AN OVERVIEW OF TECHNICAL DEVELOPMENTS AND ADVANCEMENTS FOR THE FUTURE OF NETWORKING

Toerless Eckert, Lin Han, Richard Li, Cedric Westphal
Futurewei Technologies Inc.
2220 Central Expressway, Santa Clara, CA, USA

NOTE: Authors in alphabetical order. Corresponding author: cedric.westphal@futurewei.com

Abstract *– It has been forty years since TCP/IP was standardized as RFC 793. The spectacular success of the Internet has validated the design choices of its protocols and architecture. However, the evolution of the services and applications running over the Internet, new societal requirements and the general unavoidable obsolescence of any protocol will at some point require rethinking the current protocols and potentially replacing them with new ones. New technology has emerged in limited domains networks, such as data centers, that may hint at a way forward for the overall Internet architecture. We present an overview of the recent and current work on post-IP networking and discuss the drivers and motivations that will push us to reimagine IP.*

Keywords – AR/VR, end-to-end latency guarantee, future Internet, high precision networking, holographic type communication, in-time guarantee, new IP, qualitative communication, remote driving, video streaming

1. INTRODUCTION

It has been forty years since TCP/IP was standardized as RFC 793 [1]. The deployment of IP and of the Internet in general has been a spectacular success, both technologically and commercially. It would have been impossible to anticipate forty years ago how much the Internet has become a part of our daily lives, and how many devices have been connected.

In parallel with IP, wireless networks have been deployed, also with unparalleled success. 5G and 6G are being researched and will be defined and standardized to bring fast, high throughput and reliable connections to a multiplicity of devices all over the world.

As the number of applications being supported by the Internet keeps increasing, one question becomes more and more relevant: what is next for networking. Of course, no technology can last for ever and IP is no exception. On the other hand, it can be argued that no technology has been deployed in so many devices, networks, use cases and applications. Replacing IP would be tremendously difficult. IP has been incredibly versatile, and because it was designed to be generic enough to support many applications, it is still to do the job, forty years later.

There are however signs that point in the direction that some new version of IP could be on the horizon, if only in the long term. In particular, there are efforts to allow the support of new network protocols, either in a virtual slice, or in a limited domain, as well as some research endeavors in industry and academia. Some SDOs are preparing for a post-IP era that is bound to happen not today, not tomorrow, but at some point in the future.

We present an overview of the current work on post-IP networking and discuss the drivers and motivations that will push us to reimagine IP.
This paper presents some of these ideas. It is organized as follows:

- Section 2 goes over the market drivers and future requirements that will enable evolution of the Internet protocols. This is rooted in a historical perspective.
- Section 3 describes protocols that are not based on the current IP networking protocols of the Internet as studied in standardization organizations, such as ETSI, IETF and 3GPP.
- Section 4 considers potential changes at the network layer and research efforts outside of standards.
- Finally, Section 5 closes the paper with some concluding remarks on the direction of networking.

While our overview is not exhaustive, as networking research has a long history and covers many domains, we hope to point out some important directions for future investigation, future protocol design, and maybe, future deployment in an evolved Internet.

2. MARKET DRIVERS AND USE CASES

One core driver for future networks research is the evolution of the networking landscape in the past two decades. It is based solidly on the forty year old IP protocol, and its twenty year old version with longer addresses, IPv6.

©International Telecommunication Union, 2022
Some rights reserved. This work is available under the CC BY-NC-ND 3.0 IGO license: https://creativecommons.org/licenses/by-nc-nd/3.0/igo/.
More information regarding the license and suggested citation, additional permissions and disclaimers is available at:
https://www.itu.int/en/journal/j-fet/Pages/default.aspx

2.1 Internet

These protocols are at the core of the Internet, which through the past decades has become the single most important network, driving many of the most financially successful companies on the planet including Google, Amazon, Facebook, Alibaba, Tencent, etc. Through both large and small “web” service companies, the Internet has become the all-encompassing foundation of global communications.

Most Internet traffic is consumer/entertainment on-demand “streaming” of media, which comprises 80% or more of Internet traffic [2]. On-demand audio/video services including Netflix or Amazon Prime do not require any stringent network quality but have been designed to operate under varying network throughput, loss and latency, simply adapting the user experience quality to what the network offers dynamically. This has allowed the fast and low-cost scale-up of the Internet, because the Internet only needs to (and does) provide so-called “Best Effort” network service with no guarantees. The global success of video streaming was also enabled by the very pragmatic approach of building it on top of protocols and components that originally were never meant for this purpose, specifically web caches.

2.2 IP beyond the Internet

The technologies designed for the Internet, especially IPv4 and IPv6, TCP and many other related IETF protocols, have also become the standard for almost every network, whether those networks are considered to be part of the Internet, connected through some security filters to the Internet or expected to be completely isolated.

