Bell Labs Consulting

NOKIA

Going Wireless: The Next Frontier in Cable Transformation

White paper

This Bell Labs Consulting paper explores the essential questions multiple system operators (MSOs) need to consider before launching new wireless services. To help MSOs define fixed wireless access, nomadic and mobile service strategies, these questions are evaluated within the context of the Future X Network architecture — an end-to-end converged network architecture for the 5G era. An example of the cost of building a wireless network is also included.

Contents

A wireless future

Today's multiple system operators (MSOs) need to grow revenues, acquire new customers, reduce churn, and address current market trends with new and emerging services. As a result, they are considering wireless services beyond Wi-Fi.[1] The first step in developing market strategies for new services is to address the following three questions[2]:

- What services can the MSO possibly offer?
- What architecture is required?
- Can legacy investment in cable and/or fiber infrastructure be leveraged?

This white paper explores key factors related to these questions — and discusses information that can help MSOs define their fixed wireless access (FWA), nomadic and mobile service strategies. Each question is evaluated within the context of the Future X Network architecture — an end-to-end converged network[3] architecture for the 5G era.

The Future X Network architecture establishes fundamental requirements for wireless strategies by identifying the "no-regrets wireless functions," that is, functions that MSOs can begin acquiring to jump-start an eventual wireless service launch. Then MSOs will need to make some risky bets to test out the markets in their serving areas. As they learn from each marketplace and evolve their wireless strategies, their initial functions can be evolved to create full-service wireless architectures that provide an industry-leading consumer experience with the right functions and scale.

A representative example of deployment costs is also provided in this white paper. It shows the cost of initially deploying an FWA service network, then expanding later to a target full-mobility service network.

The Future X Network architecture

A profound network transformation is occurring through the ongoing digitization and automation of many aspects of our lives — from communication and content to human experiences and physical systems of all types. This "automation of everything" underlies our current industry trends, including the move to cloud-based services, massive wireless connectivity and high-performance service delivery.

This transformation will lead to a new Future X Network architecture that incorporates radical shifts in technologies and business models in order to meet the digital needs of the future. It will ultimately transform not only the telecommunications business, but the way we live by creating time for a variety of new activities. The Future X Network architecture is a catalyst for this transformation.

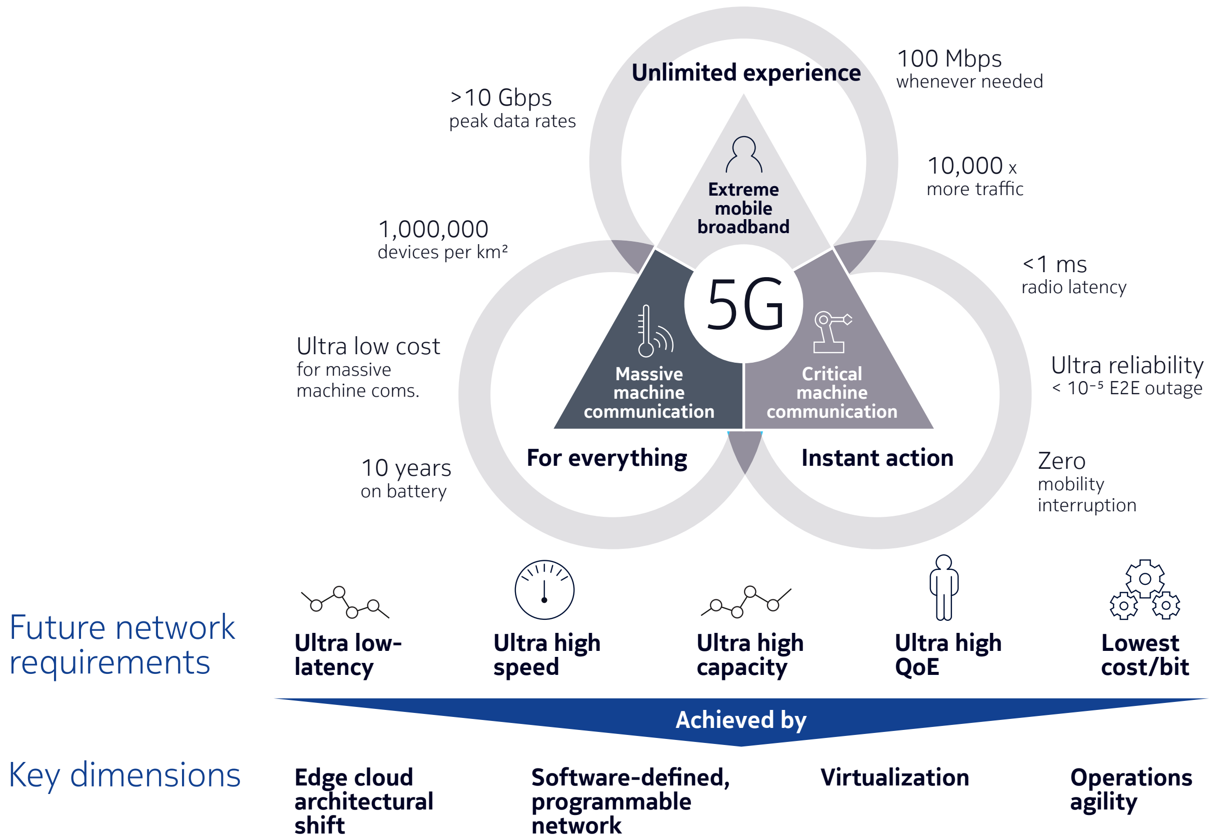
Figure 1 shows the dramatic impact on future network requirements created by 5G-era networks, the internet of things (IoT) and industrial automation-based services.

1 Some MSOs already offer mobility services, and many are investigating LTE, 5G, IoT, fixed wireless access and industrial automation.

2 Additional strategic questions are identified in the Conclusions section of this paper.

3 *The Future X Network, a Bell Labs Perspective*, Marcus Weldon, et al., CRC Press – Taylor & Francis Group, March 1, 2016.

