TOWARD AN INTELLIGENT, MULTIPURPOSE 5G NETWORK

Enhancing Mobile Wireless Networks

Jin Yang and Yee-Sin Chan

Fifth-generation (5G) networks are evolving from special purpose-built networks to software-defined, intelligent, multipurpose networks, enabling service innovation and autonomous network operation. In this article, we present an intelligent mobile edge network based on standardized 5G network function entities and New Radio (NR) radio access networks (RANs). We propose a multitier, self-organizing network (SON) with a middle-tier SON (mSON), centralized SON (cSON), and distributed SON (dSON) to support increasing network dynamicity for different verticals and to take advantage of the latest high-layer F1 interface. This is essential to support low-latency applications and ultrahigh-reliability services. It also enables more dynamically tight interworking of 5G NR and LTE with dual connectivity, expanding initial 5G NR coverage. We analyze a lower-layer RAN split to optimize fronthaul and so further improve radio efficiency by utilizing the multitier SON among various radio nodes as well as distributed units (DUs) and centralized units (CUs). This will facilitate massive multiple-input/multiple-output (MIMO) antenna systems and accelerate centralized and virtualized RAN deployments.

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Traditional wireless networks are specifically built for voice and Internet data services among human beings. The architecture is application specific, lacking the kind of scalability and flexibility that would allow for service innovation. 5G mobile wireless networks are fundamentally changing from connectivity-based networks to service-based intelligent networks, exemplified by the recent shift of connections from primarily human beings to "everything," including connected pets, shipping containers, bikes, LED street lights, and other functions such as tracking medicinal drugs and trucks. Thus, 5G networks are envisioned to broaden our reach for a variety of services, including enhanced multimedia mobile broadband (eMBB), massive machine-type communication (mMTC), and ultrareliable low-latency communication (URLLC) services [1]. Verizon [2] predicts double-digit growth and expects game-changing 5G services. Intensive field tests [3] have demonstrated distinguished radio characteristics for such Internet of Things applications.

To meet service-centric requirements, 5G architecture is transforming to a highly scalable, software-configurable dynamic network with increased performance requirements. Specifically, 5G technology is evolving from a hardware-centric, special-purpose network to a software-defined, multipurpose, intelligent network, enabling services innovation, network configurability, and dynamicity while minimizing operation and management costs.

The 3rd Generation Partnership Project (3GPP) successfully completed the first 5G NR specifications [4]. This standard has set the stage for the global mobile industry to start full-scale deployment of 5G NR. Large-scale trials and commercial deployments are expected for 2019. The standards body is continuing to develop other architecture options with the next-generation 5G core (5GC) and to enhance end-to-end network functionalities. This 5GC network is crucial for operators to further explore the advanced capabilities for consumers, enterprises, and different vertical market segments. The 5GC supports end-to-end network slicing and differentiated quality of service (QoS) awareness from radio, transport-to-core, and application servers.

Intensive research has been conducted to explore this new architecture for various deployment scenarios and different application services. The European Telecommunications Standards Institute issued a white paper on multiaccess edge computing (MEC) in 5G [5]. The 5G architecture enables a more flexible software-based network on a distributed cloud platform. The tradeoffs between latency and reliability with spectral efficiency and coverage are analyzed for tactile Internet services [6]. A SON is essential to enable software-defined networking for novel applications [7]. Efficient supports for these new low-latency use cases with high scalability and reliability have driven standardized RAN splitting interfaces. Various functional split options supporting CUs and DUs are intensively studied in [8] and [9]. However, while the new RAN split architecture provides better adaptivity for different use cases and allows more scalable and cost-effective hardware implementations, it also creates more challenges from the operation and management point of view. In particular, one urgent issue that needs to be resolved is that of how to manage the increasing network entities and effectively optimize real-time performance in a broader virtualized network.

