THE FUTURE X
ARCHITECTURE
For the Future of Digital Services and Networks
The Future X architecture envisions an end to end network with massive increases in capacity and reliability, and massive decreases in latency to drive the 4th industrial revolution. Existing network architectures must radically transform:

- From highly centralized to massively distributed architecture
- From loosely interconnected to tightly coupled or converged domains
- From singular monolithic systems to a multitude of microservices
- From statically configured to dynamically adaptive
- From manual management of elements to intelligent automation of everything
- From few physical separate private services to myriad virtual private services
- From billions of smart devices to trillions of simple sensors
- From increased human awareness to full human augmentation

In this primer, the essence of the Future X Network architecture is described for each of the nine domains.
Vision
We are on the verge of a device revolution; after a decade of aggregating digital services into a single primary device – the smartphone – we will reverse this trend to create a set of new human interface devices that produce a natural ‘sixth sense’ with human hyper-awareness and human-machine symbiosis.

Today
The smartphone has driven a new era of connectivity to digital information and services. But as we enter the era of human augmentation and industrial automation, the form and function(s) is no longer optimal, as it is increasingly intrusive and incompatible with human sensory and cognitive interactivity and needs. In particular, augmentation of physical reality to enhance human cognition, communication, and multisensory content and state – including our own physiology – is not well served today. In addition, human-machine interaction is currently primitive. The recent advent of wearable devices and new AR/VR headsets (often leveraging smartphone technologies and devices) are precursors to what will be the dawn of a new era.

Tomorrow
Breakthroughs in miniaturized electronics and optics will result in new sensor technologies, that will become massively distributed and pervasive throughout the physical world and integrated into everything, and everyone, creating a new cyberphysical fabric. There will be a new set of highly optimized, human-augmentation devices, built from these next generation sensory technologies, and incorporating novel human-infrastructure and human-machine sensing and control technologies. These devices will effectively combine to create first digital sense that will connect humans, machines, systems, processes and infrastructure. These devices will be continuously and optimally coupled via massive scale access to augmented cognition systems and dynamic data security frameworks running in the converged edge cloud, allowing real time analysis, understanding and automated assistance for all tasks.
Vision
The next industrial revolution will be driven by the connection of 100s of billions of devices with a diverse set of requirements and the need for massive scaling of the access network in capacity, latency, reliability, and efficiency, with convergence of technologies & infrastructure.

Today
Over the past 30 years, there has been a 100,000-fold increase in access network speeds, from ~10 kb/s to 1000 Mb/s – made possible by Moore’s Law scaling of the constituent processing technologies. Moreover, sophisticated digital signal processing techniques that allow high order modulation and interference cancellation have allowed wireless broadband data services with full mobility. Similarly, legacy copper-wire based access solutions (twisted pair or coax) have approached the performance of fiber-based solutions, driving new broadband access economics. However, current wireless access solutions remain ~10x lower in capacity due to the limited spectrum available, and are therefore only utilized where fixed broadband connectivity is unavailable or uneconomical.

Tomorrow
We are at beginning of a new era of access networks, as industrial automation, and new infrastructure and information systems will require capacities of 1-10Gbps and latencies of 1-10ms, with ultrahigh reliability, and adaptability. We have exhausted the use of traditional low band (<1 GHz) spectrum operating at the Shannon limit, so radical changes are required in multiple dimensions: i) Massive antenna arrays will form wireless beams increasing the spectral efficiency by >5x; ii) new deeply distributed nodes will allow access to new spectrum bands (e.g. mm-Wave wireless and 1GHz bandwidth over copper) and 10x capacity increase; iii) new L1/L2 protocols will support ultralow latency; iv) multi-access will allow optimized service delivery and continuity; v) outdoor and indoor access technologies will interwork seamlessly. The result will be a new highly converged massively scalable access domain with a virtualized control plane in the converged edge cloud, supporting myriad simultaneous application flows, dynamically managed by augmented cognition systems.
**Vision**

The current centralized cloud architecture will be augmented by massively-distributed, interconnected edge cloud infrastructure located within 100km of the end device/user, to support high-performance and mission-critical services requiring ultralow latency and ultrahigh capacity, with dynamic, high-scale augmented intelligence and security.