Figure 1. Future wireless requirements

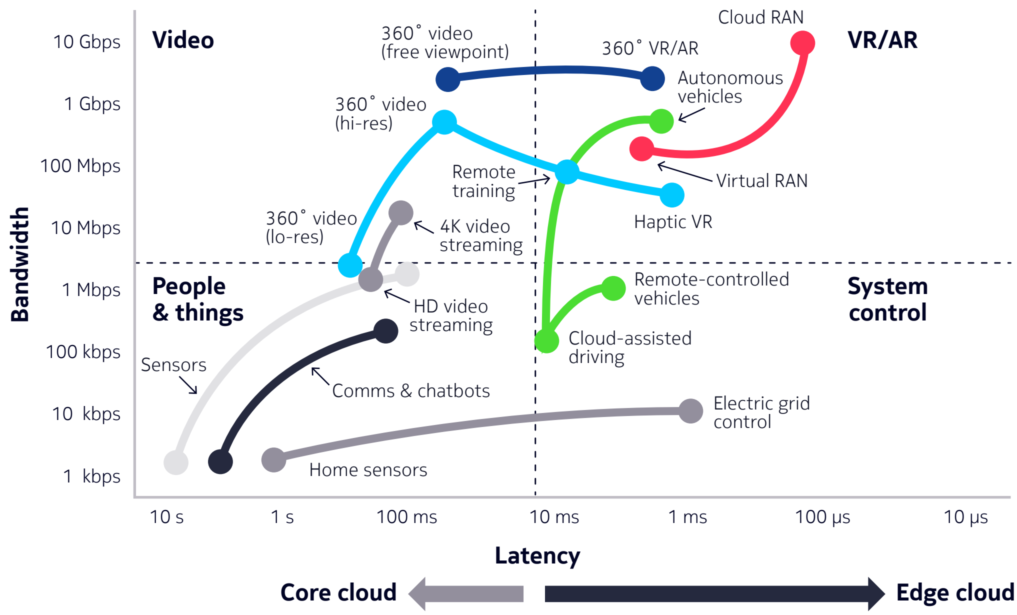


These changing network requirements grow out of:

- Demand for unlimited and instant experiences for fixed and mobile broadband
- Massive numbers of devices including those requiring machine-to-machine communications
- Mission-critical communications

As a result, networks must often address diverse and competing requirements for ultra-low latency, ultra-high speeds, ultra-high capacity, ultra-high quality of experience (QoE) — and low cost per bit. Figure 2 shows examples of various emerging services and their requirements.

Figure 2. Bandwidth and latency of services



- **Ultra-low latency** – Future mission-critical and immersive services — such as augmented reality (AR) or virtual reality (VR), teleoperation of robots and drones, and industrial automation — require networks with single-digit milliseconds of latency.
- **Ultra-high speed** – Other future services, such as 360-degree video, will demand much higher network peak data rates than are now available. Some required rates will be well beyond 1 Gbps.
- **Ultra-high capacity** – Future networks will require higher capacity than today's networks to carry high volumes of traffic from billions of mobile and IoT devices.
- **Ultra-high QoE** – 5G and the emergence of the next industrial revolution require ultra-high QoE for delay- and latency-sensitive mission-critical system controls, automation and AR/VR services.
- **Low cost per bit** – Current networks need to be cost-effectively evolved to support future services. When MSOs deploy greenfield networks, they need to be affordable from the outset.

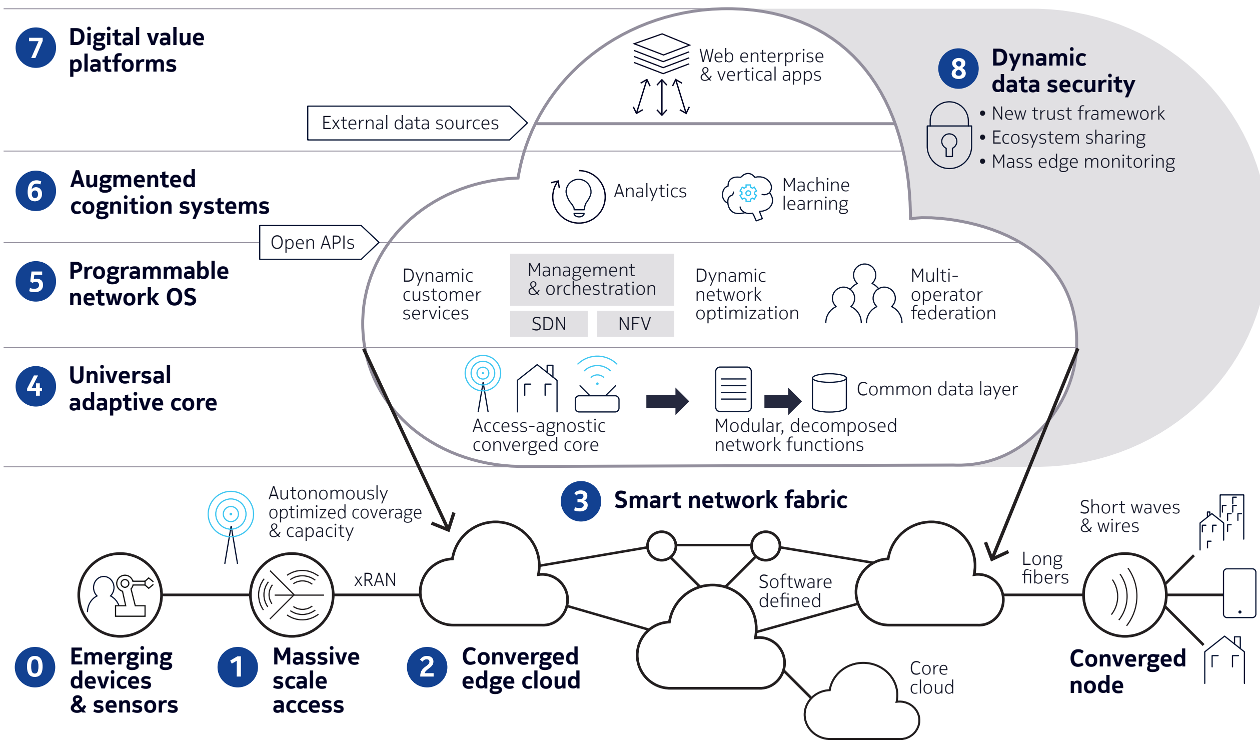
The future wireless requirements shown in Figure 1 are achieved by shifts in the dimensions of the Future X Network architecture, illustrated in Figure 3:

- **Core clouds to edge clouds** – A centralized core cloud model is suitable for today's consumer services. But speed-of-light propagation delays make it unsuitable for emerging services that require network round-trip delay times of less than about 5 milliseconds. Overcoming current limitations to enable MSOs to provide low-latency services will require shifting to an edge-of-the-network cloud architecture, such as data centers in cable hubs.
- **Software-defined programmable networks (SDN) and network function virtualization (NFV)** – SDN and NFV are the prime ingredients of a future programmable wireless and wireline cable network. They will provide MSOs with network and service flexibility, low cost per bit and automated operations. A programmable network operating system (NOS) will provide control and management that intelligently orchestrates the underlying cloud infrastructure to support end-to-end network services. The NOS is composed of NFV management and orchestration, along with SDN control and service orchestration capabilities.

- **Agile network operations** – Separating session data from (stateless) network functions simplifies network scaling, improves resilience and enables more agile network operations. This means new MSO services can be introduced more rapidly.
- **New IoT network platforms** – New digital, value-based IoT platforms enable rapid creation of new services and provide robust analytics. MSOs gain the tools they need to identify and create new revenue-generating opportunities.

These requirements and dimension shifts come together in the end-to-end Future X Network architecture shown in Figure 3.

Figure 3. Future X Network architecture



The Future X Network architecture has nine domains. They are where radical changes in technological capabilities are required and are already happening.

0. **Emerging devices and sensors** provide the basis for the network to interact and communicate with humans, devices, robots, drones and other networks. This includes MSO and consumer wireline and wireless devices and sensors that are connected across coax, fiber and wireless access.
1. **Massive scale access (MSA)** enables orders-of-magnitude scaling of capacity. The increases are achieved through ultra-small, ultra-close access nodes, spatial multiplexing and new spectrum — as well as by synergistically coupling next-generation fixed and wireless access technologies. (The Distributed Access [cable] Architecture (DAA) is one example.[4]) MSA also empowers wireless endpoints by delivering lower latency and lower total cost of ownership (TCO).

4 This topic is discussed further later in this paper.

2. Head-end locations in the MSO network are a natural location for deploying MSA endpoints. The **converged edge cloud** deployment enables distributed micro data centers much closer to the network edge, such as in a cable hub. It can then deliver cloud and virtualization benefits for radio and fixed access, mobile core and IP edge — and host MSO low-latency and high-bandwidth applications and services.
3. Distributed clouds are cohesively linked together, to large enterprises, the internet and other networks. The connection is provided by the **smart network fabric** — a flexible, scalable, dynamically reconfigurable IP/optical metro and core network. It uses physical and virtualized components with software-defined centralized programmability, resource management and optimization.
4. Core/IP edge network functions are converged with the **universal adaptive core**. It provides a common, unified core for multiple access technologies — such as 5G radio, LTE radio, Wi-Fi and fixed access — powered by a modular functional architecture and common data layer. This type of core is the basis for future flexible MSO wireless and wireline networks.
5. The **programmable network OS** provides end-to-end automation and orchestration across distributed and centralized clouds, WANs and MSA. It includes software-defined networking control of both multi-tenant virtual overlay and smart network fabric underlay connectivity. It also orchestrates programmable network slicing and facilitates multi-operator programmable network federation. With these capabilities, a programmable OS enables MSOs to dynamically and flexibly control their future networks.
6. **Augmented cognition systems** support the cloud transformation by enabling leading-edge automation using cognitive techniques. Their methods incorporate extensive data gathering, analytics and machine learning autonomics to provide contextualized services and dynamic network operations and optimization.
7. Networks that enable dynamic deployment of services and applications will unlock whole new levels of value creation opportunities for **digital value platforms**[5] — both within and beyond the network. Being able to leverage on-demand service creation and orchestration, as well as virtual network-as-a-service (NaaS) constructs, will be the critical capability for advanced MSO global-local service delivery.
8. A **dynamic data security** architecture, based on digital trust and automated security, will enable end-to-end cloud, network and end-point security for MSOs. The architecture's cognitive autonomics can provide both proactive and reactive threat identification and containment.

All domains of the Future X Network architecture work together to enable the automation of everything. They will overcome the critical limitations of current networks with respect to scale, flexibility, bandwidth and latency performance, as well as automation, programmability, security and operational efficiency.

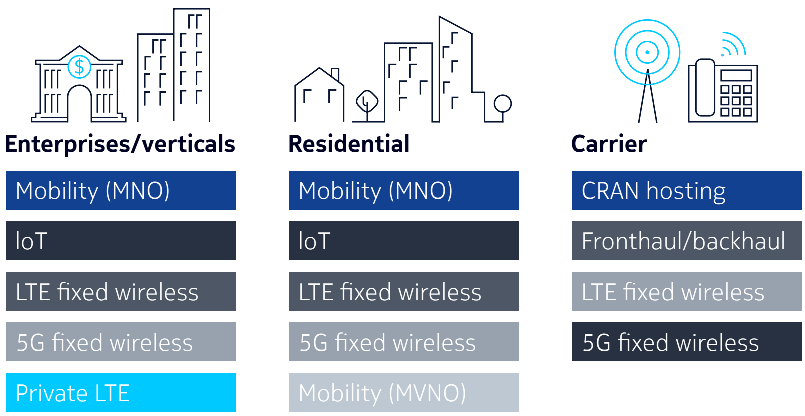
The remainder of this paper explores the three key questions listed earlier, beginning with: What new services can the MSO possibly offer?