In this article, we discuss some key components in an intelligent mobile edge network to expedite network upgrades and provide innovative service delivery. We propose a multitier SON architecture with an mSON, a cSON, and a dSON to take advantage of the latest standardized high-layer split. This is required to support various URLLC applications. It also enables tight interworking of NR and LTE technologies. This dynamic and robust dual connectivity is essential to expand initial, limited 5G NR coverage. We also discuss the need for a flexible lower-layer split coordinated with a dSON to allow interoperability among different vendors' radio components, from radio units (RUs) to DUs and CUs. This expands deployment options, accelerates the adaptation of massive MIMO antenna systems as well as centralized and virtualized RANs, and maximizes radio efficiency and user performance.

A 5G Intelligent Mobile Edge Network

The 3GPP 5G network architecture is evolving from a point-to-point link approach to a service-based architecture, as illustrated in Figure 1 [10]. The user equipment (UE) connection to the RAN is controlled by the access and mobility management function (AMF), which includes the network slice-selection function (NSSF). User traffic data are connected to the data network through the user plane function (UPF), which is controlled by the session management function (SMF). Compared to the mobility management entity in the evolved packet core (EPC) in LTE, the separation of access control and session management in the 5GC provides greater flexibility and scalability, particularly for control-plane-only traffic or non-Internet Protocol (IP)-session applications. The Serving Gateway and Packet Gateway functions in EPC are separated as GW-control (C) and GW-user (U), supported by SMF and UPF, respectively. The policy control function provides a policy framework that incorporates network slicing, roaming, and mobility management, similar to the policy and charging rules function in EPC in LTE. The application function requests dynamic policies or charge control. Unified data management stores

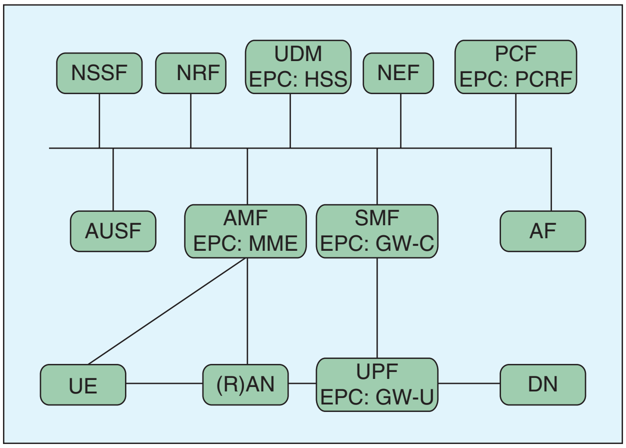

FIGURE 1 The 3GPP 5G architecture. NRF: network resource function; UDM: unified data management; HSS: home subscriber server; NEF: network exposure function; PCF: policy control function; PCRF: policy and charging rules function; AUSF: authentication server; MME: mobility management entity; AF: application function; DN: data network; GW-C: Gateway-control plane; GW-U: Gateway-user plane.

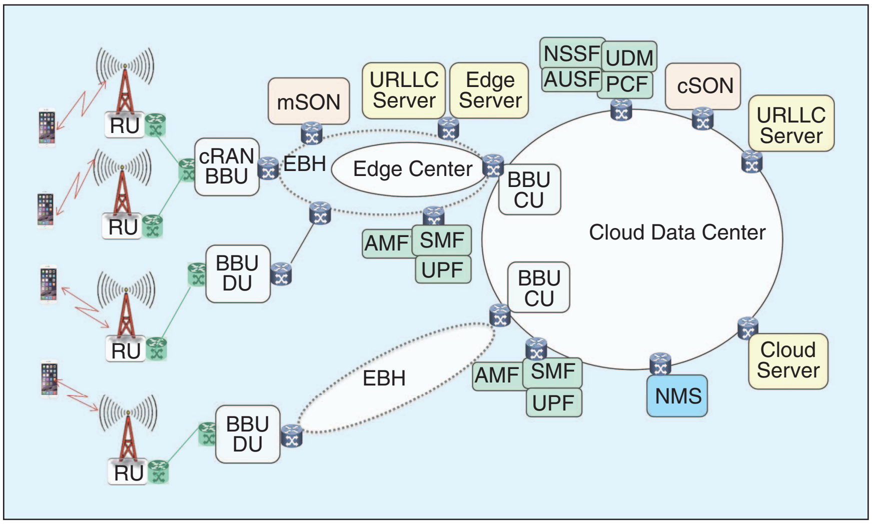

FIGURE 2 A 5G intelligent mobile edge network. EBH: Ethernet backhaul.

subscriber data and profiles, similar to the home subscriber server in LTE.

