobile Networks

- Tightly coupled Control and Data Planes
- Proprietary Interfaces, Vendor Lock-in
- Distributed Intelligence
- Existence of multiple Radio Access Technologies
  - Fragmented Control and Management of RATs
- User Association and Mobility
  - Signal strength based User Association to Network
  - Change in user association due to Mobility
  - Uneven load across network elements
  - Dual/Multi Connectivity

3GPP LTE Architecture – Compatibility with SDN?



Courtesy: *3GPP TS 36.300, "Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Overall description,"*

3GPP LTE Architecture – Compatibility with SDN?

- RAN
  - Control plane consists of
    - Radio Resource Control, Radio Resource Management etc.
  - Data plane consists of
    - Radio Interface Stack consisting of PDCP, RLC, MAC, PHY layers
    - S1-U/X2-U Interfaces comprising of GTP-U/UDP/IP layers etc.
    - Packet Forwarding, Ciphering, Rate Enforcement
- Core
  - MME - Control Plane Entity
    - UE Authentication and Control signaling
    - Bearer Management
  - SGW/PGW - Both data and control plane functionality
    - Terminating Control Plane Protocols: GTP-C, Diameter
    - UE Mobility Anchoring
    - UE IP address Management
    - Session (Bearer) Management
    - Packet Forwarding and Filtering
- Issues
  - Separation between the Control and Data Plane
    - neither open nor standardized
  - Distributed Intelligence in RAN
- Control and User Plane Separation (CUPS) in LTE Core has been taken up in 3GPP Release 14 to make it compatible with SDN
  - Both SGW and PGW have been separated into SGW-C/PGW-C and SGW-U/PGW-U

Questions to think

- How to apply SDN to Mobile Networks
  - SDN originated in wired/IP based networks
  - The concepts, which are important in SDN based wired networks, are they useful in Mobile networks also?
    - Concept of flows are quite commonly used in SDN based wired networks
    - OpenFlow protocol is based on the abstraction of flows
    - Is the concept of Flows useful for SDN based Mobile Networks?
  - Typically Mobile Networks comprise of two parts
    - Radio Access Network
    - Core Network
  - SDN for Core Network and SDN for RANs - Are the issues same or different?
- SDN related Issues
  - Scalability in SDN based Mobile Networks
  - Timing Constraints and SDN based Architecture
  - Hierarchical Architecture – Does it help?
- Mobility handling and SDN
- Interference Management and SDN
- NFV
  - How do we apply NFV to Mobile Networks?
  - How does it help?

Let us look at some Research Proposals first

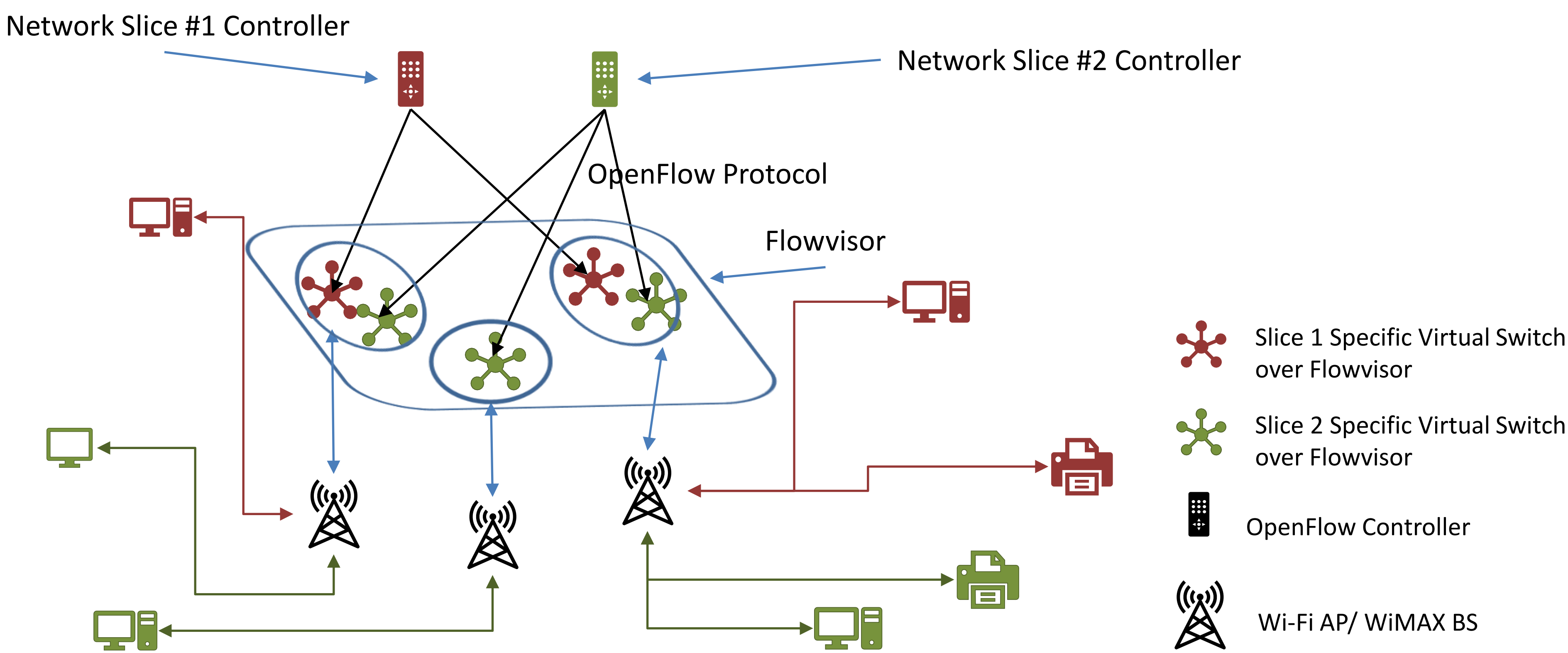
OpenRoads – An OpenFlow based Platform

- An SDN based platform for wireless networks
  - Supports Control of Mobile network comprising WiFi APs and WiMax BS
- Goal - to verify and validate
  - Mobility Solutions, e.g., HO Algorithms
  - Routing Protocols
- Comprises of
  - A Controller
  - Data Path elements - WiFi APs, OpenFlow Switches, WiMax BS
- Provides control of the network
  - Datapath Control with the help of OpenFlow – Forwarding Control
  - Control of the device configuration through SNMP
- SNMP enables
  - Configuration of the switches and wireless access points
    - Parameters, e.g., transmit power - Impacts the performance
  - Reporting of events to Controllers
    - such as a Station joining a WiFi AP
- OpenFlow enables
  - Redirection of Flows and therefore the Mobility
- Mobility Algorithms can be tested over the platform

Courtesy: *Kok-Kiong Yap, Masayoshi Kobayashi, Rob Sherwood, Nikhil Handigol, Te-Yuan Huang, Michael Chan, and Nick McKeown, "*OpenRoads: Empowering Research in Mobile Networks" ACM Sigcomm 2009

OpenRoads – Network Slicing

- Supports Network Slicing through Flowvisor
- Divide the flow-space in sub-spaces – Network Slices



Courtesy: *Kok-Kiong Yap, Masayoshi Kobayashi, Rob Sherwood, Nikhil Handigol, Te-Yuan Huang, Michael Chan, and Nick McKeown,* "OpenRoads: Empowering Research in Mobile Networks" ACM Sigcomm 2009

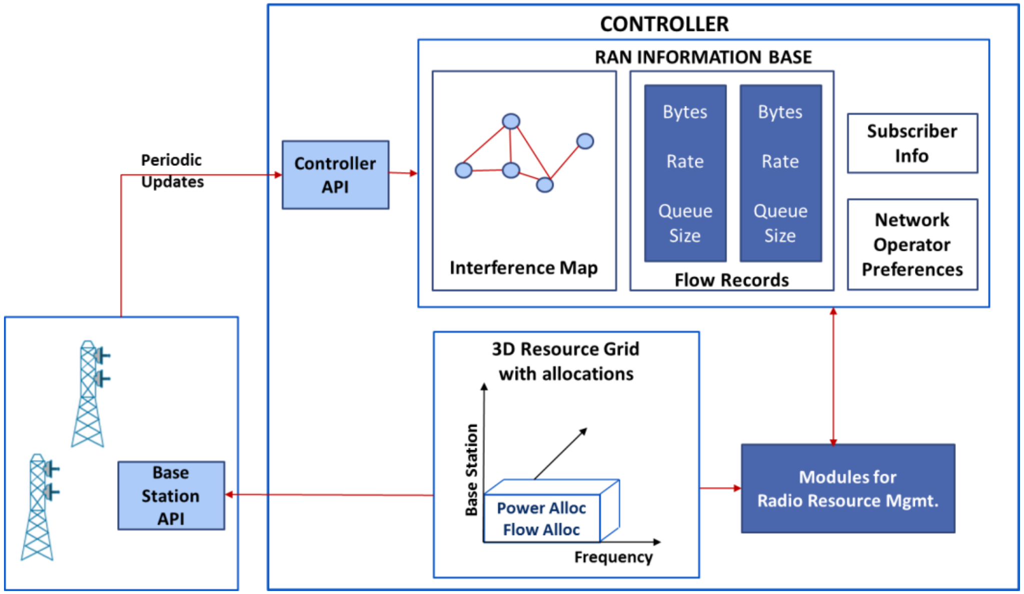
OpenRoads – Discussion Points

- IEEE 802.11 MAC layer has many similarities to Ethernet MAC
  - Possible to view WLAN APs (with 802.11 MAC) as Ethernet switches
  - OpenFlow protocol can be used to control APs
- Using Flow level abstraction as interface between the control plane and the data plane in mobile networks
  - Allocation of Radio Resources, e.g., Bandwidth to each of the Network Slices (flow-space)
    - Hidden from the SDN Controller
    - Responsibility of the data plane entities (APs) instead
    - However APs unaware of the network slices
      - Flowvisor responsible for creating the slices
      - Over the flow-space manifested by APs (sub-spaces)
    - APs unable to maintain slice specific separation over radio resources
- Allocation of radio resources to different slices may vary over time
  - Due to the time and user specific variation in radio channels

OpenRoads – Discussion Points

- Support for Cellular Networks BSs - LTE/5G NR ??
  - LTE and 5G-NR follow a much more complex radio protocol structure than IEEE 802.11 WLANs
  - Concept of Tunnels/Bearers
- Movement of Flows during UE Mobility
  - UEs may have multiple Flows
  - How to associate a Flow to a UE
  - A UE may be accessing Multiple Slices simultaneously

SDN for Cellular RAN - SoftRAN



- Proposed to harness the dense deployments of base stations
  - Dense Deployments with Frequency Reuse One
  - Users spend more time @cell boundaries
  - Distributed Control may have issues
- SoftRAN
  - Control functionality of multiple base stations abstracted as a large base station : Controller
- Physical base stations
  - Radio elements with data plane and some control function (for localized decision making)
- Controller - A global view of the network
  - Network state maintained in a Database – RAN Information Base
    - Interference Map, Flow Records, Operator Preferences
  - Decisions affecting other BS made at Controller
    - Handover
    - Transmit Power Control
    - UL RB Allocation
  - Decisions not affecting neighbours or shorter time scale made locally at physical BS
    - DL RB Allocation

Courtesy: *A. Gudipati, D. Perry, L. E. Li, and S. Katti, "SoftRAN: Software Defined Radio Access Network," ACM SIGCOMM workshop on Hot topics in software defined networking, 2013.*

SoftRAN – Discussion Points

- Hierarchical Control of RAN
  - Global Controller
    - Managing a large number of Base Stations
  - Local Controllers
    - At Individual Base Stations
- Focused towards Dense LTE Networks and Frequency Reuse One Scenario
- Proposed Architecture similar to
  - Centralized RRM/SON architecture
  - Base Station Controller ~ Centralized RRM or Centralized SON Server
- No Change on the User Equipment side
- How the LTE RAN looks like in terms of protocol Stacks
  - Not clear

Courtesy:*A. Gudipati, D. Perry, L. E. Li, and S. Katti, "SoftRAN: Software Defined Radio Access Network," ACM SIGCOMM workshop on Hot topics in software defined networking, 2013.*

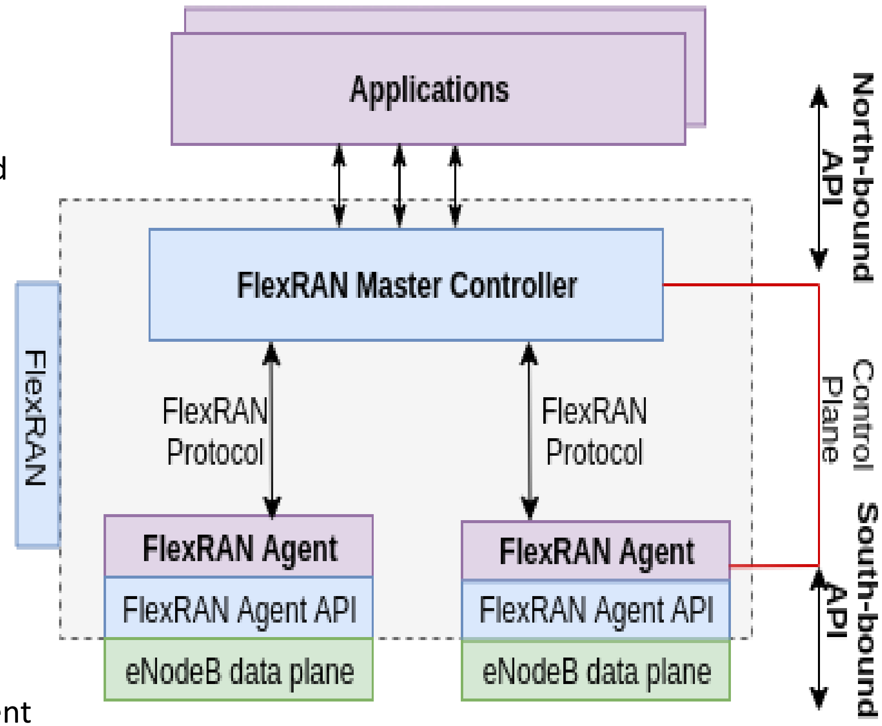
SoftRAN and Radiovisor

- Radivisor - A Solution for LTE RAN Slicing
- Tries to address some of the Issues with OpenFlow based Slicing
- Based on SoftRAN Architecture
- Interference – one of the key issues in Wireless Networks
  - Additional factor for slice creation and management
- Spectrum Resources allocated for each slice
  - Must be isolated
  - Not Interfere with one another
- Provides mechanisms for Slice splitting, Merging
- Supports inclusion of per-slice Controller and Applications
- Flexible and Independent Deployment of per slice configuration
  - MAC Scheduling
  - Physical layer Configuration
- Though has some of the same Issues as SoftRAN

Courtesy:*Katti, S., Li, L.E.: Radiovisor: A Slicing Plane for Radio Access Networks. In: Presented as part of the Open Networking Summit 2014.*

FlexRAN

- Software defined RAN for cellular networks
- Designed and implemented for LTE networks
- Possibly extensible for future RATs
  - some of the necessary steps for the same described
- Hierarchical architecture
  - A centralized master controller
  - A FlexRAN agent (local controller) at every eNodeB
- Control functionality within RRC, PDCP, RLC and MAC
  - Moved to the Master Controller
- Master controller performs
  - radio resource scheduling decisions centrally for eNodeBs under its control
- Provides flexibility to use FlexRAN in bandwidth constrained environments
  - Introduces control modules known as Virtual Subsystem Functions (VSFs) within the FlexRAN agent
  - scheduling policies and resource configurations
  - Allows for localized operation at eNodeBs
- Suitability of FlexRAN for
  - Interference management
  - Network slicing
  - User centric networks