5 Digital value platforms enable new services to be created quickly and easily.

Wireless services

Bell Labs Consulting considered a representative set of wireless services (Figure 4) that MSOs will be able to offer to existing or new consumers to remain competitive and improve monetization of their already deployed infrastructure.

Figure 4. Services and consumer market segments



Some services may be specific to a consumer market segment, while others may be common across multiple segments, such as residential and enterprise. Services include:

- Mobile virtual network operator (MVNO)-provided services – An MVNO is a wireless service provider that does not own any, or only some, of the functions necessary to provide end-to-end mobile wireless services. For example, the radio access network[6] (RAN) is not owned by the MVNO. Three types of MVNOs are defined in this paper[7]: MVNO-A where an MSO owns only the billing functions, along with provisioning interfaces, of an MNO network. This approach is useful when operators have a large customer base for cable services and a retail presence — but do not want to make large capital investments into network evolution. In the MVNO-B option, an MSO owns billing and authentication functions such as the home subscriber server (HSS), so they can own and consolidate the authentication infrastructure with their Wi-Fi network. Finally, in a full MVNO, the MSO owns the mobile core network to control both the user and data plane functions. Therefore, they can provide streaming and other content to wireless consumers as well. This creates synergies between the MSO's content-rich cable network and wireless services.
- Mobile network operator (MNO)-provided services – These mobility services are provided directly by the MNO. Unlike an MVNO, the MNO owns a RAN, as well as all other parts of the end-to-end network. An MNO may also own spectrum or lease it from a third party. This is the most flexible, but also the costliest option for MSOs.
- LTE[8] fixed wireless access – This form of non-mobile voice and data broadband wireless access uses LTE wireless technologies. It can be a supplement to MSO cable networks or, in some cases, may be an alternative form of access.
- 5G fixed wireless access – This type of non-mobile voice and data broadband wireless access uses 5G wireless technologies. As with LTE, 5G fixed wireless can be a supplement to MSO cable networks or may sometimes offer an alternative form of access.

6 The radio access network would be owned by a partner, such as a mobile network operator.
7 Variations may also be included.
8 LTE and 5G fixed wireless access services are listed to distinguish potential differences in services and in infrastructure for each, from an MSO perspective.

- CRAN hosting – MNOs can use this centralized cloud-based service to host their RAN computing and other resources. The service lets MSOs leverage their hub/clouds and fiber infrastructure.
- Backhaul – Backhaul transports traffic between distributed cell sites and network-based mobile switching control centers. MSOs can use it to leverage their fiber for macro cells and/or small cells.
- Fronthaul – This form of transport carries traffic between centralized wireless baseband controllers and standalone wireless radio heads. It also enables MSOs to use their fiber networks.
- IoT – These services are provided to and/or enabled by physical devices, such as sensors, relays, cameras, etc., which are distributed throughout the network, residences, enterprises and vehicles.
- Private LTE – This mobile or fixed access LTE is established for the private use of an enterprise or a government entity. MSOs can participate in an adjacent market opportunity by enabling enterprises to build private networks.

Wireless functions and architectures

After identifying potential services, Bell Labs Consulting began answering the question: What architecture is required? The first step was to define the wireless functions that are necessary for building the previously described services, because wireless services are built from a set of wireless functions. Then wireless architectures are built from those functions.

- Virtual Evolved Packet Core (vEPC) – For some scenarios, it is more efficient to have an integrated core network than to use individual core functional network elements. This approach is extremely effective when a wireless network must be deployed for public safety — or when a network must be deployed quickly for disaster recovery. It also is effective in limited geographic regions for niche applications.

  vEPC represents an integrated core network with key functions such as the virtual mobility management entity (vMME), virtual serving gateway (vSGW), virtual packet data network gateway (vPGW), virtual home location register/home subscriber server (vHLR/vHSS), and potentially other functions. Note that in other scenarios discussed elsewhere in the paper, these functions could be deployed as stand-alone functions as well and not purely within an integrated vEPC.

  More specifically, the vMME is a primary network control node that manages subscriber mobile devices and bearer channels, selects vPGWs and vSGWs, and establishes and tears down data sessions. The vPGW is a gateway that provides an IP anchor point for bearer channels, routes and forwards data packets, and provides access from the vEPC to external packet data networks. The vSGW is a data packet forwarding and routing gateway that provides an interface between the RAN side of the network and the vEPC. It is also an anchor-point for mobility handovers and an interface to lawful intercept. The vEPC is essential for an MSO to provide wireless services.
- Virtual Policy Control Resource Function (vPCRF) – The vPRCF provides real-time policy enforcement for capabilities such as quality of service (QoS), bandwidth allocation and charging. It not only allows MSOs to provide differentiated services to consumers, but also allows them to manage network resources by controlling various attributes, such as monthly usage.
- Virtual home location register/home subscriber server (vHLR/vHSS) – This centralized database contains subscriber and service subscription-related information and provides mobility management support, including call and session establishment, subscriber authentication and access authorization.

- 5G core – A 5G core network is different from an LTE-EPC, both functionally and architecturally. New functions that have been added include Network Exposure Function (NEF), Network Slice Selection Function (NSSF), Network Repository Function (NRF) and Unstructured Data Storage Function (UDSF). They enable the 5G network to be more agile and allow MSOs to monetize their network by giving third-party providers secure access for authenticating users, along with cloud native implementation and scalability. With UDSF, for example, virtual network functions (VNFs) can be stateless for dynamic life-cycle management of these network functions, which helps promote efficient use of network resources. Network services can be also delivered in many diverse scenarios using the same underlying infrastructure.