The 5GC introduces a key concept of end-to-end network slicing that allows differentiated allocation of the required network features and resources to various services. These network functions and services are registered in a network resource function. The network exposure function acts as a centralized point for service exposure and authorizes all access requests from external systems. The NSSF assists in the selection of suitable network slice instances for users and services. The AMF is responsible for access authentication and authorization, mobility management, termination of the control plane interface and nonaccess stratum, lawful intercept, and security functions. It is further connected to the authentication server for these functions. The SMF supports session management, IP address allocation and management, selection and control of the UPF, the control part of policy enforcement, QoS management, policy control and charging functions, downlink data notification, and roaming functionality.

This newly defined network architecture enables a more refined standardized network virtualization and allows intelligence to allocate network resources at the core and various edges to support diverse applications and services. The RAN, core network components, network management and controller, and application servers are based on more general-purpose hardware platforms, dynamically configurable under a flat architecture, as seen in Figure 2. The choice of general-purpose hardware and, thereby, the cloud implementation facilitates operators' provision of various services—for example, connected cars, virtual reality, and augmented reality—under a common physical platform, enabling resource sharing and pooling, service integration, and service customization. The RU and baseband unit (BBU) are more intelligently utilized through the Ethernet backhaul. This supports a centralized RAN (cRAN) and a separated CU and DU, commonly known as *CU/DU split*.

While network architecture is becoming service oriented, the network management system (NMS) is also evolving from traditional pure-performance monitoring that closely interworks with a semi-automated SON in LTE to a fully autonomous 5G network. Various self-configuring, self-optimizing, and self-healing mechanisms enable zero-touch network provisioning and minimize human intervention, from installations to commercial operations. We discuss these SON mechanisms further in the sections "An mSON Utilizing a High-Layer Split" and "A Multitier SON."

The virtualized network and application servers allow operators to create new value-added services for their customers with less dependency on the underlying hardware, and they make the services transparent across the entire network. This enables low-latency and ultrareliable services by pushing core network components and servers toward the edge for MEC. To further facilitate RAN virtualization and cRAN implementation, different RAN functional CU/DU splits are under intensive investigation by both academics and industry forums.

An RAN Functional Split

RAN CU/DU functional splits facilitate the virtualization of RAN networks into software-defined components, allowing easy modification and customization through emerging network features, such as network slicing and the SON. The splitting of RAN architecture into CUs and DUs needs to cater to different deployment scenarios and challenges, including supporting the introduction and evolution of various RAN capabilities, such as coordinated/joint processing, massive MIMO, and advanced receivers. It also must facilitate new use case developments and allow business innovation, such as eMBB, cellular vehicle-to-everything services, and mMTC devices. The splits should further attempt to minimize fronthaul throughput requirements, scaling as a function of user throughputs.

The 3GPP has defined various split options between the CU and the DU based on the reference models in [11]. The most widely studied and commercially viable split options are illustrated in Table 1. Option 2 has radio resource control and the packet data convergence protocol (PDCP) in the CU, while the radio link control (RLC), medium access control, physical layer, and RF are in the DU. Option 7 splits within the physical layer (known as an *intra-PHY split*), while option 8 has the traditional physical layer and RF layer split (known as a *PHY/RF split*), as typically defined by the Common Public Radio Interface (CPRI).