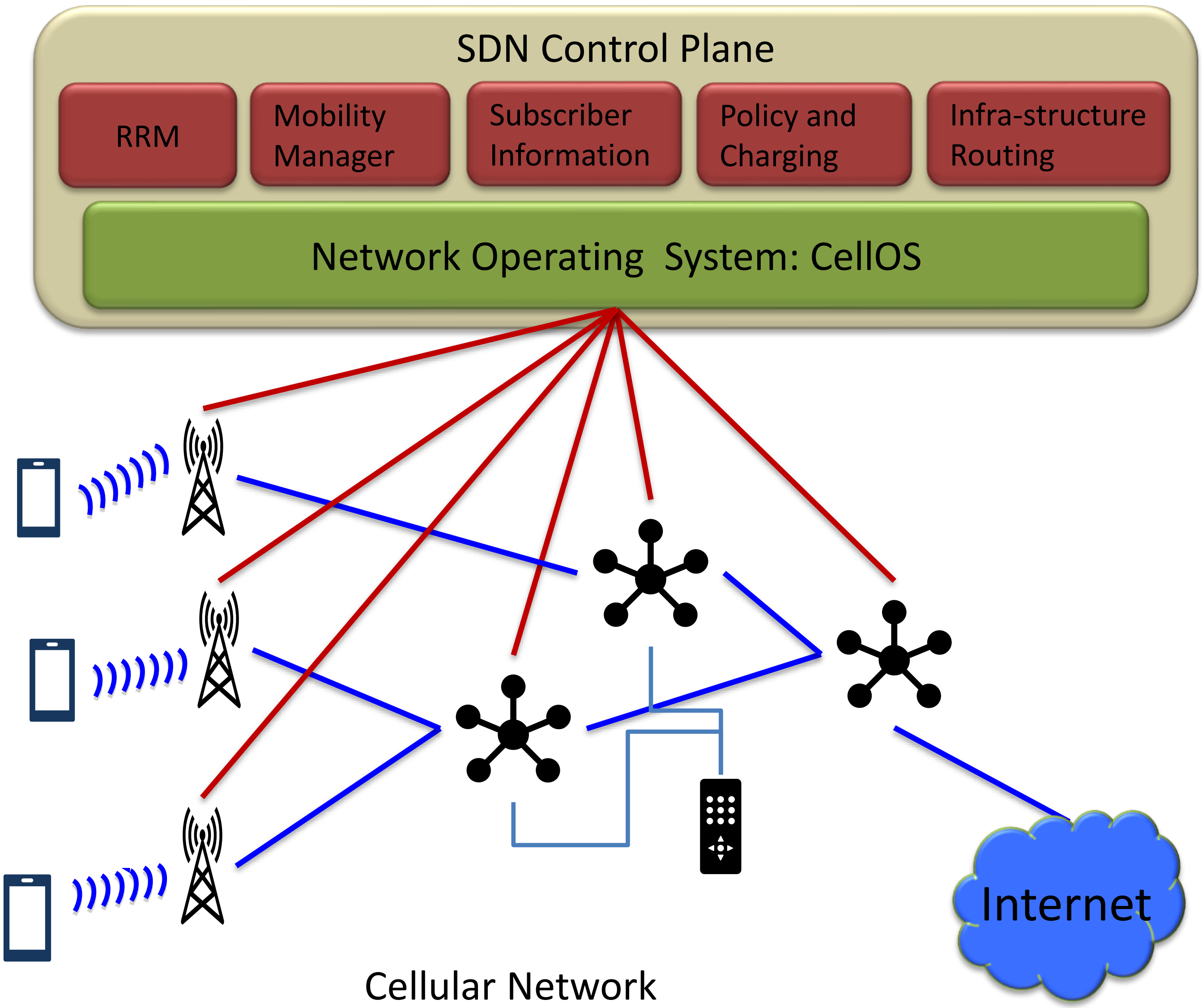


Source: Foukas, X., Nikaein, N., et. al. .: FlexRAN: A Flexible and Programmable Platform for Software Defined Radio Access Networks

SDN for LTE – CellSDN, SoftCell

- Related Proposals
- Utilizes SDN to address issues with LTE Network
- Challenges of LTE Network
  - P-GW centralizes certain data-plane functions
    - Monitoring
    - Access control
    - Quality-of-service
  - All traffic is tunnelled and goes through P-GW
    - Difficult to host popular content inside cellular network
  - Scalability and Cost of Equipment (P-GW)
  - Vendor-specific configuration interfaces
  - Large Number of Tunable Parameters
  - Difficult for Operators to manage
  - Distributed Control – Multiple Control Plane Entities

CellSDN – Proposed Architecture



- Existing LTE Network entities are modified/replaced
- SDN Controller
  - Logically Centralized Control
  - Applies Subscriber Specific Policies
  - Common Control Protocol – OpenFlow
  - BSs across different RATS, though focus on LTE
- SDN Switches
  - OVS type Switches, Packet Forwarding functionality
  - May support DPI etc.
- Middleboxes
  - Content adaptation, Optimization
- eNB RRMs are centralized – part of the SDN Controller

CellSDN - Features

- Express Policy in terms of Subscriber Attributes
  - CellOS translates subscriber specific policies into switch specific rules, say, IP address based rule
- Local Control Agent at each switch
  - Simple Control Plane actions, e.g., changing the weight/priority of a queue when traffic exceeds a threshold
  - Control Plane Scalability
- Switches - Flexible Data-plane Functionality
  - Deep Packet Inspection, Header Compression
  - Reduction in the no. of Middleboxes
- Granular Packet Classification and Flexible Routing
  - Lesser load on Middleboxes
- Seamless Mobility Support - Proactive Flow Creation

Courtesy: *Li Erran Li, Z. Morley Mao, Jennifer Rexford, "Toward Software-Defined Cellular Networks"*

CellSDN – Discussion Points

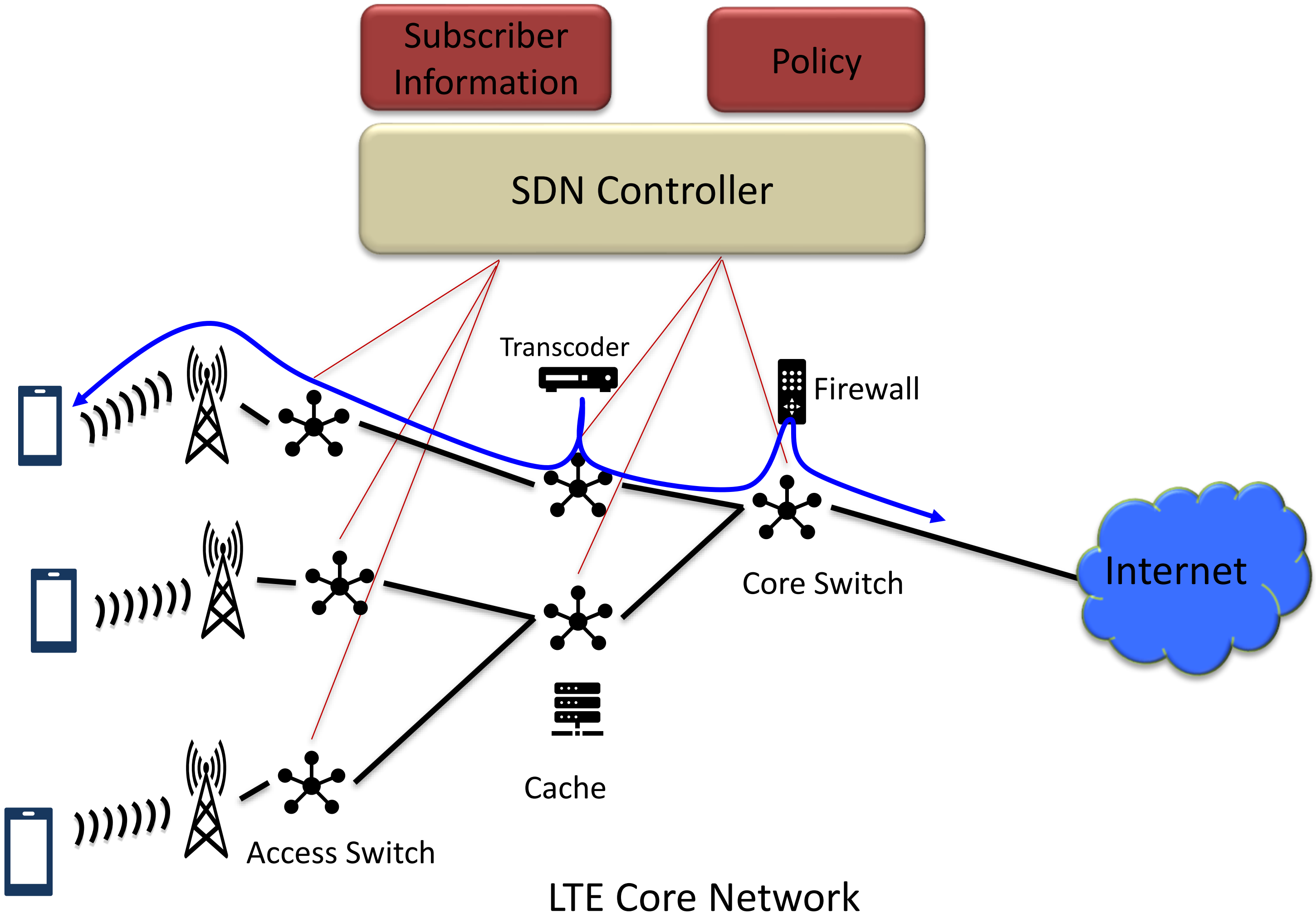
- Influenced by OpenRoads Architecture
  - Extended to LTE Cellular Network
- Virtualization of BSs
  - FlowVisor to be extended to virtualize/slice BS resources
    - to create virtual Base Stations
  - Virtualization of Resources - Time-slots, Subcarriers, and Power
- How to support BS Virtualization
  - w/o modifying the physical-layer protocol
  - Controller can convey high-level information, e.g., id of virtual provider through the control plane to the UE
    - w/o physical broadcasting of the provider information
  - Allows UE to display the virtual provider
  - Does it mean changes in the LTE SIBs and the RRC protocol?
  - The idea sketched at a high level
- How Mobility is supported?
  - Are GTP tunnels used? OpenFlow does not support GTP tunnelling
- Hierarchical SDN Control to an extent
  - Some state maintained at Local Control Agent

SoftCell – Proposed Architecture

- SDN based Architecture for LTE Core Network
  - Similar to Data Centre architectures
  - Enhancement of the CellSDN Architecture – Focus on Core Network
- Three types of components
  - SDN Controller
  - Middleboxes
  - Switches
    - Access Switches
    - Core Switches
- No specialized Core network forwarding elements
  - No S-GWs and P-GWs
  - No GTP-Tunnels
- Controller
  - Implements high-level service policies
  - Installs switch-level rules to direct traffic through middleboxes
  - To compute the paths, accesses Subscriber specific Attributes and Application specific Policies

Courtesy: *Xin Jiny, Li Erran Li, Laurent Vanbevery, and Jennifer Rexford, SoftCell: Scalable and Flexible Cellular Core Network Architecture*

SoftCell – Proposed Architecture



SoftCell – Discussion Points

- UEs
  - No Modifications in UE, similar to the existing LTE network
  - IP address allocated to UE does not change as it moves across base stations
  - Changes in the cellular core network not visible to the UEs
- Middleboxes
  - e.g., firewall, cache server
  - Stateful middleboxes - all packets of a connection to traverse the same instance
- Switches
  - OVS type Switches, perform packet forwarding function
- Base stations
  - Uses existing protocols to connect to UE
- No GTP-Tunnels
  - Mobility support through a separate location dependent IP address for routing within the Core Network and Internet
  - Access switches perform the address translation

SoftCell – Discussion Points

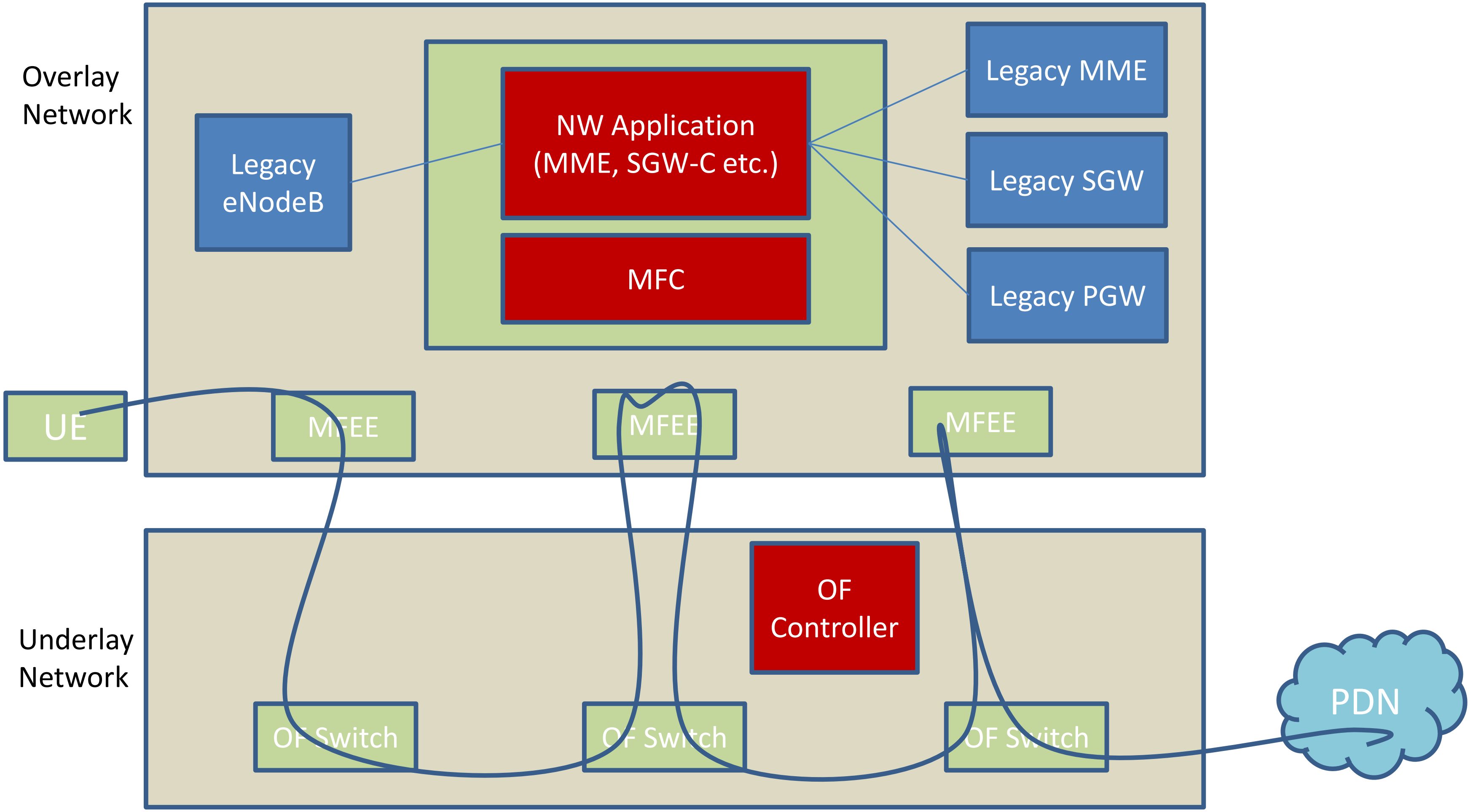
- Focus on LTE Core Network
  - Based on the CellSDN Architecture
- Complementary to approaches focussed on SDN based RAN
  - SoftRAN
- Enables usage of Middleboxes in the Core as well as the Edge
- In a way, tries to utilize the concept of service function chaining in core
- Incremental Deployment in existing cellular networks
  - Thru deployment of CN proxies at BSs
  - Proxies serve as the GTP tunnel end-points
  - The Core network between BSs and the Internet is an IP core
    - Managed by the SoftCell SDN Controller
- Interworking with LTE networks
  - For interworking, SoftCell controller needs to communicate with eNodeBs and MMEs using standard LTE protocols
- Hierarchical Control
- Handling Controller Failure
  - Controller Replication
  - Querying Local Agents

MobileFlow - SDN based end-to-end Architecture

- Mobile Network is treated as an Overlay Network
- Comprises of forwarding elements and a Controller
  - MobileFlow Controller(MFC)
  - MobileFlow Forwarding Engine (MFFE)
- Mobile Flow Controller and Applications used to steer traffic thru MFFEs
- Backward compatible with 4G core networks
- SDN based network architecture
- Tries to address the integration issue between SDN-based Mobile networks and legacy mobile networks, e.g., 4G LTE
- Focussed on separation of Control plane and data plane in Core
- Not clear how SDN concepts is applied in RAN

Courtesy: *Kostas Pentikousis, Yan Wang, and Weihua Hu, "MobileFlow: Toward Software-Defined Mobile Networks," IEEE Communications Magazine • July 2013.*

MobileFlow - SDN based end-to-end Architecture



Courtesy: *Kostas Pentikousis, Yan Wang, and Weihua Hu, "MobileFlow: Toward Software-Defined Mobile Networks," IEEE Communications Magazine • July 2013.*

SDN based Architecture for Ultra Dense Networks

- SDN Architecture for Ultra Dense Networks
  - Microwave base stations (BSs),
  - Dense Microwave small cell base stations (SBSs)
  - ultra-dense mmWave Access Points
- MM-Wave Access Points (AP)
  - Primary data transmission point for users
- Microwave cells are for
  - Network control, Information Measurement, Control Signal transmission
- Hierarchical SDN Architecture
  - SDN Controllers classified into two levels
  - Centralized superior SDN controller
  - Localized subordinate SDN controller

Source: Guanding Yu, Rui Liu, Qimei Chen, and Zhenzhou Tang, "A Hierarchical SDN Architecture for Ultra-Dense Millimeter-Wave Cellular Networks"

SDN based Architecture for Ultra Dense Networks contd.