  Other main functional elements have either evolved into independent functions or have been enhanced from the LTE core to enable more agile deployment. They include: the Authentication Server Function (AUSF), Access and Mobility Management Function (AMF), Session Management Function (SMF), Unified Data Management (UDM) and Unified Data Repository (UDR). The 5G core network also uses a service-based architecture — rather than a reference-point based architecture — to implement these functions as micro-services. 5G core details can be found in 3rd Generation Partnership Projects (3GPP) specifications.[9]
- Trusted wireless access gateway (vTWAG) – With this gateway, mobile devices can connect to a vPGW, via a trusted Wi-Fi network, to provide Wi-Fi/mobile service interworking. A vTWAG could leverage extensive MSO Wi-Fi network deployments to offload traffic from the cellular network for more cost-effective use of network resources.
- Online charging system/offline charging system (vOCS/vOFCS) – The systems support pre-paid and post-paid services, invoicing and tracking, and feed into billing functions.
- Billing – This function creates call detail records and consumer bills.
- IoT service capability server (IoT-SCS) – The IoT-SCS function connects IoT application servers to the mobile service provider's network, so they can communicate through specific 3GPP-defined services. This helps accelerate deployment of IoT services using an MSO cellular network from third-party IoT service providers or vice versa.
- IoT Service Capability Exposure Function (IoT IWK/SCEF) – This function enables secure service and capability exposure, standardized by 3GPP-defined network interfaces.
- IoT analytics – Data collected from IoT services and devices can be analyzed to discover patterns and to predict future events.
- Virtual baseband unit (vBBU) – This network device sends and receives radio signals via connections to cell site locations. The vBBU is a core component of wireless networks.
- Radio access network (RAN) – Residing between the consumer equipment and the core network, the RAN provides wireless connectivity. It includes[10] radio units, RF processing, antennas, baseband units and fronthaul/backhaul transport networks. In different scenarios, radio and/or baseband processing can be accomplished locally at the cell tower site or remotely at the edge cloud and/or hub locations.
- IoT gateway (GW) – This gateway integrates multiple protocols, manages data storage and analytics, and ensures secure data flow between IoT devices and network clouds.

9 https:/www.etsi.org/deliver/etsi_ts/123500_123599/123501/15.02.00_60/ts_123501v150200p.pdf

10 Ancillary equipment such as cabinets, cable, splitters, power, etc. are also part of the RAN.

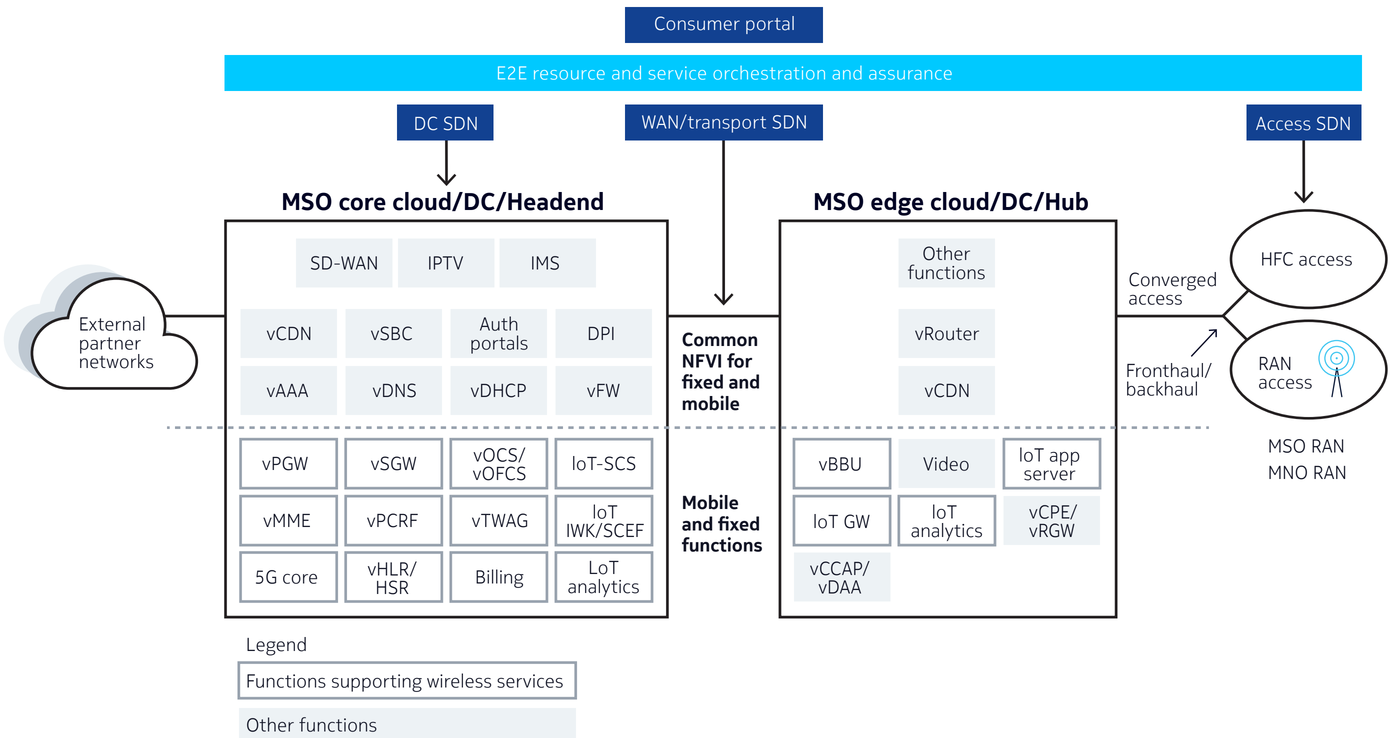
Table 1 identifies the fundamental wireless functional building blocks required to deliver services previously described in this paper. Functions common to both wireless and wireline services, such as the IP multimedia subsystem (IMS), or wireline functions that have no specific role in wireless services are not included in this table.