The different split options determine the tradeoff between fronthaul bandwidth and latency requirements as well as the centralization gain due to improved cell coordination capabilities, as indicated in Table 1. The lower the split point, the higher the centralized spectral efficiency gain, at the expense of a higher bandwidth and stringent latency fronthaul requirements. For example, option 2 requires approximately 10-ms round-trip time latency with a bandwidth roughly equal to the user packet data rate (P), while the latency requirement for option 7 is about 250 μs. The bandwidth requirement for option 7-1 proportional to the number of transmit-and-receive (TRx) ports is much higher than for option 7-2, proportional to the number of layers. The conventional CPRI fronthaul bandwidth is proportional to the multiple of the number of antenna elements and the number of layers. Thus, its bandwidth requirement is much higher than option 7, as the number of antenna elements is much higher than the number of TRx ports in a massive antenna system.

These split options and their variations present different deployment opportunities and challenges. While specifying more split options results in greater deployment flexibility, it becomes more difficult for interoperability and the building of the ecosystem. Thus, it is generally agreed that the standardization of two to three split options should be a good compromise between deployment flexibilities and development complexities.

Option 2 for a high-layer split and option 7 for a lower-layer split provide logical compromises in terms of the transport network requirements for different radio frequencies, support of coordinated RUs with different radio capabilities, RAN virtualization, and application-specific QoS settings. The high-layer split is generally preferred for mm-wave products and deployments, while the lower-layer split will be considered in sub-6-GHz NR deployments for features such as massive MIMO. We provide more analyses of these two functional split options in the following sections.

An mSON Utilizing a High-Layer Split

An option 2 high-layer split enables more efficient central radio control with the centralized PDCP and distributed functions below the RLC. It has been specified as the F1 interface in [12], and it is expected to be extended to evolved LTE as the V1 interface [13]. Thus, we propose a new fast-response mSON control function that fully utilizes this F1 interface to complement the conventional dSON at the base stations and cSON functionality at the central NMS level. The mSON allows control of traffic routing for ultrareliable and low-latency services as well as dual connectivity and spectrum sharing among various 5G NR and LTE radio nodes. Thus, it can manage radio resources efficiently to differentiate different network slicing based on end-to-end service requirements.

A traditional cSON with a response time longer than 1 s functions as a long-term network management tool, providing services such as automatic network configuration, remote electrical antenna tilting, core network slicing, and end-to-end traffic steering. Taking advantage of the F1 interface, this new mSON, with a response time lower than 100 ms, allows the managing of traffic by controlling the aggregation points and routing among the DUs based on radio resource availability and user service requirements. Therefore, this mSON is particularly suitable for radio network slicing, handover decision, QoS provisioning, dual-connectivity management, spectrum-sharing management, and load balancing across multiple bands.

A high-layer split is particularly attractive for mm-wave due to its moderate transport bandwidth requirements. Specifically, the F1 interface has bandwidth requirements similar to user data rates and can tolerate a more relaxed latency of 10 ms compared to other lower-layer split options. Thus, it supports a wide range of deployment scenarios. In the following sections, we describe two specific use cases to illustrate the advantages of mSON in the emerging 5G network management architecture: URLLC and interworking between NR and evolved LTE.

***Table 1** RAN splitting and performance tradeoff.*

Splitting Options	Splitting Points	Fonthaul Required		Centralization gain	Preferred Products
		Latency	Bandwidth		
Option 2 (F1)	Layer 2 PDCP/RLC	10 ms	P: packet data rate	Low, among CUs only	mm-wave
Option 7 (oRAN)	Layer 1 Intra-PHY	250 μs	7-2: Px#layer 7-1: x#TRx	Medium, among CUs and DUs	Sub-6 GHz 7-2: Eight or more TRx ports 7-1: fewer than four TRx ports
Option 8 (CPRI)	PHY/RF	250 μs	Px #layer x #antenna	High, among CUs, DUs, and RUs	Legacy radios

#layer: number of layers; #TRx: number of transmit-and-receive ports; #antenna: number of antennas.