- Subordinate (Localized) SDN Controller
  - Resource allocation and traffic scheduling
  - Reduced computational complexity and network delay
  - Each subordinate SDN Controller has a service area
    - Comprising microwave Small cell BSs and mmWave APs
  - Users in a service area served by subordinate SDN Controller
    - User Association, Load Balancing, and Resource Allocation within its service area
  - Each user is associated with a
    - Small Cell BS for signalling
    - mmWave AP for data transmission
  - The service areas of different subordinate SDN Controller are non-overlapping
    - Ensures each user served by only one subordinate SDN
- Superior SDN Controller
  - Load Balancing and Energy Efficiency
  - Subordinate Control and Management
    - Change in Service Area configuration
    - Addition/deletion of free mmWave Access Points
    - Exchanges of mmWave Access Points among subordinate SDNs
- Similar to other hierarchical SDN based architectures

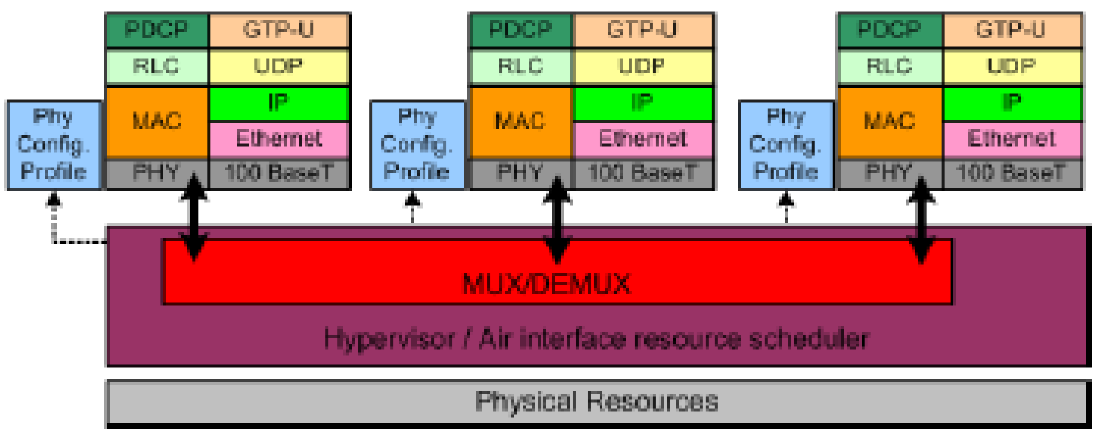
NFV based Approaches

Using Network Function Virtualization in RAN

- NFV aims to
  - Utilize Industry Standard Infrastructure
    - High capacity Servers, Switches and High volume Storage
  - Instantiate different Network equipment types over the shared infrastructure
    - Leveraging standard virtualization techniques
- The equipment could be located in
  - Data centres
  - Network Nodes
  - End-user Premises
- Packet Core of the Mobile Network Utilizing NFV
- Challenges in using NFV in RAN
  - Execution of RAN functionality on COTS hardware and software platform
  - RAN lower layer (PHY and MAC) function are time-critical

Virtualization of LTE RAN

- Multiple virtual eNodeBs over a physical eNodeB platform
  - Hypervisor-based Scheme
  - Network Function Virtualization
  - Focus on Air Interface Virtualization
- LTE Hypervisor responsible for virtualizing the eNodeB Into multiple virtual eNodeBs
- Each virtual eNodeB may be used by a different operator



Courtesy: *Yasir Zaki, Liang Zhao, Carmelita Goerg; "LTE Wireless Virtualization and Spectrum Management"*

Virtualization of LTE RAN

- Physical Resources scheduled among different virtual eNodeBs
  - Similar to XEN hypervisor
  - Focus on Radio Resource Scheduling
    - LTE uses OFDMA in the downlink
    - OFDMA sub-carriers (PRBs) are scheduled between virtual eNodeBs
    - Essentially splitting the frequency spectrum between them
- Hypervisor collects information from the individual virtual eNodeBs
  - User channel conditions
  - Load
  - Priorities & QoS Requirements
  - Contract of each of the operators
- Hypervisor uses the collected information to schedule the PRBs across virtual eNodeBs

Courtesy: *Yasir Zaki, Liang Zhao, Carmelita Goerg; "LTE Wireless Virtualization and Spectrum Management"*

Virtualization of LTE RAN – Discussion Points

- NFV Based Scheme
  - Though predates NFV standardization
- It is not entirely clear how the radio resources of a cell/eNB is shared across these virtual eNBs
  - In terms of standard PRB bandwidths (6, 15, 25, 50, 75 PRBs) or a more flexible scheme?
  - Does the PRB allocation change over time?
  - How control channel resources (PDCCH etc.) are allocated to virtual eNodeBs?
- eNodeB Data Plane Virtualization
  - Apparently the virtual eNodeBs do not contain the control plane functionality
- How eNodeB control plane works in this scheme?
  - Do the virtual eNBs broadcast their system information individually over the air?
  - Do the UEs perceive these virtual eNBs as individual eNBs?
- How would this scheme work in Uplink?

Courtesy: *Yasir Zaki, Liang Zhao, Carmelita Goerg; "LTE Wireless Virtualization and Spectrum Management"*

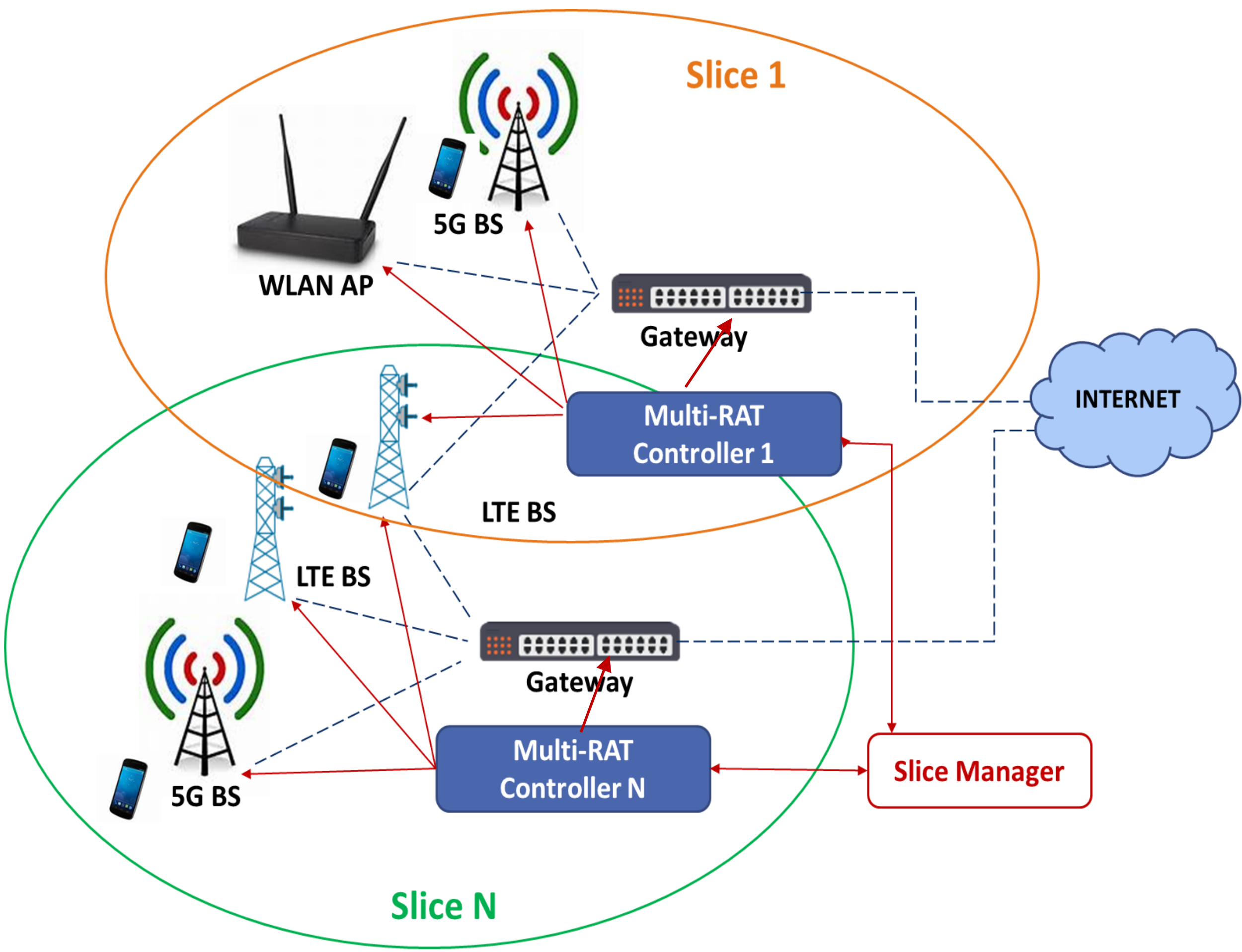
Cloud RAN - Network Function Virtualization

- Cloud RAN - One of the early proposals in this direction
  - Predates the NFV standardization
  - Proposed by International Business Machines Corporation (IBM)
- Centralization of base band processing of base stations in Cloud/Datacenter
- Comprising of three key components
  - BBU Pool
    - Located at a centralized location like a cloud or data centres
    - Multiple BBU nodes with high computational and storage capabilities
    - Responsible for processing radio resources and assigning them to RRUs based on the network needs
  - Remote Radio Head
    - Radio Transmission/Reception Functionality
  - Fronthaul or Transport
    - Connection layer between a BBU and a set of RRUs
    - High bandwidth link to support the requirements of multiple RRUs
    - Fronthauls can be realized using
      - Optical Fiber, Cellular communication or Millimeter wave communication
    - Optical Fiber considered ideal in C-RAN
      - Provides the highest bandwidth requirement
      - Comes with high cost though
    - Cellular communication or millimeter wave communication cheaper and easy to deploy
      - Less bandwidth and More latency than optical fiber

Additional Research Proposals in the context of 5G

SDN based Architecture for Multi-RAT Networks

- One of the early works on SDN based integrated Multi-RAT Network
- Separate data plane and control plane entities
  - Separated through a programmable interface
- Base Stations & Gateways
  - Data Plane Entities
- A Virtualization Layer over the Data Plane
- Logically Centralized Controller for end-to-end Multi-RAT Network control
  - Enables a unified view of the network
- Usage of Network Slice
  - Achieves control plane scalability
  - Service differentiation



Source: Abhay Karandikar, Pranav Jha, Akshatha Nayak, *"Methods and Systems for Controlling an SDN based multi-RAT Communication Network" US Patent Publication No 20170238362.*

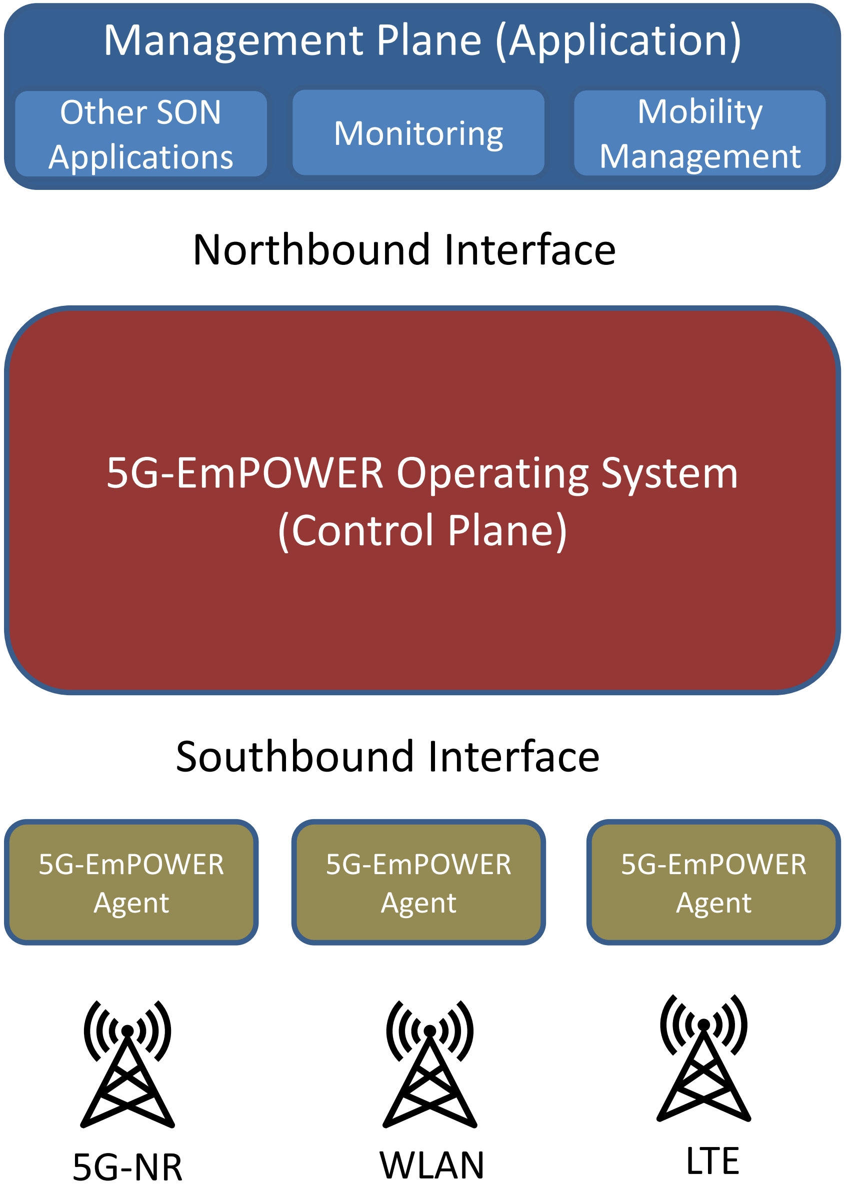
5G-EmPOWER

- SDN based multi-RAT Controller
- The solution provides a framework to control and manage LTE and WLAN with the help of a Unified Controller
- Aligned with three plane SDN based architecture
- Application Plane - Management Applications, e.g.. SON Applications
  - The management functionality running over the 5G-EmPOWER operating system
- Control Plane
  - An Operating System (OS) known as 5G-EmPOWER
  - Behaves as the Controller, Responsible for
    - Allocating data plane resources for Users (Slices)
    - Providing isolation between users (Slices)
    - RAT-agnostic view of resources to management by abstracting network resource details
- Data Plane
  - RAN Node
  - 5G-EmPOWER agent placed on every RAN node - To be configured by the OS
- OpenEmpower
  - A New Management Protocol

Source: Coronado, E., Khan, S.N., Riggio, R.: 5G-EmPOWER: A Software-Defined Networking Platform for 5G Radio Access Networks