Table 1. Wireless functions and their potential locations and services

Potential location	Function	Full mobility	MVNO A	MVNO B	MVNO full	LTE FWA	5G FWA NSA	5G FWA SA	CRAN host	Fronthaul	Backhaul	LoRA/ NB-IoT	Private LTE
Cloud, DC, headend	LTE core (vSGW, vMME, vPGW)	X			X	X	X						
	5G core	X			X			X					
	vPCRF	X			X	X	X						X
	vHLR/ HSS	X		X	X	X	X						X
	vOCS/ vOFCS	X			X	X	X						X
	vTWAG	X			X	X	X						X
	Billing	X	X	X	X	X	X						X
	NB-IoT SCS and GW											X	
	NB-IoT IWK/ SCEF											X	
	NB-IoT analytics											X	
	RAN	X				X	X	X				X	X
Cloud, DC, hub	vBBU	X				X	X	X	X				X
	vEPC	X				X							X
	LoRA-IoT GW											X	
	LoRA-IoT app server											X	
	LoRA-IoT analyics		X									X	
Coax, fiber	DOCSIS coax										X		
	Fiber									X	X		

Figure 5 provides a composite architectural view of the functions described within an MSO network.

Figure 5. Composite functional wireless architecture and potential function location



The composite functional architecture[11] shows all the functional elements required for various wireless services, including some functions at multiple network locations, such as at the edge and core. However, not all the functional elements are required for every service. Table 1 indicates which individual functions are needed for a particular service.

Wireless functions are shown at their most logical placement in a typical MSO network topology. Core network locations, such as cloud data centers or headends, are ideal for functions shared by multiple services and numerous subscribers, if the services do not have strict latency/delay requirements. Such deployments can lead to economies of scale through the efficiencies provided by large cloud implementations, as well as by amortizing the cost across many users and services.

On the other hand, edge network locations, such as edge clouds, local data centers or hubs, are ideal for functions that are shared by fewer services and subscribers — or that have strict low-latency requirements. Virtual functions (identified by a “v” preceding the function name) may be located anywhere in the network, as determined by criteria such as cost, latency, bandwidth needs and ability to share the function. Exact determination of function placement requires a detailed MSO-specific engineering and design analysis.

IMS, software-defined WAN (SD-WAN), content delivery networks (CDN) and virtualized router (vRouter) are illustrated for completeness, but are not discussed. External partner networks can provide various wireless functions to MSOs, based on specific business relationships and service strategies.

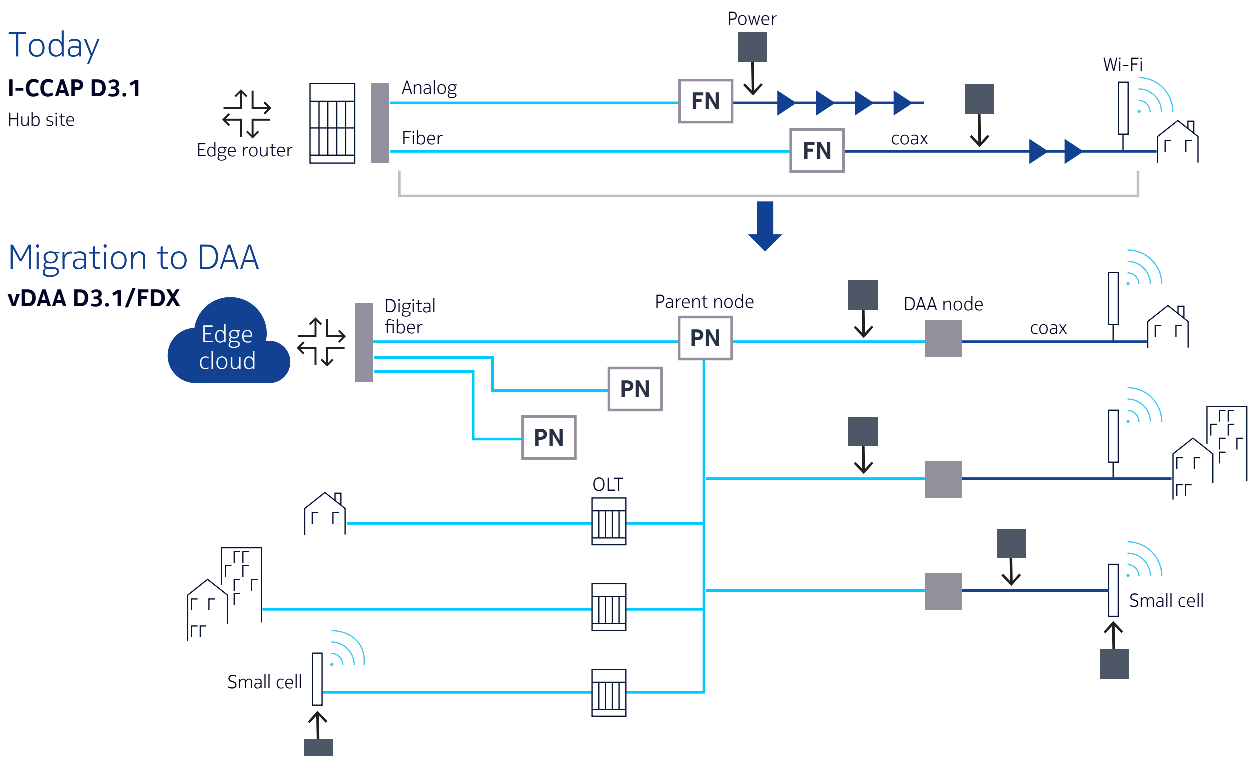
11 Corresponding with Table 1, this figure represents the LTE core as broken into its functional components.