URLLC

URLLC requires an intelligent core network and mobile edge computing. The high-layer split provides the opportunity for network management to direct traffic flexibly utilizing a high-layer aggregation point based on service requirements and deliver service at either a localized or virtualized RAN. A potential architecture to enable URLLC services under various latency levels is illustrated in Figure 2. This architecture supports URLLC with the UPF and control-plane function and application servers located at edge data centers and cloud data centers, respectively. With the mobile edge computing architecture, more stringent URLLC services could be provided at the edge with no dependency on the rest of an operator's transport and core networks. AMF, SMF, UPF, and URLLC servers can be implemented physically at the customer site or designated edge server or virtually through operator cloud data centers. The mSON can provide middle-tier traffic routing control and regional parameters optimization, such as the level of power boosting and retransmission or repetition, subject to constraints on both latency and reliability requirements. It can also provide support for cSON cloud-based traffic routing, depending on latency, reliability, and other service requirements.

LTE and 5G NR Interworking

Tight interworking based on dual connectivity between LTE and NR is essential to extend initial NR coverage, particularly with a significant portion of initial NR on mm-wave. A deployment of only mm-wave becomes challenging for coverage and blockage because of the nature of its propagation characteristics. Dual connectivity in both 5G NR and LTE is achieved through a PDCP/RLC split interface. This alignment between LTE/NR tight interworking and a functional split is beneficial from network migration, operational, and management perspectives.

The 3GPP provides three different types of LTE and NR RAN tight integration based on dual connectivity. The main difference is the anchoring technology: 1) LTE, as the anchoring access technology, connected to EPC; 2) NR, as the anchoring access technology, connected to the 5GC; and 3) evolved LTE, as the anchoring access technology, connected to the 5GC. The type of NR and LTE interworking can be generalized, as shown in Figure 3, where the primary BBU could be a master node, such as a master eNB in LTE, with the secondary BBU being the secondary node, such as a secondary gNB in NR. As the network evolves and 5G penetration increases, the primary BBU could be an NR gNB, while the secondary node could be the legacy LTE eNB.

The high-layer split supports a natural point for mSON control of traffic steering, load balancing, and LTE/NR interworking. It can also coordinate multiple transmission points from multiple DUs and activate dual connectivity based on coverage, delay requirements, and traffic patterns. For example, in the use case of mMTC (transmission of small delay-tolerant data traffic), one could choose either LTE or NR to minimize signaling. Also, mm-wave carriers could be activated to support high data rates wherever mm-wave coverage is adequate, thereby reducing LTE network resources and minimizing device power consumption. A high-fidelity video may require aggregation or joint coordination among several carriers or DUs at the PDCP to minimize latency and handover interruption time. The IP Multimedia Subsystem-based services, such as voice, will be directed to LTE only for ubiquitous coverage because of the initial limited availability 5G NR. Thus, the proposed mSON provides fast, autonomous radio resource management among various radio BBUs. This enables low-latency and high-reliability, mission-critical applications and enhances the user experience across various radio technologies.

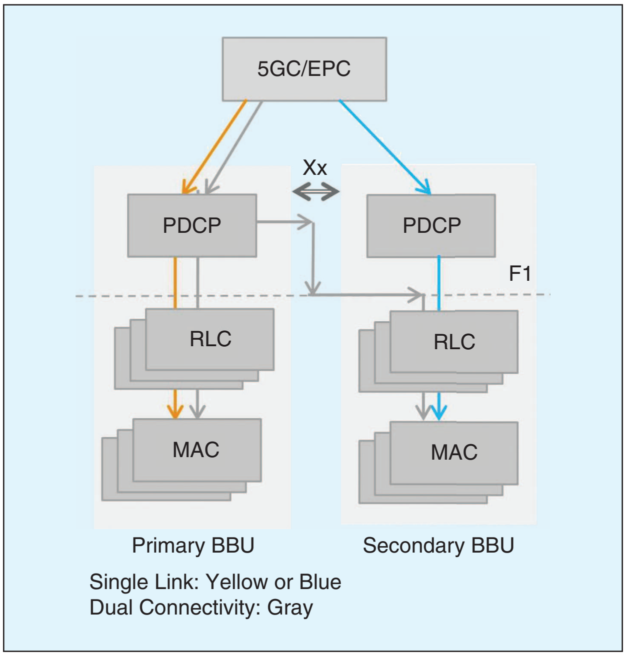

FIGURE 3 The NR and evolved LTE interworkings. MAC: medium access control.