5G-EmPOWER

- Supports RAN slicing for LTE network
- The proposed slicing mechanism places
  - A Hypervisor over the Physical Layer
- The hypervisor abstracts the physical resource grid
  - Virtual Physical Resource Blocks (PRBs)
  - Grouped into virtual PRB groups for use
- A Slice Resource Manager placed at the MAC Layer above the hypervisor used for managing the Slice lifecycle
- Multiple slices with independent schedulers can be created
- Virtual PRB groups created with the help of the hypervisor
  - Allocated to be used by Slice Specific Schedulers
- However, authors do not provide details on how slicing could be performed over WLAN



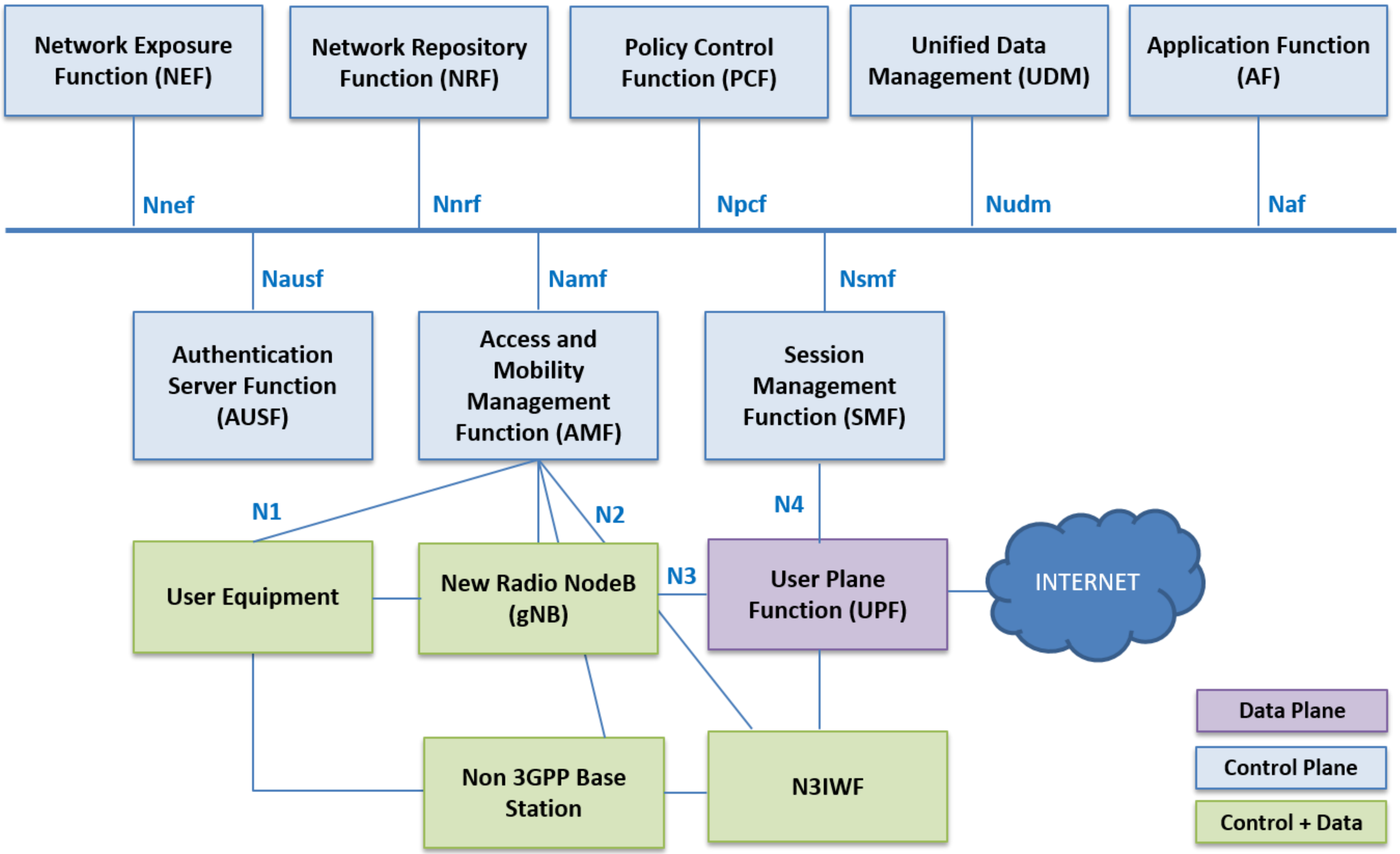
Source:

SDN, NFV and Standardization for 5G

3GPP 5G Standardization – SDN and NFV

- 3GPP 5G explicitly leverages SDN and NFV
- Network Function Virtualization
  - Specifies Components as Network Functions and not Network Entities/Nodes
    - Compare AMF & SMF with MME
- Software Defined Networking
  - SDN based Hierarchical Architecture
    - Core and RAN
  - Separate Data and Control Plane Functions
    - Both in Core and Radio Access Network (RAN)
    - Independent Scalability and Evolution
    - Flexible Deployment
      - Centralized location or Distributed Location
      - C-RAN or Distributed RAN Nodes
  - Data Plane and Control Plane Functions separated thru standardized interface
- Only partially used in 4G and earlier systems

3GPP 5G Network Architecture – Impact of SDN and NFV



3GPP System Architecture: Courtesy TS 23.501

3GPP 5G Network Architecture

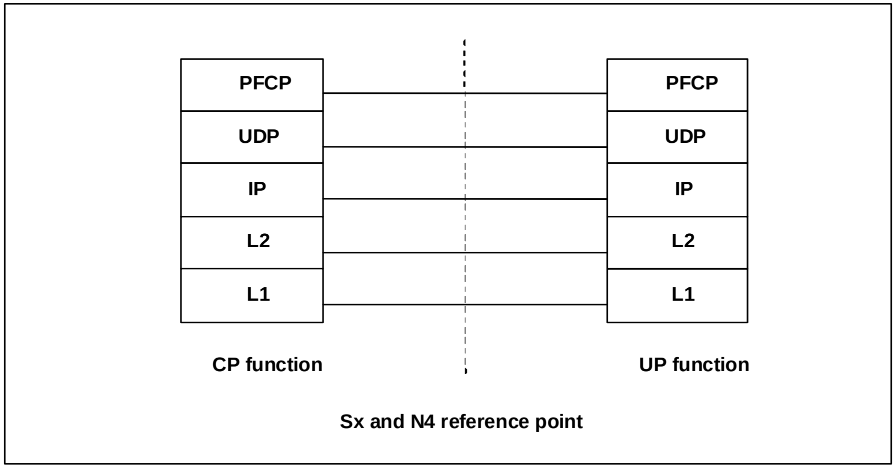
- Control Plane Functions in Core Network (CN)
  - Access & Mobility Management Function (AMF)
  - Session Management Function (SMF)
  - …
- Data (User) Plane Function in Core Network
  - User Plane Function (UPF)
- Support for Network Slicing
- Resources decoupled from each other
  - Supports "stateless" Network Functions
- Converged Core Network with a common AN - CN interface
  - Integration of different Access Types, e.g., 3GPP and non-3GPP access
  - Centralized Core Network Control Plane - RAT independent Control
- Service-based Interactions between Control Plane Functions
- Modular Function Design
  - To enable flexible and efficient network slicing

3GPP Core Network – Key Functions

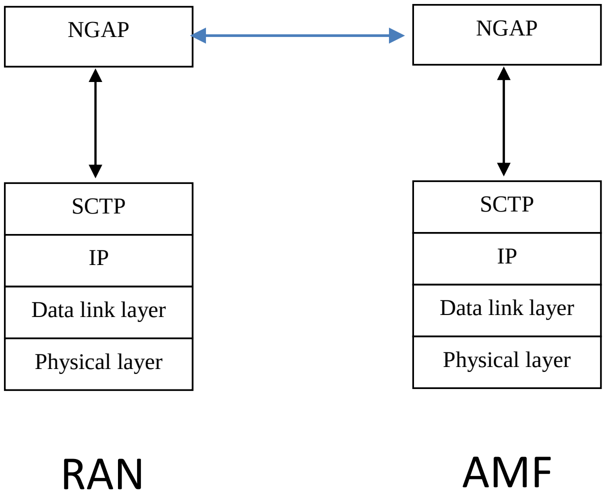
- Access and Mobility Management Function - Essentially a UE Control Entity
  - Termination of RAN Control Plane interface
  - Termination of UE Non-Access Stratum Procedures
  - UE Registration & Connection management
  - UE Mobility Management
  - Enable Transport for SM messages between UE/RAN and SMF
  - UE Access Control - Authentication and Authorization
- Session Management Function – Network Controller for Core
  - Session Management - Session Establishment, Modification and Release
  - UE IP Address Allocation & Management
  - Traffic Configuration at UPF to route traffic to proper destination
  - Termination of Interfaces towards Policy control functions
  - Charging Control
- User Plane Function
  - Anchor point for Intra-/Inter-RAT mobility
  - External PDU Session point of interconnect to Data Network
  - QoS handling for user plane, e.g. UL/DL rate enforcement, Reflective QoS marking in DL
  - Packet Routing & Forwarding
  - Packet inspection - Application detection based on service data flow template
  - Policy Rule Enforcement, e.g., Gating, Redirection, Traffic steering
  - Traffic Usage Reporting
  - Transport level packet marking in the uplink and downlink

3GPP 5G Protocols for SDN

- PFCP
  - Node Related Procedures
    - Heartbeat Procedure
    - Load Control
  - Session Management Procedures
    - Session Establishment
    - Session Modification
    - Session Deletion
    - Session Reporting

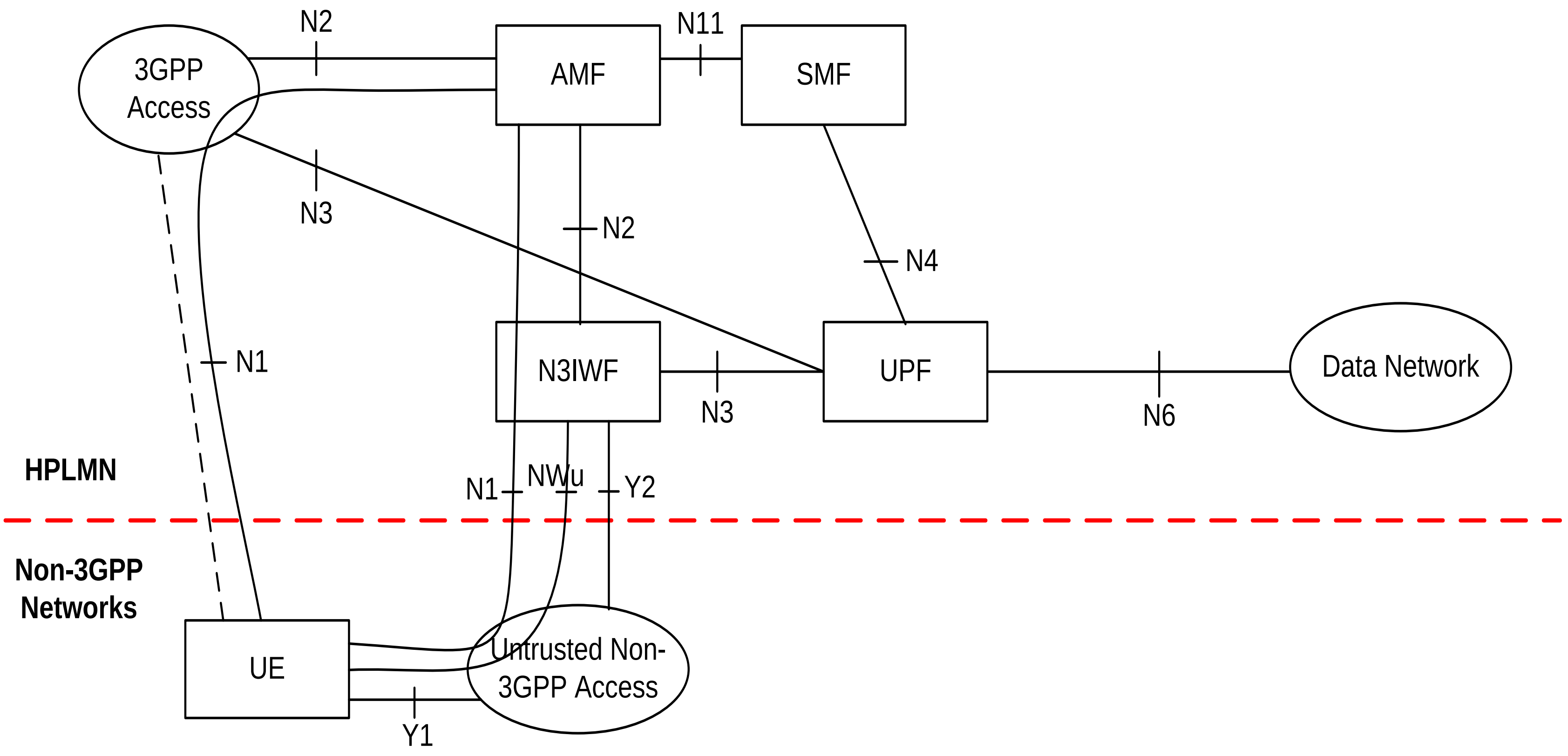


- NGAP
  - Protocol for Hierarchical SDN based Control between RAN and Core
  - Interface Specific Procedures
    - Interface Management
    - AMF Load Management
  - UE Specific Procedures
    - UE NAS Transport
    - UE Context Management
    - UE Session Management
    - UE Mobility Management



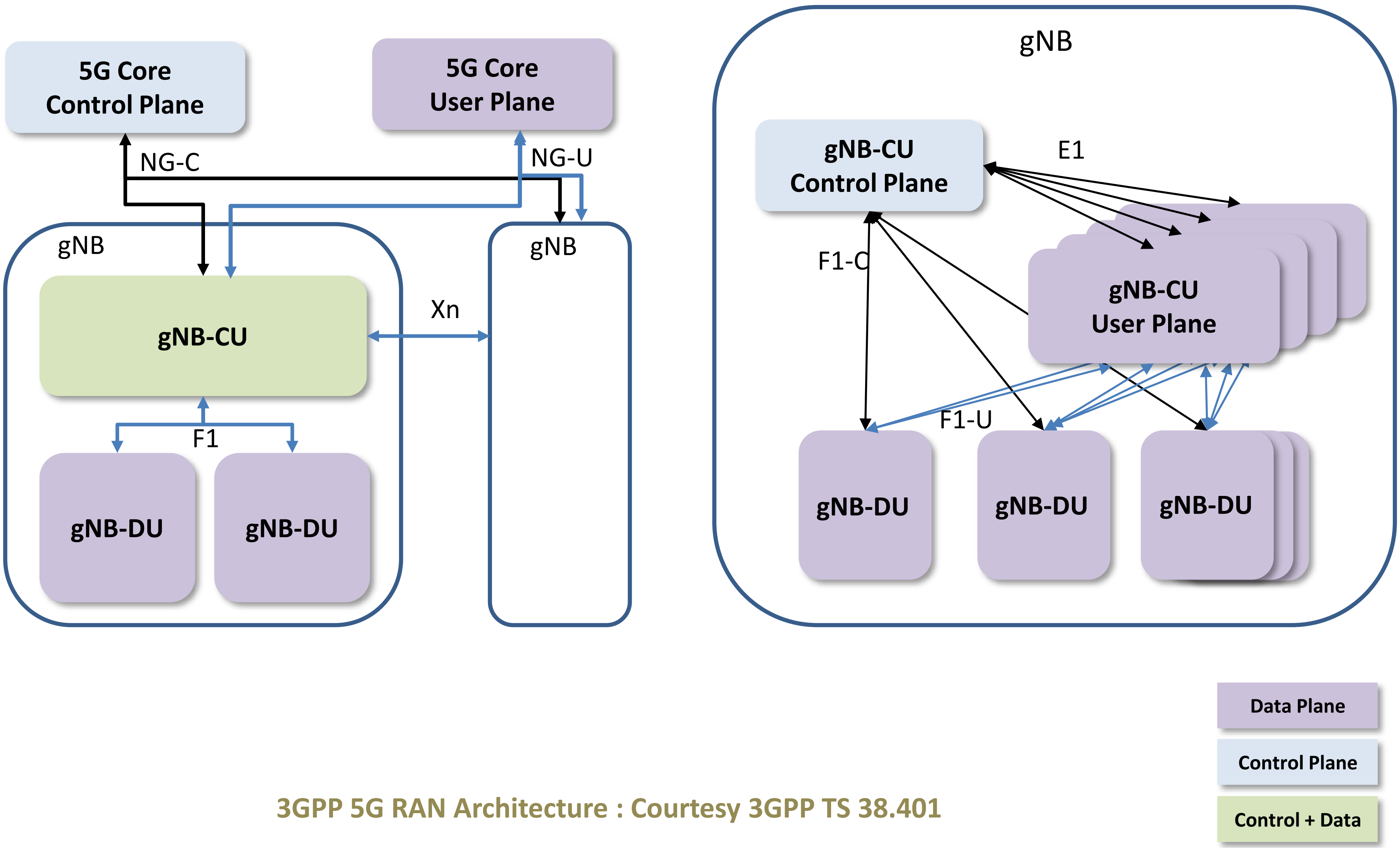
Courtesy 3GPP

3GPP 5G Network Architecture – Unified Core



3GPP System Architecture: Courtesy TS 23.501

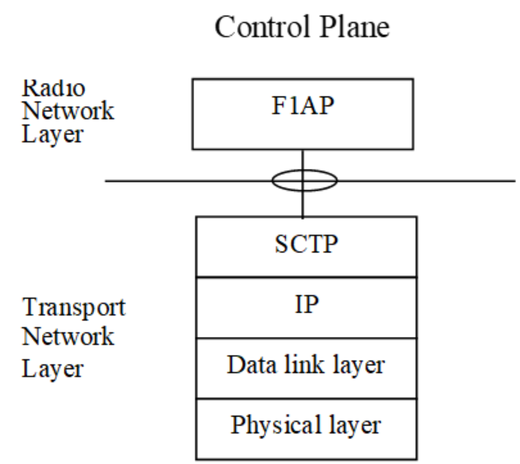
3GPP 5G RAN Architecture – Compatibility with SDN