Leveraging hybrid-fiber/coax (HFC) networks

After determining the architecture required for specific wireless services, Bell Labs Consulting turned to the third key question: Can legacy investment in cable and/or fiber infrastructure be leveraged? They examined the following factors.

Fiber is being pushed much deeper into cable access networks to increase reuse of spectrum, increase average bandwidth per consumer and migrate to digital fiber to reduce maintenance.[12] This results in much smaller fiber nodes (FNs). Migration from an integrated-converged cable access platform (I-CCAP) to DAA[13] also pushes fiber deeper as FNs become parent nodes (PN) that are locations for aggregating fiber that connects DAA nodes located very close to consumers (Figure 6). DAA nodes also reduce cable hub space and power consumption.

Figure 6. Migration to deep fiber architectures



Fiber can be used to provide backhaul for access points such as small cells, as well as provide fronthaul and backhaul services for mobile network operators. Similarly, the HFC-based Data Over Cable System Interface Specification (DOCSIS®) network can provide backhaul for small cells, wherever the network can meet wireless service bandwidth and delay requirements.[14]

12 "An economic analysis of distributed access architectures: The next major cable transformation," Bell Labs Consulting whitepaper, https://media-bell-labs-com.s3.amazonaws.com/pages/20171211_1915/Bell_Labs_Consulting_economic_analysis_of_distributed_access_white_paper_EN.pdf

13 DAA is typically comprised of two architectures: Remote PHY (RPD), which centralizes the MAC layer and distributes the PHY layer to the DAA node, and Remote MAC/PHY, which distributes both the MAC and the PHY layers to the DAA node. Either DAA can be leveraged, based on its deep fiber requirements.

14 "DOCSIS® Technologies for Mobile Backhaul," CableLabs Technical Brief, Belal Hamzeh, Jennifer Andreoli-Fang, May 2018.

The cost of building wireless networks

Building a wireless network can require a significant investment. Therefore, MSOs need to understand the cost of functions common to multiple wireless services, as they plan for incremental or phased service offerings. This knowledge can help in managing investment costs and providing competitive service offers.

This section provides an example[15] of how common functions and specific functions can be provided flexibly for two services. The focus is on an LTE-based FWA service deployed in a suburban morphology, with later deployment of a targeted full mobility service in suburban, urban and rural morphologies.[16] Figure 7 shows the relative costs for providing common and service-specific functions as a percentage of the targeted full mobility service-based architecture.

LTE-based FWA and full mobility

Table 1 shows a common set of functions required to support LTE-based FWA along with full mobility services. It also indicates the functions specific to each[17] service. However, please note that these services will require either a 5G core or an LTE-based EPC core network — but not both. Deploying functions common to both services provides an agile architectural foundation, which enables MSOs to begin with the FWA service in a specific area. Then they can add functions later, as needed, to provide a full mobility service in an expanded area.

Cost analysis example

Figure 7 shows an example of the relative cost[18] of deploying common functions for a LTE FWA service in a suburban morphology — along with the incremental cost delta to later provide a full mobility service across suburban, rural and urban morphologies. The costs shown are based on a detailed Bell Labs Consulting wireless network model and analysis. Such models typically use hundreds of input parameter values to produce detailed results. Appendix A identifies the parameters and values that have the greatest impact on the modeling results illustrated in Figure 7. Even minor changes in these key values can have a dramatic impact on the modeling results.

The costs within the FWA network for a suburban morphology include: RAN, transport, core and other ancillary functions, such as the authentication, policy and management functions needed to support an end-to-end service. Costs for a full mobility network service are shown on the right side of Figure 7. These costs are similar for any existing wireline service provider that does not have a wireless network but wants to enter the wireless business.

MSOs have an inherent advantage with their deep-fiber HFC networks. That's because future wireless network deployments are expected to become denser, especially in urban and semi-urban environments. This increased density will be needed both for capacity needs and for growing use of higher frequency spectrum. Consequently, these deployments will require real estate assets and efficient backhaul connectivity, which may be provided by MSOs' existing assets.

MSOs will be disadvantaged compared to existing wireless service providers in several areas, including their need for experienced wireless staff and operations experience and because they do not have existing wireless infrastructure to capitalize on.

15 Many examples are possible; the example provided was chosen as a possible phased scenario for some MSOs.

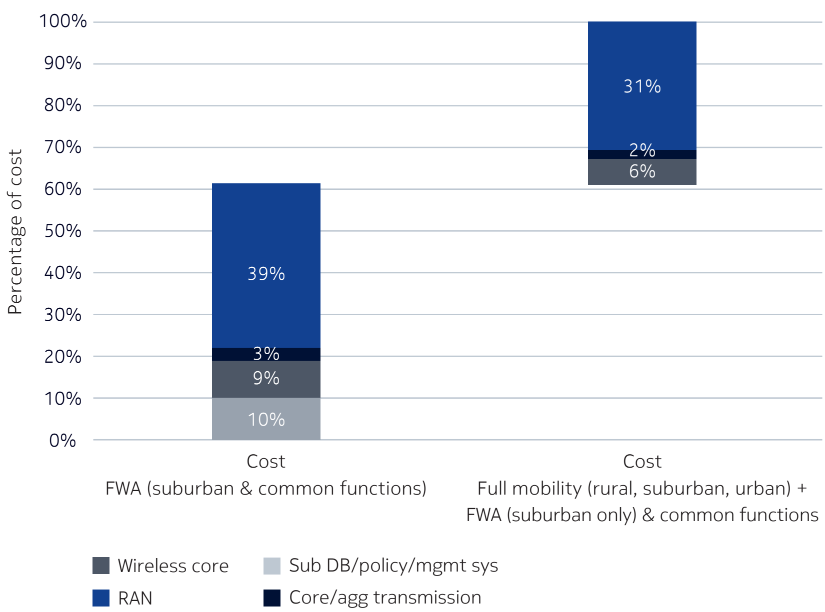
16 The FWA service is maintained in the suburban morphology and is not deployed in the urban and rural morphologies.