**Today**

The internet has been defined by the build-out of an immense amount of global network infrastructure and commensurate data center (cloud) infrastructure to host the web services and platforms that have come to redefine how we live and work. However, this global web infrastructure is built with human response times of ~100ms, allowing for the cloud to be located as much as 10000 km away from the user. The bandwidth is also limited given the number of shared (statistically multiplexed) network links traversed. The advent of Content Delivery Networks (CDNs) at peering points has mitigated the bandwidth issue for popular media content, but a more general, higher performance solution is required to support the automation of industrial and infrastructure systems, such as cloud RAN, AR/VR, 360o video and autonomous system control.

**Tomorrow**

The future converged edge cloud will be comprised of the following critical performance elements: i) Deterministic low latency switching infrastructure with novel optical and IP/Ethernet forwarding elements; iv) Dynamic SDN control for optimal multi-edge cloud service instantiation and adaptation; iii) Hardware acceleration functions for optimized cost, performance and density for complex functions (e.g. image processing, physical layer/packet processing); iv) Optimized serverless computing functionality for low latency, low footprint scaling. In combination, these elements will support services with a 100x decrease in latency, 100x increase in capacity, and as close to 100% service availability as possible.
Vision

The era of cognitive, autonomous networking is coming – the current ‘set and forget’ methodology will be replaced by dynamic, diverse end-to-end path computation with deterministic performance for millions of virtual private services.

Today

We have reached the Shannon limit for each transport link with only a factor of 2-3 more in optical carrier bandwidth left to exploit using conventional approaches. In addition, switching and routing interface capacity has started to exceed transport line rates, and the diversity, dynamism, scale and ‘anonymity’ of encrypted or private flows has reached the point where conventional policy-based methods with manual configuration and management of separate networking domains is no longer viable. Last, the cost-to-performance ratio for network fabrics must decrease by 10-100x to enable the digitization and automation of all systems and processes.

Tomorrow

The future of smart networks will require exploitation of the ‘spatial’ dimension with Spatial Division Multiplexing (SDM), using multimode or multicore propagation down a single fiber to achieve many times higher capacities. This will require a massive amount of opto-electronic integration, along with advanced signal processing. In addition, new advanced ultrawideband amplification technologies will be required for terrestrial and submarine links. There will also be an increased integration between IP and optical layers and components to allow optimal capacity utilization with deterministic performance across multiple dimensions (latency, capacity, reliability, security). Finally, predictive path computation by augmented cognition systems will be used in concert with the programmable network OS, to select routes taking into account all constraints and virtual private service requirements and the evolution and degradation of links over time.
Vision

Future services will be connectivity agnostic with the expectation of seemingly infinite service quality and continuity everywhere. This will be enabled by convergence and massive scale in access, coupled to a new universal core function that provides seamless service control and continuity for all devices and associated flows.

Today

Wireline and wireless core packet networks have evolved in separate ecosystems, limiting support for network agnostic service delivery or multi-network connectivity. With the advent of network function virtualization, disparate core platforms are now available on common cloud infrastructure. Increasing commonality in the functionality and scale of wireless and wireline solutions, has resulted in a universal core solution now being feasible.

Tomorrow

A new universal adaptive core function will be created that will allow devices and services to move from in-building (e.g. unlicensed) wireless contexts served by a wireline access core network to outdoor (any spectrum) wireless access networks served by a common core network. It will provide optimal service continuity and adaptability as well as a shared data layer providing unified access to all user, network and service data. This new core will support dynamic flexibility and the ability to create and manage end-to-end network slices with diverse requirements for scalability, latency, reliability and connectivity with dynamic traffic steering and multipath flow allocation across multiple access networks. Consequently, it will form the essential control fabric of the next industrial revolution, unifying private and public, wired and wireless, licensed and unlicensed network services.
**Vision**

The era of manually configured, static, closed networks is at an end. The need to support new virtualized network infrastructure and millions of simultaneous virtual private services with dynamic flow identification and adaptation will drive the creation of a new ‘network OS’ with cloud-like intelligent automation and scaling, but with deterministic performance.

**Today**

Current network management systems are designed for human operation, based on well-defined protocols, metrics and heuristics, and a limited number of services that are natively supported (primarily voice, data, video and VPNs), with a limited number of configurable options. Moreover, the operations support systems (OSS) are closed systems built with adaptors to support multiple element management systems (per domain) from multiple suppliers. SDN and NFV has driven a move towards standard model frameworks (e.g. YANG) and open interfaces to network elements (e.g. NetConf, OpenFlow), but manual control remains, augmented by scripted policies and templates.