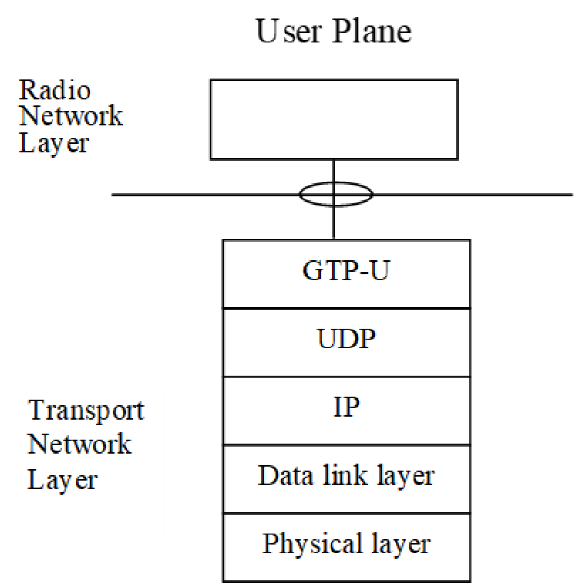
3GPP 5G RAN Architecture : Courtesy 3GPP TS 38.401

3GPP 5G RAN Interfaces for SDN

- F1 Interface Supports
  - Control Plane and Data Plane Separation
- F1 Control Interface
  - System Information Broadcast
  - UE Context Management
  - UE RRC Message Transfer
  - Warning and Paging Message Transfer
- F1 Data Interface
  - Transfer of User Data
  - Flow Control



F1 Control Plane Stack

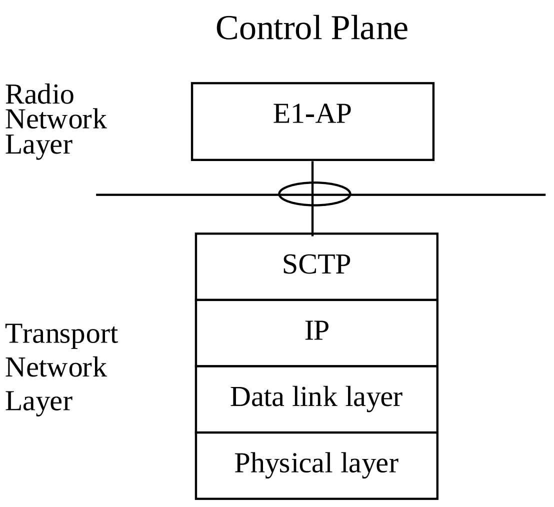


F1 Data Plane Stack

Courtesy 3GPP

3GPP 5G RAN Interfaces for SDN

- E1 Interface
  - Control – Data Plane Interface
  - Interface Management Procedures
    - Interface Setup/Reset Procedure
  - UE Specific Procedures
    - Bearer Setup
    - Bearer Release
    - Bearer Modification

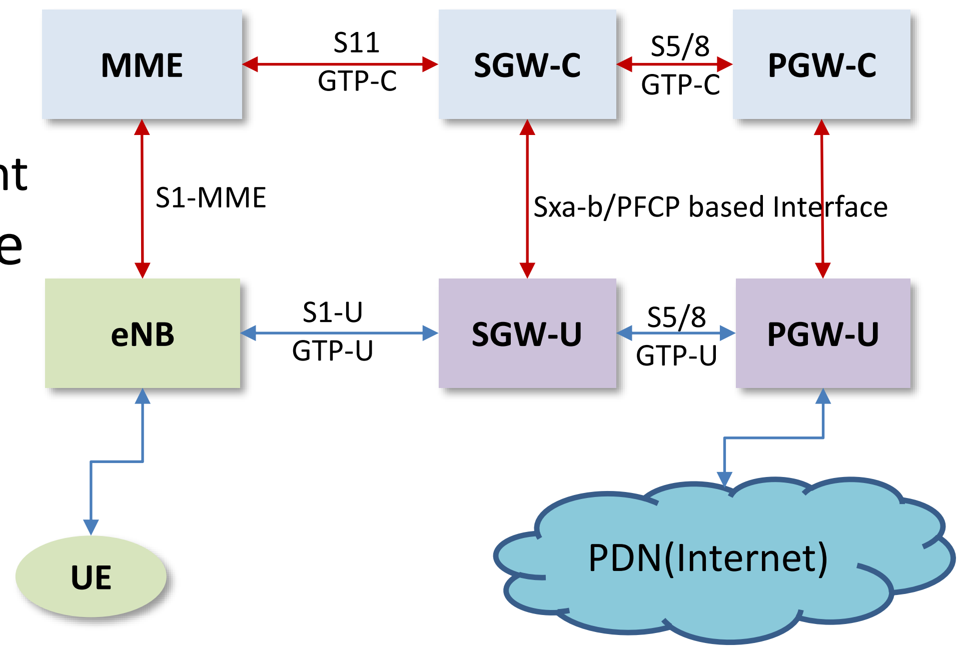


E1 Control Plane Stack

Courtesy 3GPP

3GPP LTE Architecture – Release 14 Enhancements

- SDN related enhancements in 4G Core
  - Control and User Plane Separation (CUPS) of EPC Nodes
    - Separation of Control and Data Plane in SGW and PGW
  - SGW/PGW Control Plane
    - Terminating Control Plane Protocols: GTP-C, Diameter
    - Interfacing
    - UE Mobility Anchoring
    - UE IP address Management
    - Session (Bearer) Management
  - SGW/PGW Data(User) Plane
    - Packet Forwarding
    - Marking
    - Rate Enforcement
- 4G RAN
  - No Change



***Courtesy: 3GPP TS 23.214**, "Architecture enhancements for control and user plane separation of EPC nodes"*
***3GPP TS 29.244**, "Interface between the Control Plane and the User Plane Nodes"*

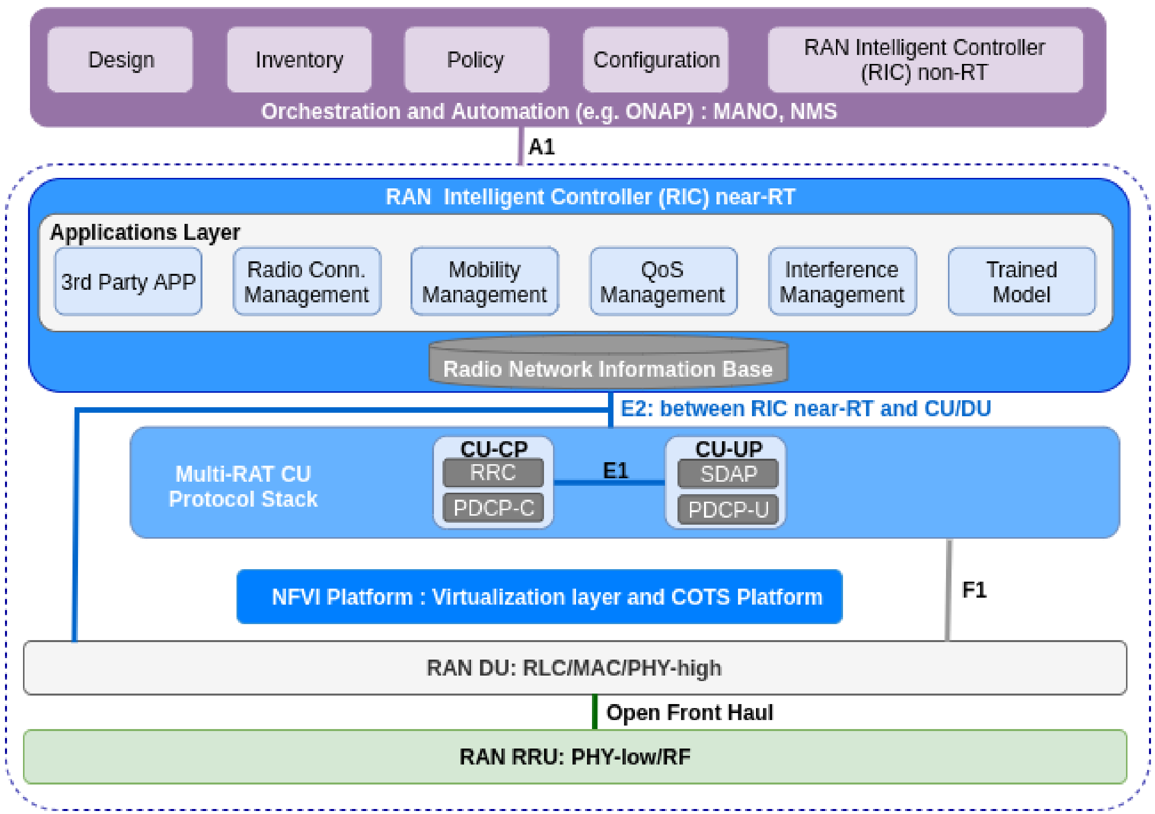
O-RAN Architecture for 5G

- A standard currently under development within recently formed O-RAN alliance
- O-RAN alliance
  - A Consortium of Cellular Network Operators
- Development of an SDN based smart RAN with open interfaces for
  - Enabling Vendor Inter-operability
  - Usage of artificial intelligence/machine learning algorithms for optimised network decisions
- APIs and Interfaces defined using 3GPP specifications as the base
- To reduce CAPEX, promotes usage of
  - Open-source software
  - Off-the-shelf hardware
- Based on the time scale of operation, Radio Interface Control functions divided into
  - Non-Real Time (RT) (> 1s)
  - Near-RT (< 1s)
- Non-RT Radio Interface Controller (RIC) is responsible for longer time-scale decisions
  - Policy management
  - Configuration
  - Training of learning models from the collected data etc.
- Near-RT RIC Interfaces Provides RRM related functionality
  - Mobility Management
  - Quality of Service (QoS) Management

Source: O-RAN Alliance: O-RAN: Towards an Open and Smart RAN (2018). [Online]. Available: https://www.o-ran.org/s/O-RAN-WP-FInal-181017.pdf

O-RAN Architecture for 5G

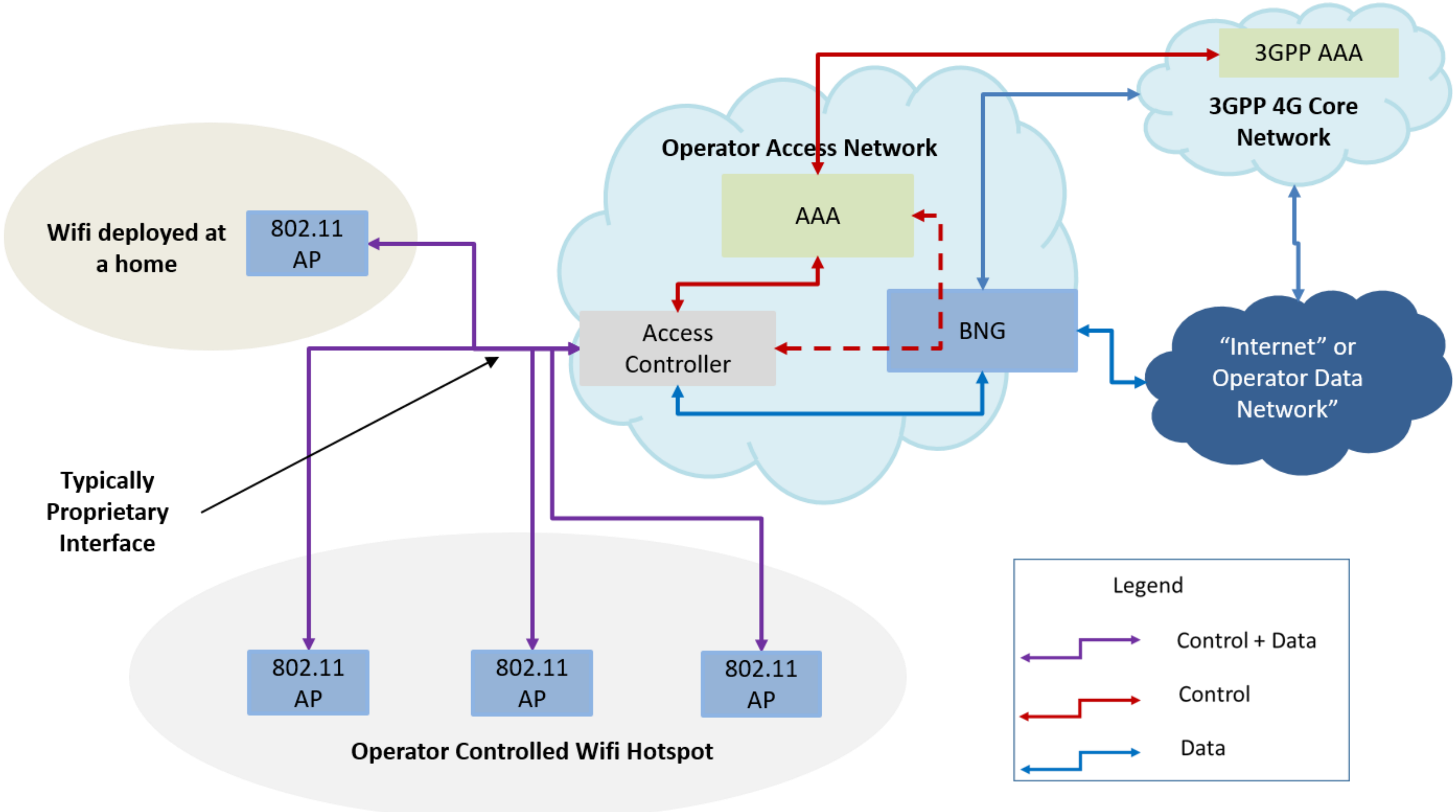
- Enables Third-party Applications to be incorporated into the network
- Supports 4G LTE and 5G NR RATs at present
- As in 3GPP 5G specs, the radio protocol stack split into CU and DUs
- Interfaces defined by 3GPP being extended for use in O-RAN standard
  - E1 (between gNB-CU CP and gNB-CU UP) and F1 (between CU and DU)
- The first release of O-RAN code-named `Amber' is expected to be released at the end of November 2019.
- O-RAN is built as an extension to 3GPP and hence does not provide any specific guidelines for slicing the RAN.
- It is intended that the mechanisms defined by 3GPP would be used as is unless explicitly mentioned within the O-RAN specifications [24]
- As a result, it is inferred that slicing within O-RAN is also implementation dependent