A Multitier SON

A multitier SON is essential to enable full control of radio resource utilization to serve various use cases and applications using differentiated network slicing. The multitier SON consists of a conventional dSON and cSON as well as the proposed mSON. Currently, the dSON has been restricted to the same vendor because of a lack of interworking among various radio components. A standardized lower-layer split is critical for an open SON environment.

A lower-layer intra-PHY split has more stringent fronthaul requirements in both bandwidth and latency than those of the high-layer split option. However, it provides improved flexibility and scalability. The architecture is particularly desirable for deploying transmission schemes that require coordination among multiple cells, such as joint processing (for example, joint transmission and reception) and coordinated multipoint (CoMP) schemes to improve spectral efficiency. It also provides more relaxed fronthaul requirements for massive MIMO compared to the RF CPRI interface, as we illustrate further.

The standardizations and specifications of lower-layer CU/DU interfaces and transport requirements are under investigation in many organizations, such as the 3GPP [14], oRAN, IEEE Next Generation Fronthaul Interface Working Group, and CPRI. In [15], oRAN has published its first specification. A lower-layer split could enable a mix-and-match of the DU and RU from different vendors, facilitating RAN interoperability and virtualization. Because of the high bandwidth requirements, a lower-layer split is considered more suitable for sub-6-GHz deployments. For example, LTE Advanced coordinated processing features have been shown to improve spectral efficiency, and they would be a necessary feature for 5G NR eMBB over frequency bands below 6 GHz. Thus, a multitier SON can take advantage of this lower-layer split to enable an open SON among RUs, digital units, and CUs.

Massive MIMO

One important use case of lower-layer split is massive MIMO, particularly for the sub-6-GHz frequency bands. Conventional RUs are connected to digital units through the CPRI interface. As the number of antennas and layers increases, the fronthaul bandwidth requirement increases proportionally over this radio interface. Thus, the fronthaul throughput requirement could be increased by more than 10 times with 5G NR, which becomes infeasible in real network deployments. Thus, a higher lower-layer split, achieved by placing more functionality in the RUs such as in an intra-PHY split, is needed to reduce the fronthaul cost.

Multiple lower-layer split options are investigated to provide deployment versatility while still maintaining tight coordination among digital units. Those variations of option 7 are illustrated in Figure 4 as one implementation for options 7-1, 7-2, and 7-3. Option 7-1 keeps the RUs relatively simple by adding only the fast Fourier transform (FFT), inverse FFT (iFFT), and cyclic prefix (CP) as well as physical random-access channel functions, while option 7-2 includes precoding and resource mapping at the RUs. Option 7-3 adds modulation and layer mapping on the downlink.

The latency requirements for all three suboptions are similar, approximately 250 μs to support tightly coordinated transmissions and receptions. However, the fronthaul bandwidth requirements are different. The bandwidth requirement for option 7-1 is a function of the number of antenna ports. Thus, it increases significantly as the number of TRx antenna ports increases. In option 7-2, the bandwidth requirement is a function of the number of layers. It allows the antenna mapping at the RU and nearly doubles the RU complexity. Option 7-3 further reduces the bandwidth to the symbol-data-rate level. However, it splits the hybrid automatic repeat-request processing and demodulation among the DU and RU on the uplink. Thus, it creates more information exchanges among the interface and further increases standardization complexity.

Figure 5 illustrates average fronthaul bandwidth requirements under various lower-layer split options.