**Tomorrow**

A radical evolution towards zero-touch network and service automation is essential to provide the digital fabric for the next industrial revolution. Intelligent and predictive automation will enable new levels of agility, responsiveness and efficiency in supporting the required automation and information services for the diverse array of industries and infrastructure. A new business and operations architecture will be created for network and service management to fully leverage data-driven machine learning, with common open source frameworks for resource control and assurance and novel AI-based systems for predictive orchestration with dynamic network and service intelligence.
Augmented Cognition Systems (ACS)
Domain 6

Vision

We are at the limit of human ability to process data and information across the myriad coupled domains that will define human existence and commerce. This mandates a new paradigm of augmented human intelligence in which machines and AI systems augment human capabilities to achieve new levels of automation and productivity.

Today

The ubiquity and diversity of web services, and the concomitant massive scale of data generated, resulted in the ‘big data’ paradigm supported by conventional statistical methods. This was almost immediately usurped by the explosion of ‘artificial intelligence’ approaches that use this data to train machine learning systems to perform advanced pattern recognition and predict new patterns and outcomes. However, the training is complex, the basis and validity of the results unknown, and the robustness to error or malicious attack is currently weak.

Tomorrow

A new approach is needed with provable correctness, minimal training, immunity to perturbation and incorporating expert human analysis and feedback. We term this approach ‘augmented intelligence’ which will form the basis of all augmented cognition systems. These systems will be used to manage and optimize all systems and processes with a scale greater than ~3000 elements/items (e.g. all domains of the Future X network), or for which no physical or mathematical models exist. These systems will increasingly run in the converged edge cloud, allowing real time analysis and control of complex systems, coupled together by the smart network fabric to create an autonomous hyperscale networked solution.
Digital Value Platforms (DVP)
Domain 7

Vision
The current consumer-driven digital platforms will be superseded by two sets of new value platforms, focused on augmenting how people perceive and understand their world, and how to control and automate it. These platforms will redefine human existence in the next decades.

Today
Over the past twenty years, web services have redefined how people shop, read, consume media, find information, and interact. But, in reality, these services have just created digital replacements for existing capabilities, increasing convenience but not manifestly changing human existence. Moreover, service and experience quality and user privacy have been sacrificed for the sake of convenience and the offer of “free” services. This has resulted in no net increase in quality of life or productivity, and the initial utility has eroded over time.

Tomorrow
The next phase of existence will be driven by the digitization of all physical systems (including human physiology) and the creation of new machine automata to assist humans in every ‘scale’ task. This will result in two new platform types – platforms that assist humans with perception of the physical world and platforms that assist humans to control the physical world. These platforms will couple to existing digital web platforms created during Industry 3.0 to create the fundamental new value set for Industry 4.0. The critical characteristics of these new cyberphysical platforms are the ability to support the massive scale of low-latency, real-time data streams from a multitude of sensors with augmented cognition systems that assist humans in creating new understanding and optimized outcomes.
Vision

The current approaches to security are completely inadequate for the next industrial revolution, where 100s of billions of simple devices will be connected with no native security and no intrinsic trust verification. A new dynamic, massively scalable, distributed security paradigm is required to enable augmented human-machine existence.

Today

The increasing scale and sophistication of cyberattacks, the rise of advanced persistent threats with diffuse and diverse signatures, and new ‘zero day’ attacks, have resulted in an exponential increase in the number of data breaches and ransomware attacks that are pushing existing security solutions to their limits. And the problem ahead is manifold greater with the massive increase in threat surface and risk profile that is imminent in the ‘industrial internet of things’ era.

Tomorrow

The future of security will rely on four critical elements: i) a massively distributed, scalable security analytics architecture that continuously validates devices and quarantines rogue behavior in the converged edge cloud; ii) Augmented cognitive systems that autonomously recognize diffuse, anomalous signatures of encrypted and/or private payloads for millions of virtual private services; iii) a new trust paradigm that allows dynamic, automated management of device group membership; iv) dynamic federation of security and trust relationships across network boundaries. In combination these elements will form the critical data and privacy protection foundation that underpins the digital fabric for the next industrial revolution.
About Nokia Bell Labs

Nokia Bell Labs is the world-renowned industrial research arm of Nokia. Over its 90-year history, Bell Labs has invented many of the foundational technologies that underpin information and communications networks and all digital devices and systems. This research has resulted in nine Nobel Prizes, two Turing Awards, three Japan Prizes, a plethora of National Medals of Science and Engineering, as well as an Oscar, two Grammys and an Emmy award for technical innovation. Nokia Bell Labs continues to conduct disruptive research focused on solving the challenges of the new digital era, defined by the contextual connection and interaction of everything and everyone, as described in the book, The Future X Network: A Bell Labs Perspective.

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