Source: O-RAN Alliance: O-RAN: Towards an Open and Smart RAN (2018). [Online]. Available: https://www.o-ran.org/s/O-RAN-WP-FInal-181017.pdf

Additional Standardization Efforts - 5G

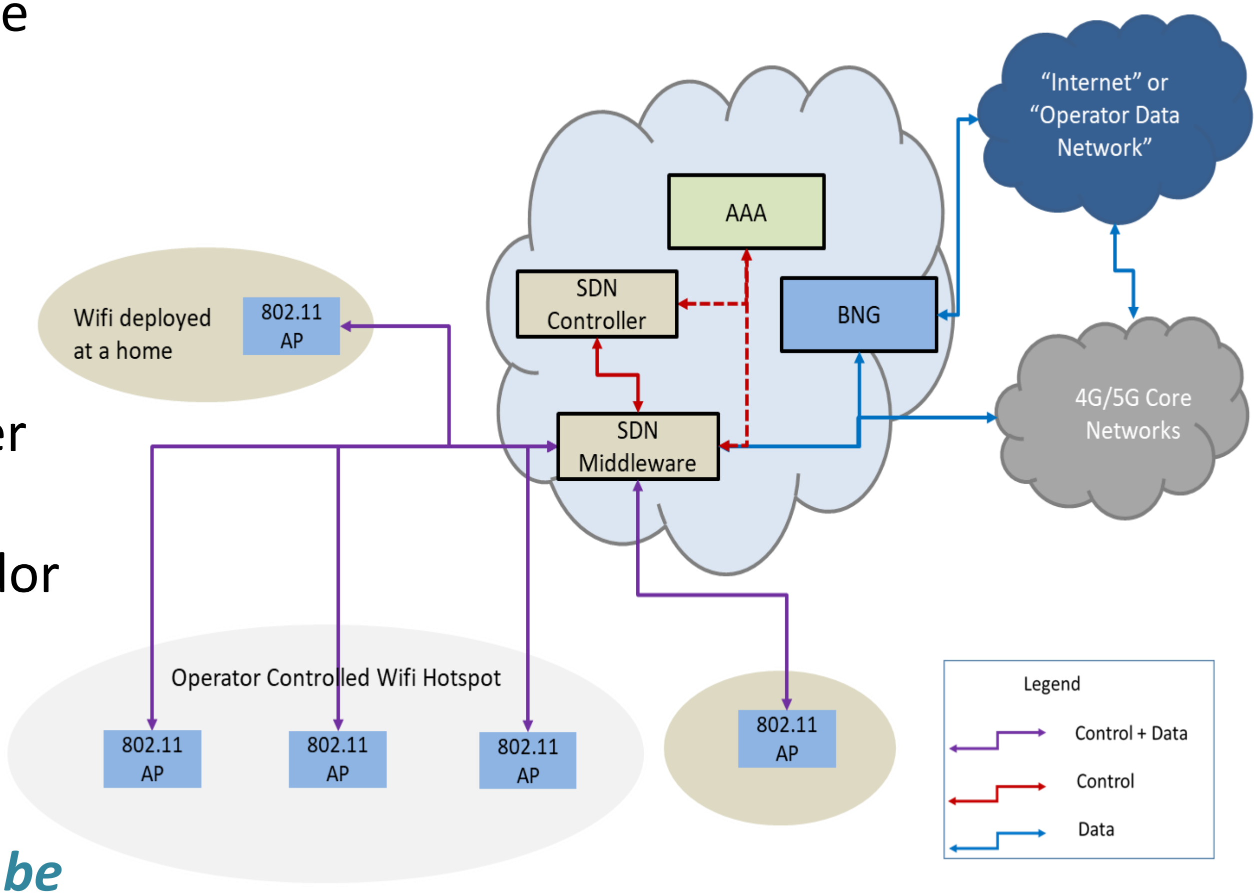
Existing Public WiFi Networks – Compatibility with SDN?



- Management and control of Access Points
  - Not compatible with SDN
- Access Controller
  - Typically Integrated control and data plane node
  - Similar to PGW/SGW in LTE
- Separation between the Control and Data Plane
  - Neither open nor standardized

Proposed Solution - P1930.1 Standard - Key Points

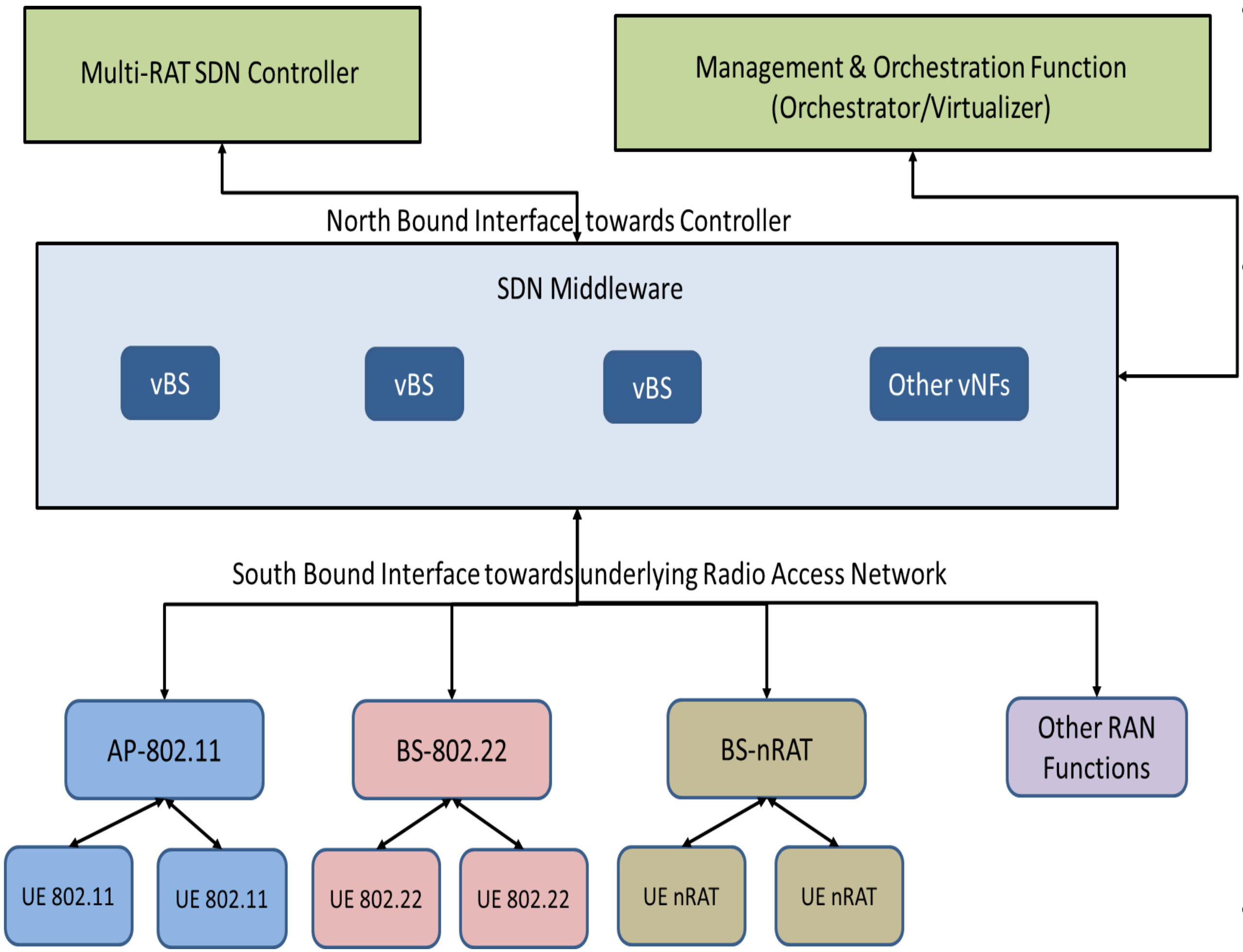
- SDN based architecture for RAN
  - With separate control and data plane functions
- Introduce a new layer between the Controller and the Radio Nodes (APs) to facilitate Vendor Interoperability
  - SDN Middleware
- "***All problems in computer science can be solved by another level of indirection***", David Wheeler



Proposed Solution - P1930.1 Standard contd.

- Replacement of Access Controllers with two new entities
  - SDN Controller
  - SDN Middleware
- Segregation of Control and Data @SDN Middleware wherever required
- SDN Controller responsible for Control of Access Network
  - Logically centralized control plane
- Interface as exposed by RAN nodes abstracted at SDN Middleware
- SDN Middleware acts as the AC to the APs
- Standard and Open Interface between SDN Middleware and SDN Controller
- Vendor independent management and control of radio access network by the SDN Controller
  - Interoperability across network elements from different equipment vendors
- AAA for UE Authentication can be reached either via SDN Middleware or via SDN Controller

IEEE P1930.1 – What else does it Achieve?



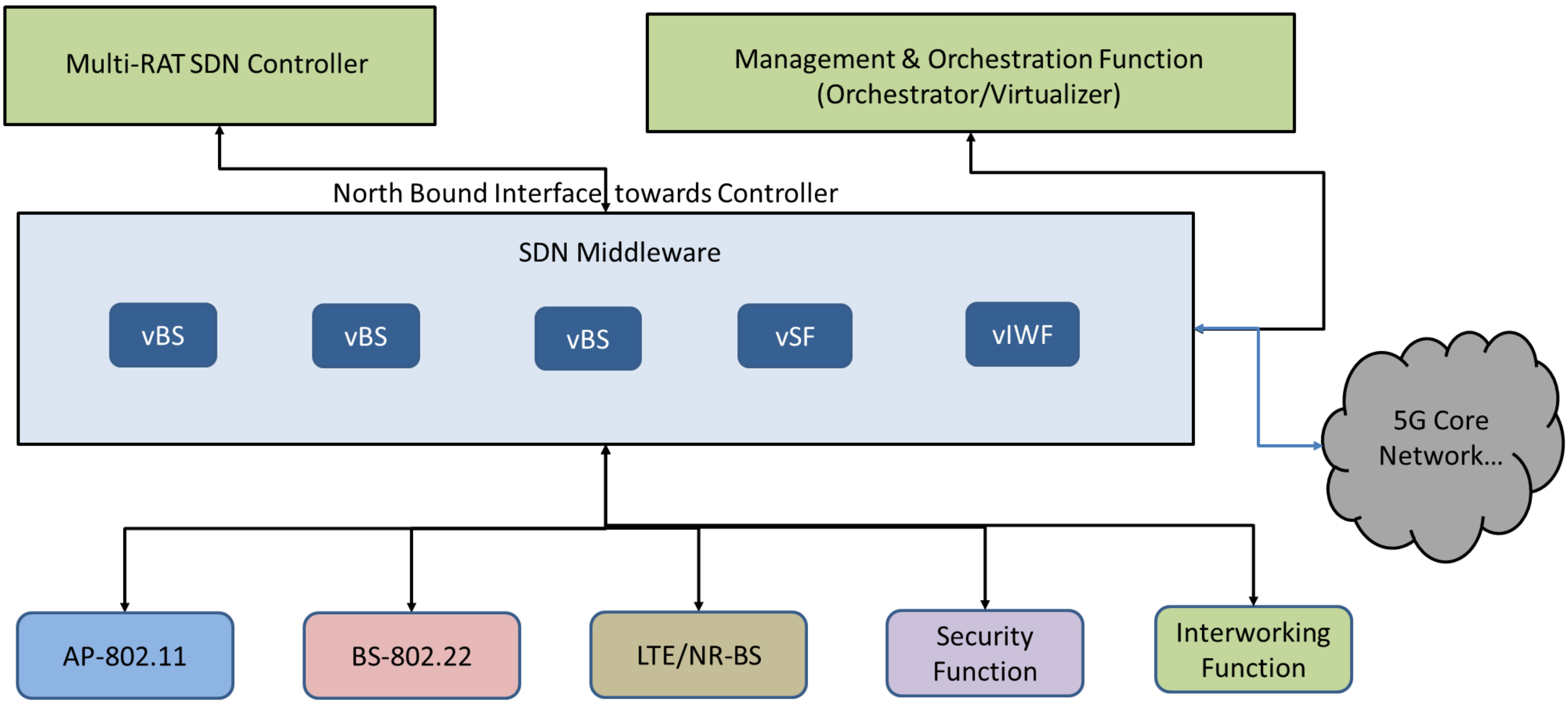
- Core Network - Moving towards a unified Core
  - 3GPP 5G Core - Supports LTE, Wifi and 5G NR RAN
- However RAN is
  - Fragmented - Controlled and Managed Independently
  - Each 5G NR - gNB has a Control function in gNB CU
  - Each LTE - eNB has its own control function
  - WiFi Access Points typically managed by an Access Controller
- IEEE P1930.1 can address this RAN Fragmentation

Unified Multi-RAT Control

IEEE P1930.1 - Unified Control and Management

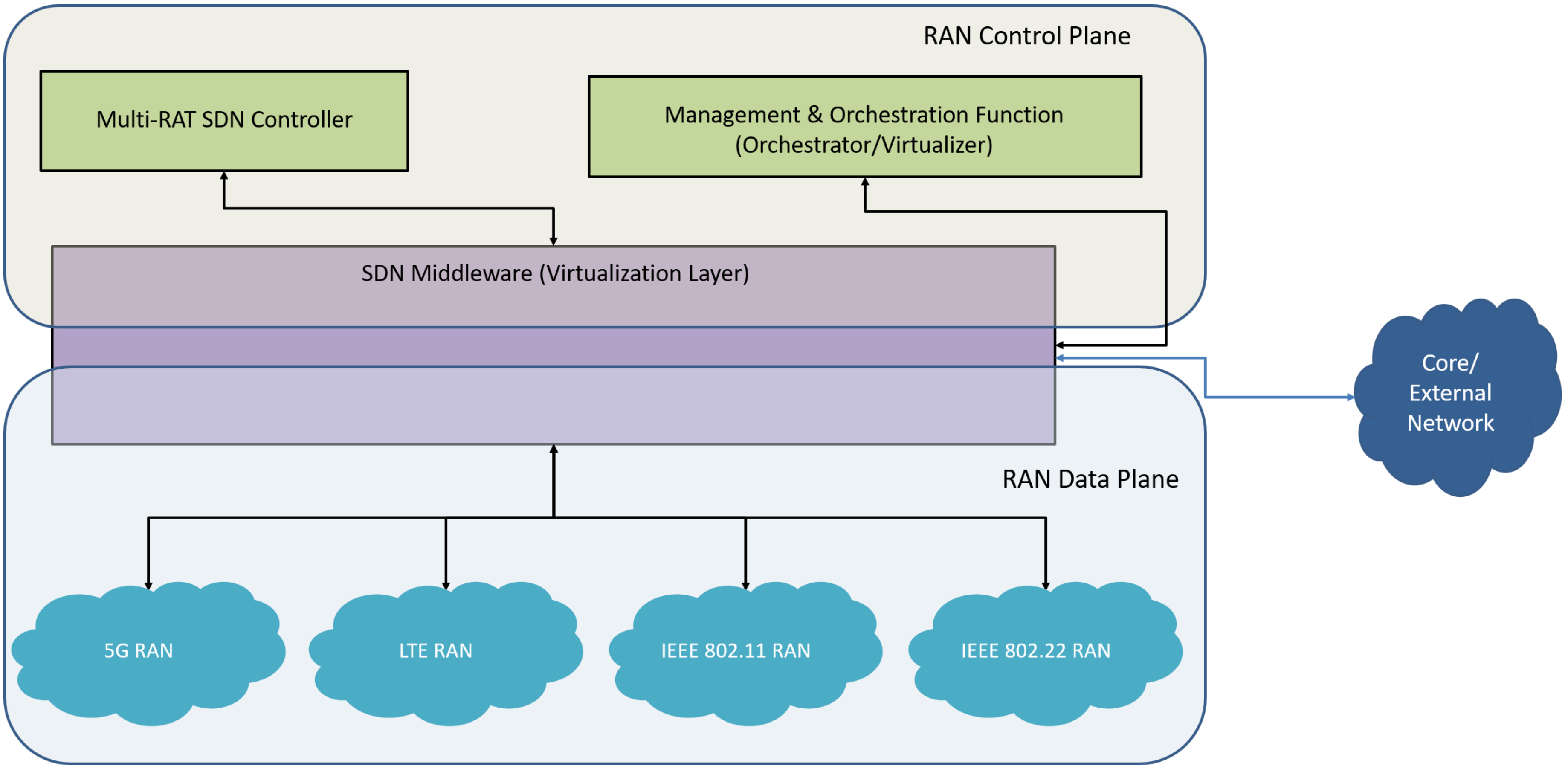
- Goal
  - Unified Control and Management of Multi-RAT Heterogeneous Access Networks
- SDN Middleware to facilitate
  - unified control of multiple RATs, e.g., IEEE 802.11 WLAN, IEEE 802.22 WRAN
  - Seamless integration of IEEE radio access technologies with non-IEEE technologies within SDN framework
- RAN can be thought of comprising of multiple functions
- Radio Tx/Rx Function
  - May include Physical Layer, MAC Layer etc.
  - BS can support this function
- Security Function
  - Encryption and Integrity Protection
  - Can be a part of the BS also
- Interworking Function
  - Interworking with Core
  - Interfacing towards Core – in case of 5G it may comprise of N2/N3 Interface Functions
- ….
- The Functions may be managed/controlled by the Controller