17 As stated earlier, exact function placement requires a detailed MSO-specific engineering design.

18 The cost illustration is for the network equipment, including fiber deployment; it does not include costs such as spectrum acquisition, marketing, staffing, store fronts, etc.

The primary difference between the costs for deploying the two services lies in the discrete nature of FWA deployment, with its focus on suburban population centers. In contrast, the full mobility service requires continuous coverage throughout the suburban and surrounding rural and urban morphologies to support subscriber mobility. Any further deployment of wireless access nodes to support mobility services would depend on how much coverage is needed beyond the geographic region of interest. It is important to note that for FWA, total monthly capacity used by a subscriber is orders of magnitude more than that provided to mobile users.

Figure 7. Cost of phasing FWA and full mobility



Additional wireless core and core/aggregation network transmission functions and equipment are required for full mobility. The bulk of incremental costs for full mobility come from adding the RAN. Full mobility reduces dependence on other service providers, provides the ability to leverage content across wireless and wireline services, and enables service convergence.

Bell Labs Consulting can provide similar analysis for a variety of wireless services, functions, architectures, and network deployments and migrations. The findings can assist MSOs in making strategic, technical, architectural and investment decisions.

Conclusions

Addressing key strategic questions noted in the first section of this paper enables MSOs to identify the wireless services and architectures that must be provided. Then they can determine more specifically how their HFC infrastructure can be leveraged. But before a network can be built and services offered, some additional strategic questions related to market, technology and operations must be answered. They include:

- What market segments should be targeted?
- What wireless technologies should be deployed?
- Should license spectrum or shared spectrum be acquired?

- How much spectrum is needed and which bands?
- What unique differentiators can be provided?
- Are the necessary in-house operational capabilities available?

Addressing a holistic set of strategic questions will enable MSOs to focus investments, begin offering wireless services quickly and evolve to a broader suite of wireless services in the future.

Bell Labs Consulting helps MSOs make the right strategic, economic and technical decisions. Contact us to learn how our experts and technologies can help you build a wireless network that supports universal broadband access, stimulates growth and enhances competitiveness.

Appendix A

Services

- Phase 1 – LTE FWA - Suburban only using small cells
- Phase 2 – Full LTE mobility using macro cells, in the following morphologies:
  - Suburban (plus FWA)
  - Urban
  - Rural

Morphology distributions

- 60% rural
- 30% suburban
- 10% urban

Average macro cell range[19]

- 1km

Small cell range[20]

- 150m

Small cell deployment cost

- 1/10 the deployment cost of a macro cell

Abbreviations

5G	fifth-generation wireless
AR	augmented reality
BBU	baseband unit
CCAP	converged cable access platform
CRAN	centralized radio access network

19 Macro cell ranges can vary significantly across morphologies; for simplification, an average has been taken across possible ranges.

20 Small cell range is based on mmWave band deployment on lamp posts.

DAA	distributed access architecture
DOCSIS	Data Over Cable System Interface Specification
DevOps	development and operations
EPC	Evolved Packet Core
Gbps	gigabit per second
HFC	hybrid fiber/coax
HLR/HSS	home location register/home subscriber server
IMS	IP Multimedia Subsystem
IoT	internet of things
IoT SCS	IoT service capability server
IoT IWK/ SCEF	IoT Interworking Service Capability Exposure Function
LTE	Long Term Evolution
MME	Mobility Management Entity
MSO	multiple system operator
MNO	mobile network operator
MVNO	mobile virtual network operator
NaaS	network as a service
NFV	network function virtualization
OCS	online charging system
OFCS	offline charging system
OS	operation system
PCRF	Policy Control Resource Function
PGW	packet data network gateway
QoE	quality of experience
RAN	radio access network
RF	radio frequency
SCS	service capability server
SDN	software defined network
SGW	serving gateway
TWAG	trusted wireless access gateway
VR	virtual reality
WAN	wide area network

About the authors

Marty Glapa is a partner and Bell Labs Fellow in Bell Labs Consulting. He is responsible for intellectual property development and R&D in fixed access networks, including architecture, network modeling and business modeling. He is also responsible for testing new long-term research hypotheses. Prior to his current role, Marty was a senior director and Bell Labs Fellow in the Bell Labs Chief Technology Office within Alcatel-Lucent. His experience includes development and delivery of consulting services around the world, network planning, modeling, systems engineering, business development, product development, research on enabling interactive applications, next-generation access architectures, cable networks, and pioneering work in interactive cable TV and VoIP over cable. Marty has four patents. He has a master's degree in computer science from DePaul University. He serves on the advisory boards for Colorado State University and the Colorado School of Mines.

Ajay Rajkumar is the Consulting Engagement Leader with Bell Lab Consulting. Dr. Rajkumar received a Ph.D. in Computer Science from Courant Institute of Mathematical Sciences, New York University. Earlier he led the SDN and Programmable Networks domain in Mobile Networks CTO at Nokia. Dr. Rajkumar has received the Bell Labs President's Award for Design and Prototype of the Base Station Router (BSR) which has, since its early days, evolved into Mobile Edge Computing and its concepts used to develop flat-IP architectures across many different cellular standards. He has received another Bell Labs President's Silver award for the first prototype that demonstrated seamless interworking across heterogeneous access networks for real-time applications. Dr. Rajkumar led the mobile industry to develop standards that enable ubiquitous coverage across heterogeneous access and was the Founding Chair of IEEE 802.21 for Media Independent Handover. He was also a Member of the IEEE 802 Executive Committee Board. He currently serves on the Computer Science Advisory Board of New York Institute of Technology, NY. Dr. Rajkumar has been a frequent invited speaker at research labs, universities, industry and technical panels. He has many reviewed publications and has received more than 70 patents in very diverse areas of technology in all regions of the world.

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Document code: SR1811030487EN (December) CID205836