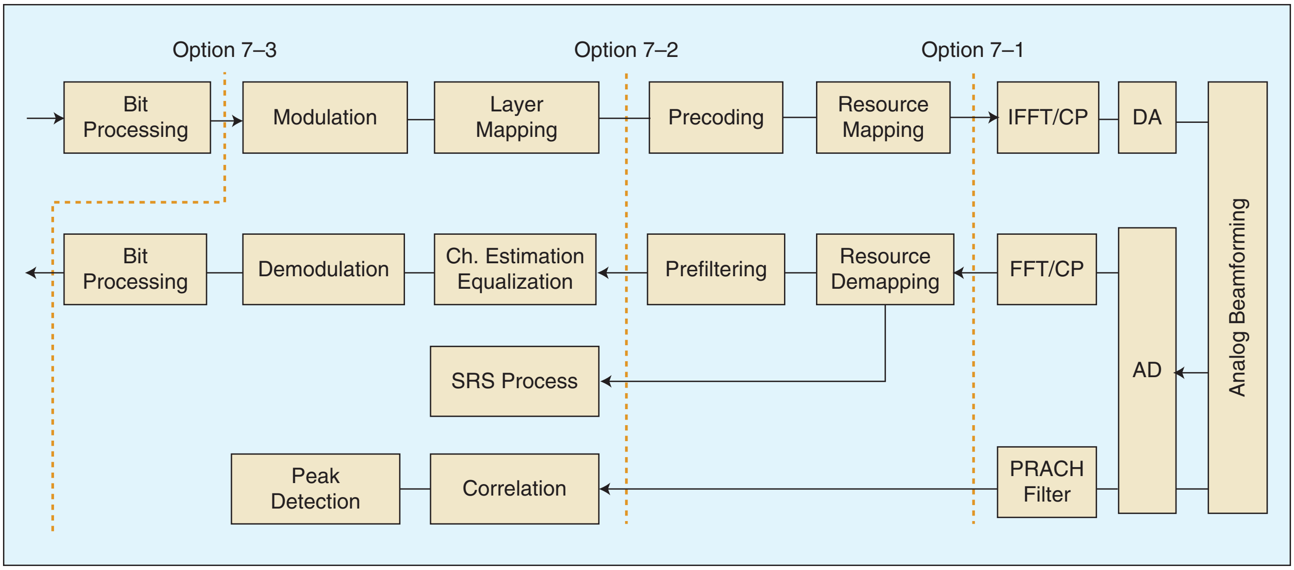

FIGURE 4 The variations of option 7 for lower-layer splitting. PRACH: physical random-access channel; Ch.: channel, SRS: sounding reference signal; DA: digital-analog converter; AD: analog-to-digital converter.

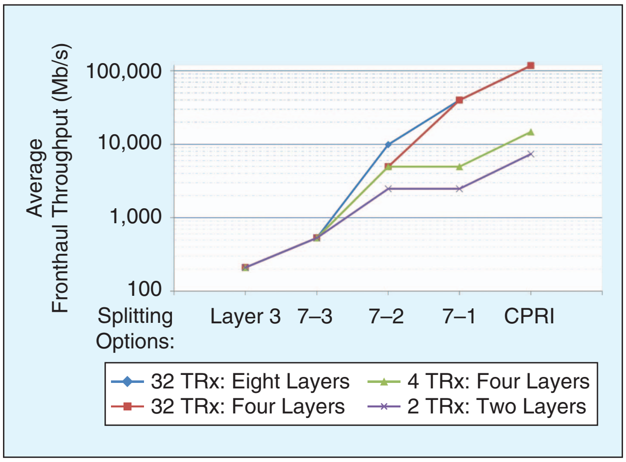

FIGURE 5 The average fronthaul bandwidth requirements.

When the number of TRx ports is fewer than four, option 7-1 can be implemented with one 10-Gb/s Ethernet connection. As the number of ports increases, option 7-2 or option 7-3 could be a more viable fronthaul transport solution. For example, for 32 TRx ports with eight MIMO layers, the fronthaul requirements can be reduced from 40 Gb/s based on option 7-1 to fewer than 10 Gb/s using option 7-2. Option 7-3 could further reduce the average fronthaul bandwidth requirement by at least one-quarter.