IEEE P1930.1 - Unified Control and Management



- There may be additional RAN Functions, not shown here
- Connectivity to 5G Core Network (other networks) may or may not be through the virtual functions
- Virtual Functions may be used for only control and management purposes by the unified Multi-RAT Controller

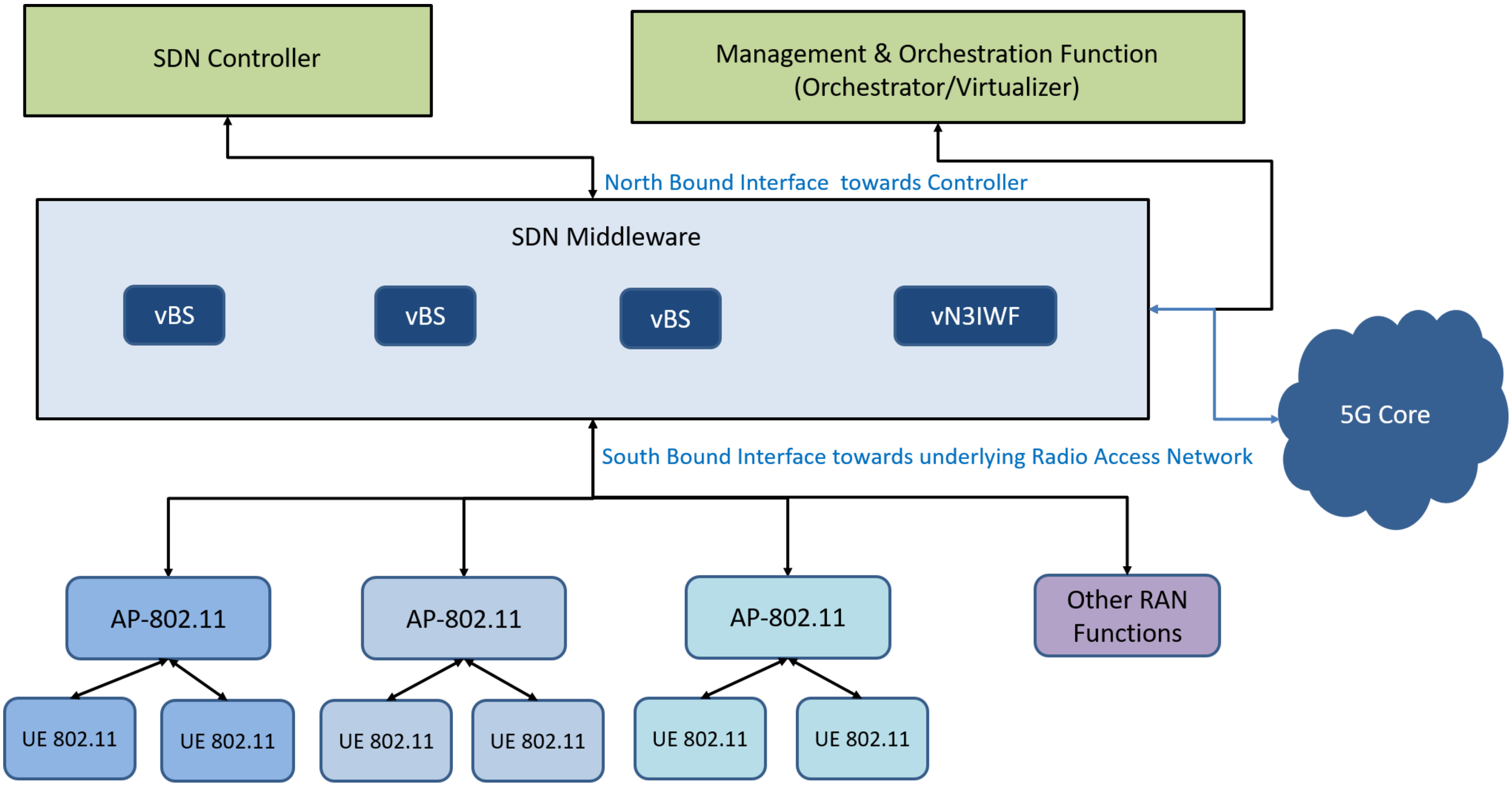
IEEE P1930.1 – Proposed Multi-RAT RAN Architecture



IEEE P1930.1 - Key Architectural Components

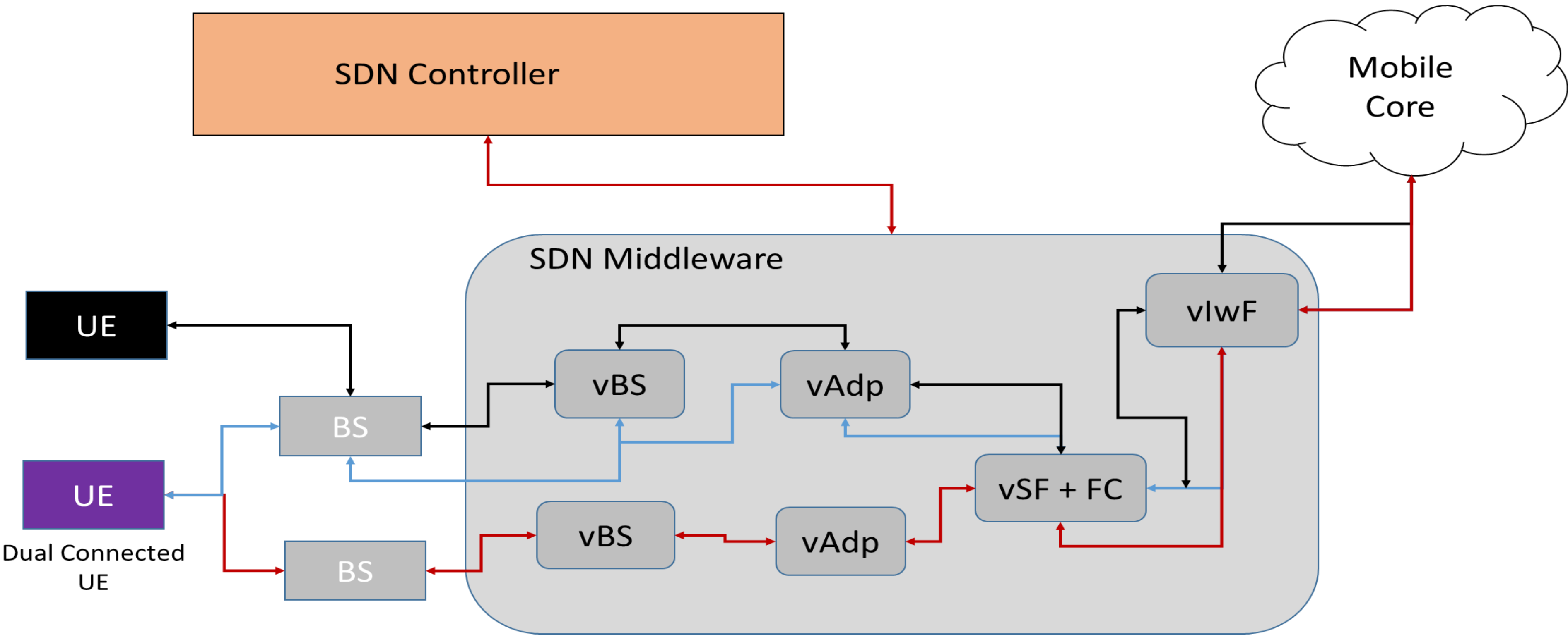
- SDN Middleware
  - Presents an Abstract Information Model of the underlying RAN
    - Through Virtual Network Entities
      - Virtual Base Stations(vBS) for Base Stations (BS) and APs
      - Other functions, e.g., for 3GPP 5G Core Interworking Function (N3IWF)
    - Enables features like Network Slicing in RAN
  - Northbound Interface of the Middleware
    - Interface between the virtual entities and the Controller
    - From the Controller perspective, it appears as if it is interfacing directly with the physical BSs
    - NETCONF for Management and Openflow for Control
  - Southbound Interface of the Middleware
    - Interface between the physical infrastructure, e.g., AP, BS and the Middleware
    - Can be based on vendor specific or standard protocols, e.g., LWAP, CAPWAP, TR-069, SNMP
  - Middleware maps the Southbound Interface with the Northbound Interface
- SDN Controller
  - Responsible for Control and Management of the Access Network
- Management and Orchestration Entity
  - To orchestrate and manage the SDN Middleware (the virtualized network entities) over the RAN Infrastructure
- Radio Access Network Infrastructure
  - Access Points, Base Stations, Network Interworking Functions

IEEE P1930.1 – WLAN Interworking with 5G Core

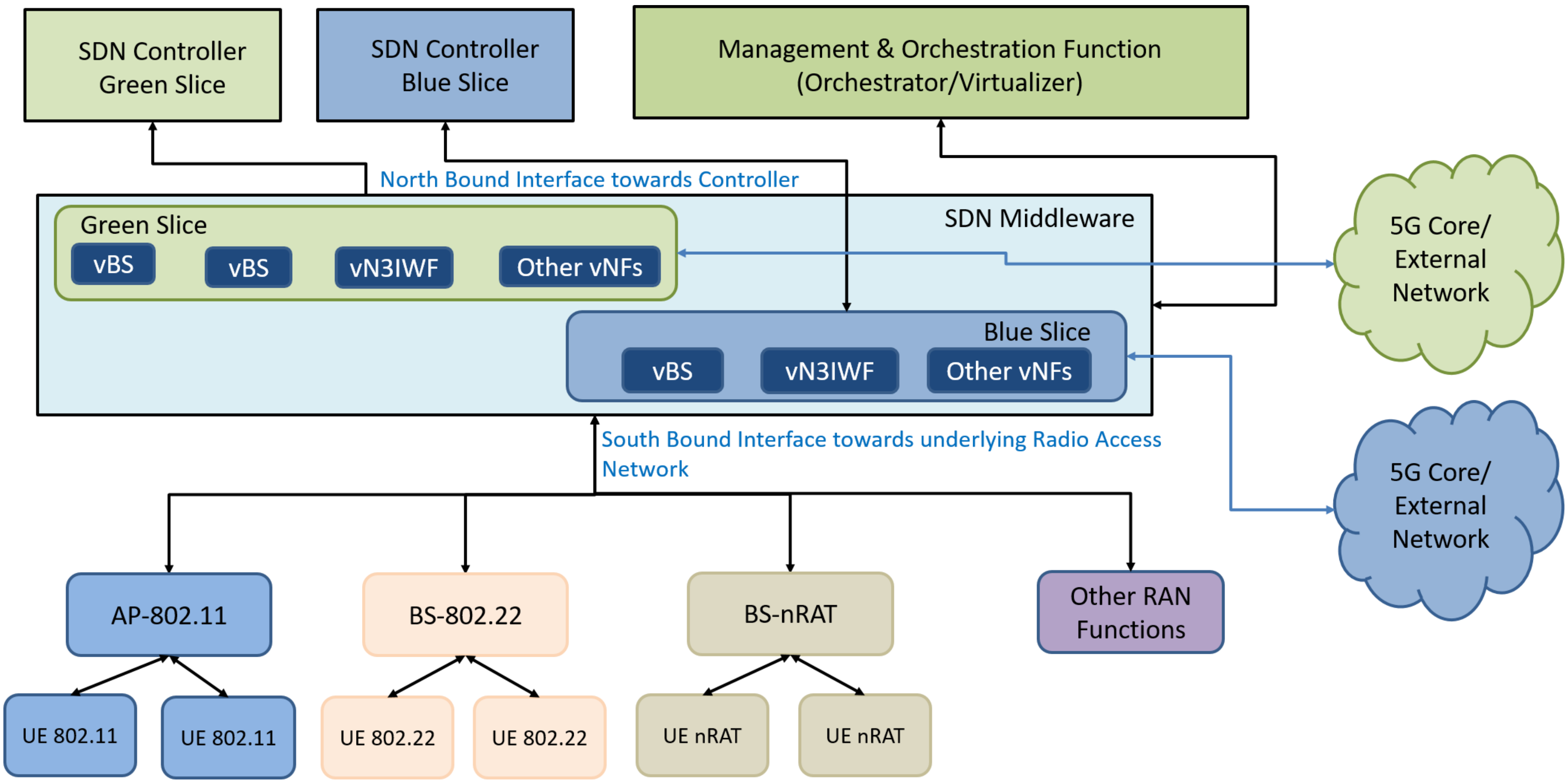


P1930.1 and Dual Connectivity Support

- One of the UEs connected to two Base Stations
- Traffic From Core
  - Via the same Interworking and Security and Flow Control Function
- Delivered through different BSs via BS specific Adaptation
- SDN Controller sets up Data path through the Middleware/BS
- Dual Connectivity across RATs supported with ease
  - LWA/LWIP/LTE DC/MR-DC (All DC variants)