These networks are often called private networks or limited-domain networks [3] and include Operational Technology (OT) networks such as in industrial/manufacturing; emergency services including fire, disaster and 911 services; critical infrastructures for the power grid including (nuclear) power plants; streets, air traffic and waterways control; train/track control; autonomous car and car to curb communications; healthcare; commercial supply chain operations; global financial operations; defense; local, regional, state and federal organization OT and IT networks; and general commercial and enterprise networks and other so-called Internet-of-Things (IoT) networks. Visibility into these networks, including their size, networking requirements and business importance to their industries, is difficult for those not involved in the respective industries or those working for the few network vendors serving those industries. Overall they are likely to constitute a much larger market and number of connected devices than the Internet.

When it comes to network protocols and their use in networks, one can therefore imagine an iceberg (see Fig. 1), where the portion above the water is the Internet and the part below the waterline represents the variety of such private and/or limited-domain networks. One of the key challenges for future networks research is therefore to better understand all those networks and their applications' needs, and build better network protocols and solutions for them. Another challenge is to connect and converge all of them together as a new better and bigger ”Internet.”

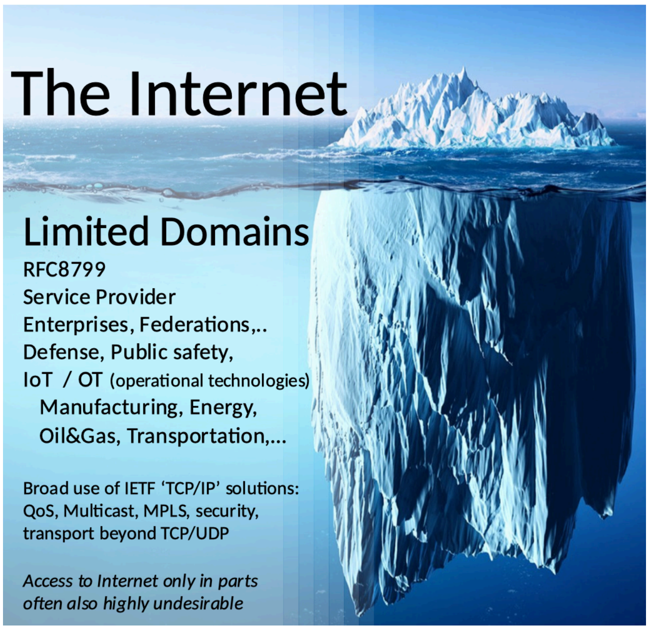


Fig. 1 – The TCP/IP networks iceberg

One key difference between the Internet and private networks is a difference in preferences for addressing. The growth of the Internet made the evolution from the 32-bit address IP protocol to a protocol with a larger address space such as IPv6 obviously necessary. Yet, private networks often see no benefits in the longer addresses of IPv6, and often prefer to stick with private 32 bit IP addresses. When IPv6 was designed, it was also assumed that IPv4 would completely disappear over time. Over the past 20 years it has become clear this will not happen any time soon, resulting in over 25 different IPv4-to-IPv6 address mapping mechanisms and an overall better understanding that for many use cases, especially in IoT and industrial networks more flexible addressing would be a significant benefit for a more flexible composition of networks, energy efficiency and simplicity of address operations.

While the Internet serves very well and at a very good price as an underlying transport layer for some part of those networks and services, it does not provide some crucial performance characteristics. Some networks need better than five nines of availability through advanced reliability mechanisms; real-time performance parameters including guaranteed throughput, zero packet loss and lowest latency. Their requirements are often at the cen-

 ©International Telecommunication Union, 2022

ter of the most critical parts of many networks and their applications.

Dedicated solutions for these problems are built using the very same “TCP/IP” protocols as the Internet, but they do employ additional (existing) functionalities and use more purpose-focused designs that can provide better network services for these applications. Nevertheless, most network industry research and development in the past decades has focused on the biggest growing market, which was the Internet market with its non-critical, non-real-time B2B and B2C Internet traffic. This has left a wide range of requirements for these non-Internet network use cases unresolved by the Internet industry. These are also more and more explored by researchers but by few SDOs.

One important area of research are extrapolations of network requirements from desirable future applications that we can see emerging today. Remote control is a core theme, whether it is a cloud-based remote Programmable Logic Controller (PLC) for next-generation manufacturing plant operations, telesurgery in medical environments, robots for remote operations in hazardous environments, home-assist robots in health and elderly care, remote driving of vehicles including cars, trucks, ships or airplanes or just physical or holographic avatars for social/entertainment or business interactions.

Several of these use cases have limited existing instances, often started early by the defense sector (remote unmanned vehicle operation), and one can expect to see inflection points in this coming decade, when enough technology components converge to take them to exponential growth.