Therefore, a properly defined intra-PHY split can allow a well-dimensioned fronthaul with more practical implementation options. This will improve radio efficiency by utilizing the multitier SON among various CUs, DUs, and RUs. It will facilitate massive MIMO as well as centralized and virtualized RAN deployments.

A Multitier SON

A lower-layer split opens the possibility of controlling distributed RUs through expanded eNB SON functionality, or dSON. This low-latency radio coordination will maximize spectral efficiency and mobility performance among multiple transmission points, even for RUs from different vendors. This will enable LTE CoMP and 5G NR enhanced multiple TRx point features across the entire RAN.

With the addition of a lower-layer split, fully coordinated radio resource management at three different latency levels can be enabled, as illustrated in Figure 6. The dSON functionality includes CoMP at 250 μs over a lower-layer interface, mSON functionality at fewer than 100 ms over an F1 interface, and cSON functionality at above 1 s over a conventional northbound network management interface.

This intelligent multitier SON expands the traditional eNB SON function to multiple vendors through standardized lower-layer splitting for provisioning, optimizing, and healing among RUs. It introduces mSON functions for tightly coordinated dual connectivity and spectral sharing, enabling traffic steering for low-latency applications among various digital units. It refines the cSON for overall RAN efficiency and performance. The multitier SON is essential to support services with various reliabilities and latencies. A higher-reliability application demands higher transmission fidelity, leading to more confined coverage [6]. Thus, it changes the cell boundary with increased handovers and overall interference levels at the dSON. Concurrently, it requires intensive traffic steering and mobile routing at the mSON as well as increased end-to-end resource allocations at the cSON. The unified and flat radio architecture supports programmable radio access components, transport components, and core and cloud components. The multitier SON will allow intelligent central control of radio resources for various applications according to the service requirements while simultaneously enabling edge computing for ultrareliable low-latency and high-reliable services.

Conclusions and Future Directions

Standardized interfaces enable various ways to intelligently manage 5G radio networks based on resource availability, service, and end-to-end performance awareness. We are expecting the SON to manage networks on multiple tiers. This will consist of an evolved dSON controlling the lower-layer split interface, an mSON controlling the high-layer split, and a traditional cSON continuing to play a key role in terms of resource management at a centralized level. These three tiers of the SON will act intelligently together

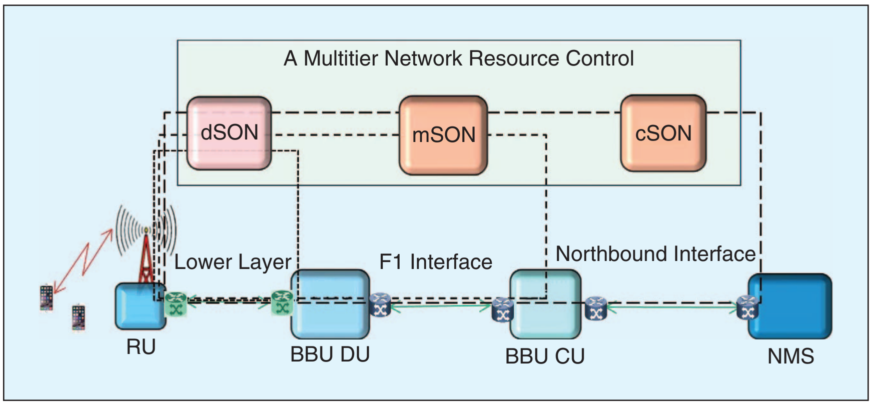

FIGURE 6 An intelligent multitier SON.

to support differentiated QoS flows and network slicing for varieties of services. They will transform mobile wireless networks in the direction of intelligent, multipurpose 5G networks.

Mobile networks have grown rapidly to serve more and more innovative consumer and enterprise applications and use cases. Further academic studies and product enhancement of multiaccess edge networks supporting different network slices to fulfill various end-to-end service performance and reliability requirements are critical. Thus, enhancing network efficiency through beam management and multiple-transmission-points coordination as well as leveraging various machine-learning algorithms for autonomous network operations is also under intensive investigation.

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