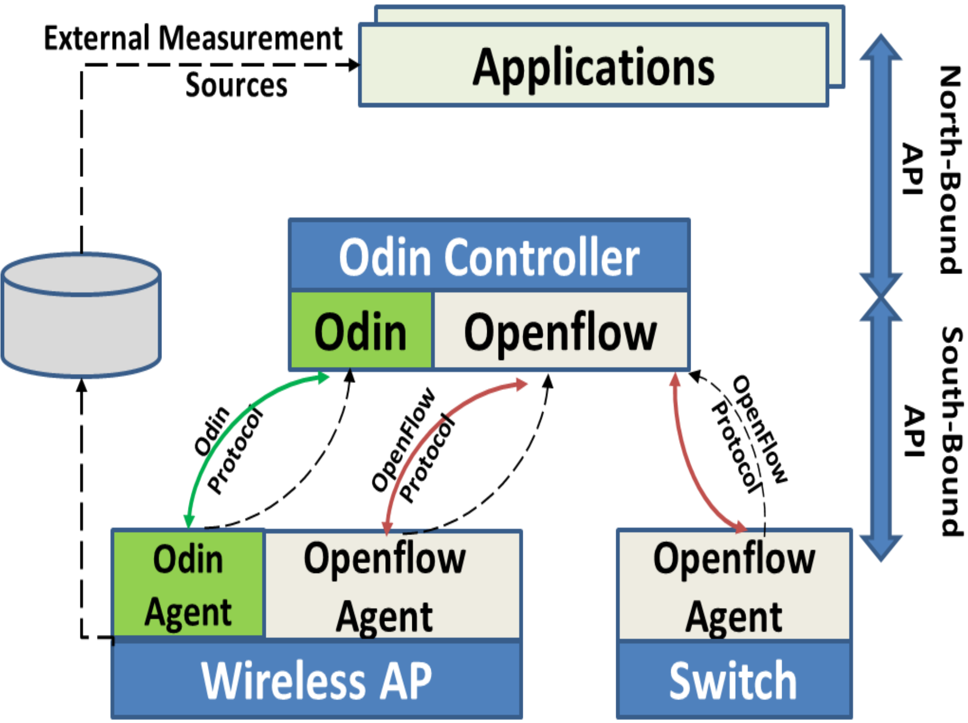


P1930.1 based Architecture - Network Slice support



Radio Resource Management and a Few Other Use cases

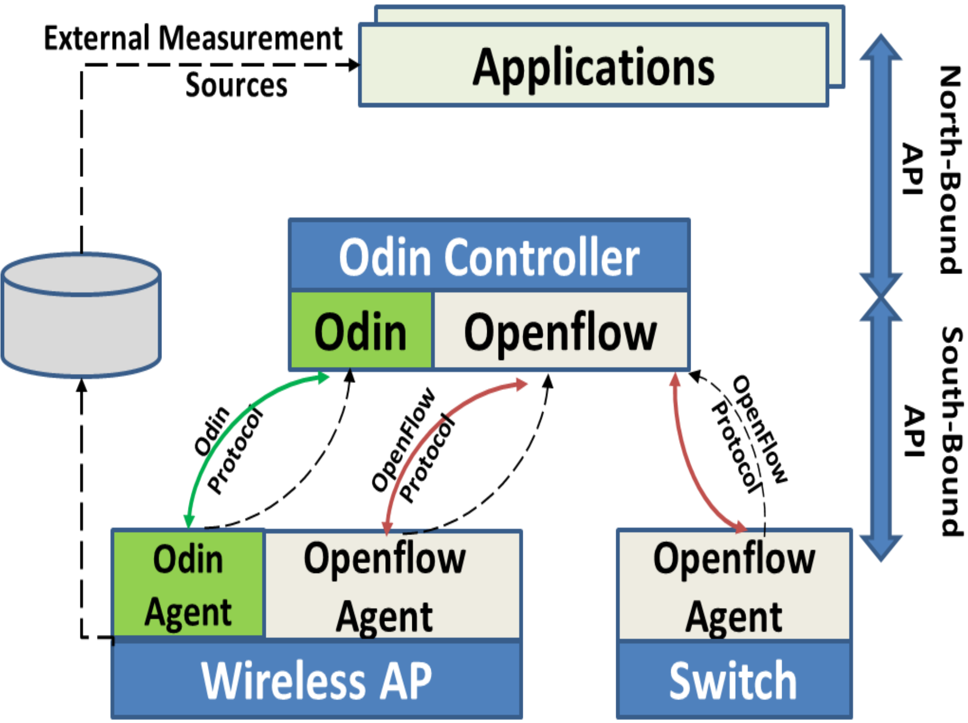
SDN based Load Balancing in WiFi Networks – Odin (1/2)



- WiFi Network - uneven load across APs is an issue
- Odin – A Software Defined Framework for Enterprise WLANs
- Concept of virtual APs
  - One virtual AP for each client (UE)
  - Instantiated on physical AP and associated with Client
- Virtual AP moved across physical APs along with the movement of Client
  - Under the control of the Controller
  - Reduced handover overheads
- Enables centralized control of load balancing and mobility

Courtesy: *J. Schulz-Zander, L. Suresh, N. Sarrar, A. Feldmann, T. Huhn, and R. Merz, "Programmatic Orchestration of WiFi Networks," USENIX Annual Technical Conference, 2014*

SDN based Load Balancing in WiFi Networks – Odin – 2/2

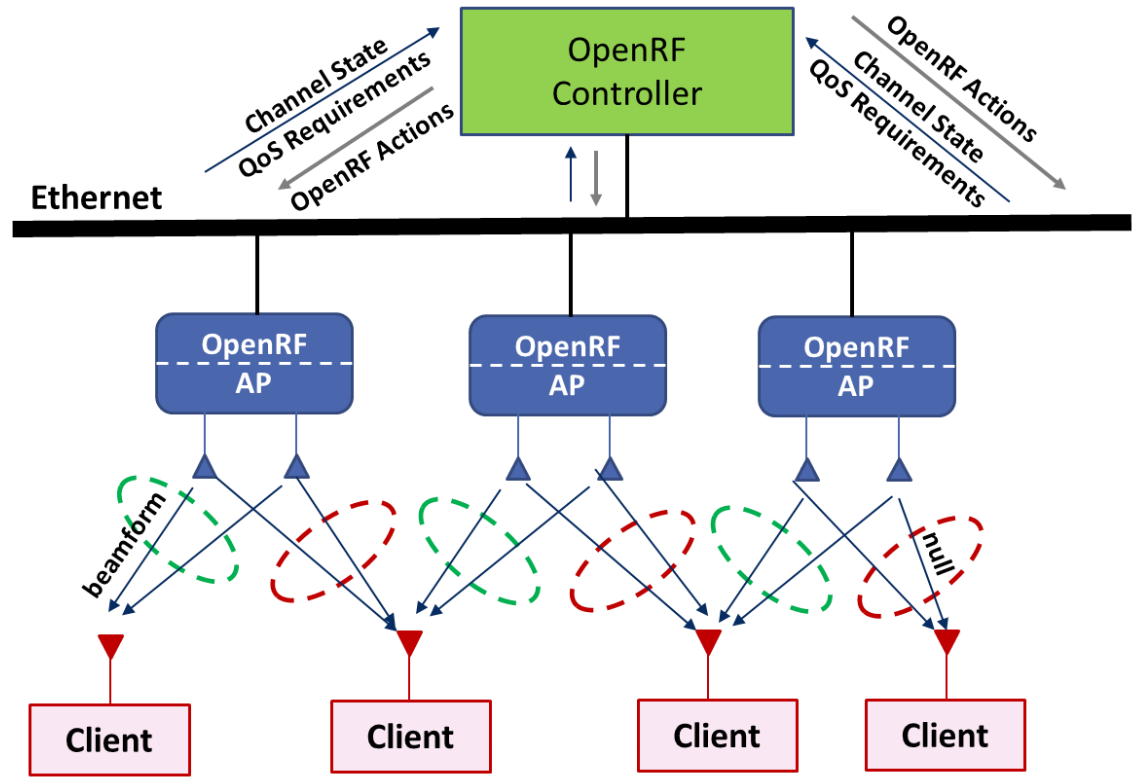


- How Does it Work?
  - Explain
- Can a similar mechanism be used in LTE/5G based networks
  - eNB/gNB?
  - What will be required?
- Advantages
  - User-centric Design
  - Probably the first example of user centric design
- Is SDN required for User Centric Design

Courtesy: *J. Schulz-Zander, L. Suresh, N. Sarrar, A. Feldmann, T. Huhn, and R. Merz, "Programmatic Orchestration of WiFi Networks," USENIX Annual Technical Conference, 2014*

SDN based Interference Management for WLAN - OpenRF

- Interference an issue for WLANs
  - Clients may receive interfering signals from neighbouring APs
- OpenRF
  - SDN based scheme for Interference Management
  - Controller manages APs
    - MIMO based scheme for Interference Management
      - Interference Nulling
      - Interference Alignment
    - APs on the same channel cancel their interference at other's clients
- Controller - AP Interface
  - Protocol modeled on OpenFlow
  - interference control information supplied to APs



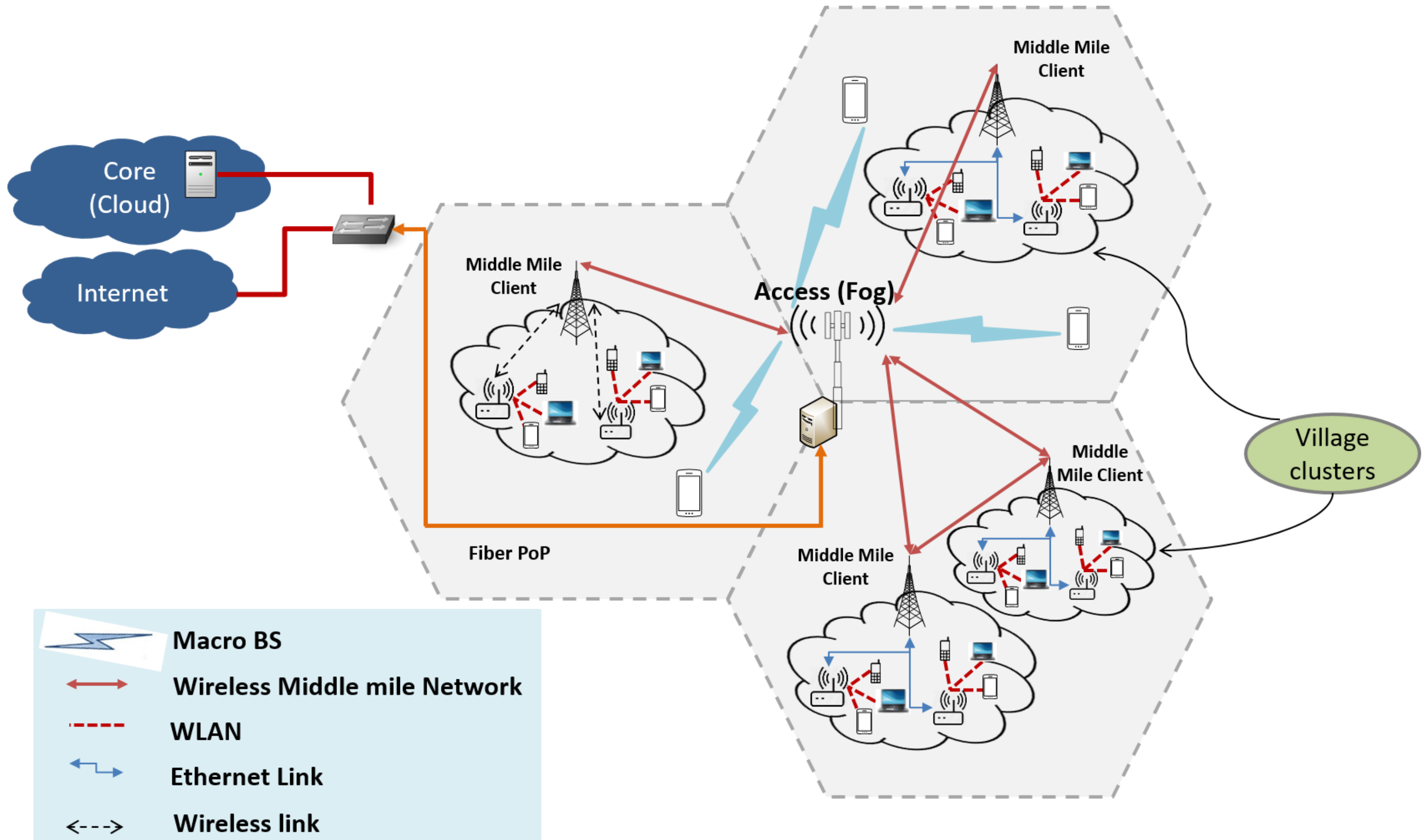
Courtesy: *S. Kumar, D. Cifuentes, S. Gollakota, and D. Katabi, "Bringing Cross-Layer MIMO to Today's Wireless LANs," ACM SIGCOMM Computer Communication Review, 2013.*

Optimal Radio Access Technology Selection Algorithm for LTE-WiFi Network

- Optimal Association Policy Algorithm in LTE-WiFi HetNet
- SDN based RAN Architecture
  - Logically Centralized Multi-RAT RAN Controller
    - Possesses a Global view of the Network Resources
  - RAT selection and offloading decisions taken by the Controller
- Voice and data users arrive or depart at any point in time
- Data user may be offloaded from one RAT to another at the time of association or departure of a user
- Problem Formulated within the MDP framework
- Addresses the inherent trade-off between
  - Total System Throughput and Blocking Probability of Voice Users
- Maximizes the total system throughput
  - subject to a constraint on the voice user blocking probability, using CMDP
- Threshold structures of optimal policies established
- Algorithms based on the Threshold Structures of Optimal Policies

Courtesy: *A. Roy, P. Chaporkar, and A. Karandikar, "Optimal radio access technology selection algorithm for lte-wifi network," IEEE Transactions on Vehicular Technology, vol. 67, no. 7, pp. 6446–6460, 2018.*

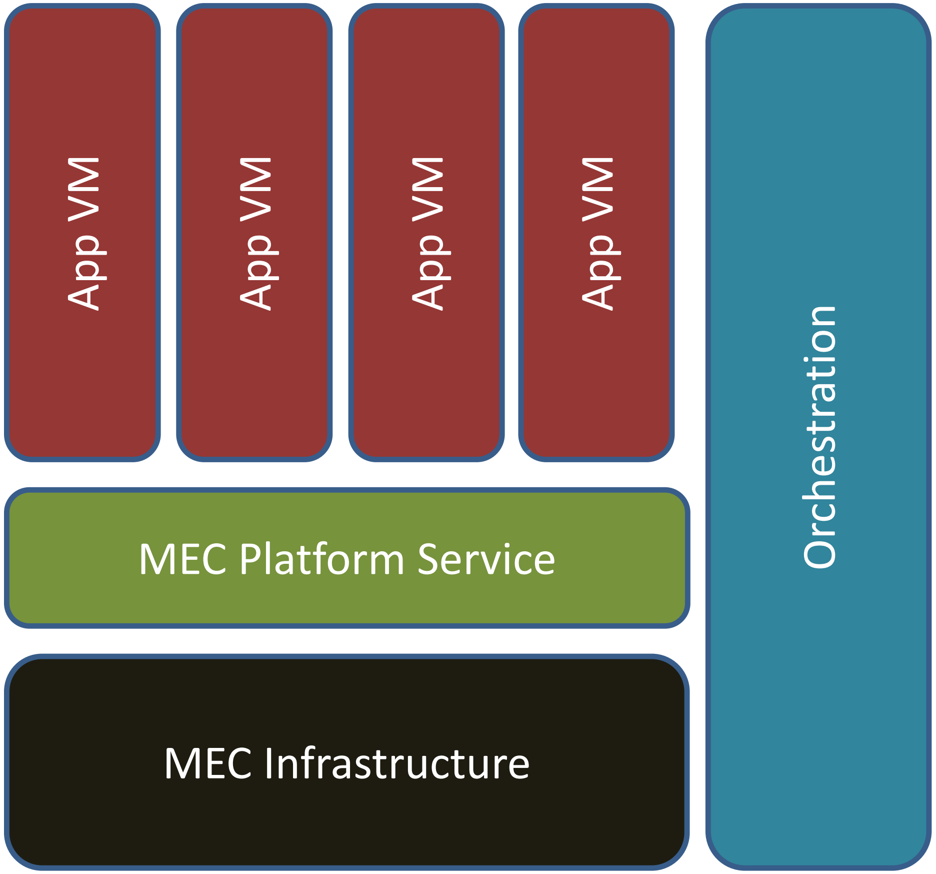
Integrated Access & Backhaul – Rural Broadband Use case (*Under Development*)



SDN based unified RAN Control	Integrated Access & Wireless Backhaul (Middle-Mile)
Usage of Virtual Network Functions	To make the system cost-effective
Intelligence at the edge	Enables Local Communication & Optimizes Resource Usage

Multi-Access Edge Computing and NFV

- MEC – An Important Use case of 5G
  - Content caching
  - Optimized Video Delivery
  - IoT
  - Augmented Reality Service
  - Connected cars
  - …
- NFV – Plays a very Important Role in MEC Deployment



Courtesy: ETSI

SDN based Wireless Network Architectures – Key Takeaways

- Effective Interference Management
  - OpenRF
- Better Mobility Management & Load Balancing
  - Odin, OpenRoads
- Efficient Radio Network Utilization
  - OpenRoads, SoftRAN, Radiovisor for Cellular Networks
- Unified Control and Management
  - Reduced Signaling Overheads and Efficient E2E Network Utilization
  - 5G-EmPOWER, MobileFlow, IEEE P1930.1
- May bring additional advantages
  - Independent Evolution of Control and Data Plane

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Questions ??

Thank you