Haptic and holographic communications: All-sense (and beyond) human/machine and human/human interfaces are one such key area of upcoming technology development. Holographic communications include holographic environment capturing and remote holographic rendering. It is the next stage of visual communications beyond AR and VR and it requires network throughput that is orders of magnitude higher than today’s 2D/3D and AR/VR visual communications [4, 5], as well as better guaranteed performance for the quality of holographic rendering required to achieve the desired benefits, lifelike visual remote presence.

Haptic communications cover sensing for remote touch and it requires better networks as well, specifically better guaranteed short round-trip-times; for example to allow the human initiator of the remote haptic communications to actually control the pressure of touch. Even smell and taste sensing are actively being researched and can be expected to be crucial for various use cases, such as remote avatar in security operations, smelling toxins, drugs or chemical indicators.

Remote driving: Even beyond the five classic senses, remote gravitational simulation is understood to be required to improve accuracy in remote operations such as for remote piloting (flying/driving)[1]. Highly reliable (zero interruptions), precise guaranteed network latency, throughput and zero loss of packets are other crucial requirements to grow these types of applications. Often severe loss of property or life can result from remote control loops even temporarily failing, experiencing performance loss or even just becoming less accurate.

Consider a remote controlled car driving across opposing traffic. The remote driver must not lose accuracy in steering or vision for even only parts of a second. Car-sharing with remote drivers is a commercially attractive use case; for example to help car fleet management in large cities. In one promising business model[2], the car-sharing company’s remote driver takes the car to the next customer location and picks up the car again when that customer has reached his or her destination. With today’s networks, this requires dual cellular network connectivity, tracking of 4G/5G coverage maps to avoid areas with unreliable mobile network coverage and limiting the remote drivers maneuvers and speed to allow for the control loop to be sufficiently safe. In another business model, bus services are using autonomous driving or remote drivers, giving them permission to only drive at much slower speeds, for example 18 Km/h (11 mph).

LEO satellite networks: One foremost currently unfolding new network technology is that of thousands of Low Earth Orbit (LEO) satellite networks planning to support the Internet and more specialized network services for a variety of customers ranging from currently hard to reach areas, moving endpoints (cars, trucks, trains, ships, planes) all the way down to residential Internet access.

In some scenarios, satellite networks may be the only connection to the Internet. Other scenarios include dynamic path and traffic diversity across a mix of such satellite networks. More traditional scenarios, such as 4G/5G mobile or wireline network services, call for even more interesting new network and routing support for such satellite networks.

Beyond 5G: The evolution of “traditional” mobile 4G/5G to 6G networks itself is also a driver for evolving the physical networks carrying mobile network traffic. Whereas mobile networks originally were physically standalone networks, they have started to evolve in the past few years, mostly since the introduction of 4G and now 5G, into software overlay processing that is running on top of physical networks from service providers, which are called the “transport” network. With more and more Internet and other TCP/IP traffic turning mobile, the requirements for the mobile network are also becoming key requirements for those physical next-generation service provider networks.

[1] See for instance: https://the-race.com/touring-car/driverless-remote-controlled-electric-car-completes-demo-lap/

[2] See for instance https://vay.io.

This includes low-latency, low-loss, high-reliability network connectivity between radio towers and an Edge Data-Center (Edge-DC) in which the softwarized mobile network processing happens. Softwarization of even the lowest layer of radio signal processing in those Edge-DCs, as well as significant increases in the user service bandwidths with 5G and 6G networks (often claimed to be up to 1 Gbps), result in raw bandwidth requirements of the underlying transport networks that are even higher.

It is not only mobile network that are built as overlays, but also many other private networks are today built in their WAN components with overlays over the Internet as an inexpensive transport. One common type of solutions for this is Software Defined WAN (SD-WAN), and many research proposals recognize the investment cost of building newer physical networks and do focus on overlay designs for incremental deployment, including ICN, Extensible Internet (EI), SCION or NewIP (discussed in Section 4)).

Overlay solutions do typically not suffice when specific service quality parameters especially zero-loss, controlled, low-latency, jitter and guaranteed throughput are required, because the service quality of consumer or commercial WAN Internet access is highly variable. Even dedicated network services such as service provider offered Virtual Private Networks (VPNs) do typically only provide very limited control of service quality parameters. For this reason, private network operators such as many of the aforementioned industries have interest in getting private network services from service providers in which more of the network service quality is under their control.

This is what the current trend for network slices is about. But such better control of network services is difficult when the currently possible network services offered by TCP/IP are not sufficient for the applications of those customers.

Hardware evolution: The slow evolution of network protocols in the past two decades is primarily caused by the market forces driving the Internet, namely its sheer market volume, its normative influence on all other private network markets. But it was also caused by dedicated network forwarding hardware which traded low-cost and high speed for limited flexibility and slow innovation cycles. This too has changed in the last decade through the evolution of network forwarding implementations.

Firstly, the speed improvements in general purpose CPU in the past two decades allowed for slower-speed (today in practice up to low 100Gbps) network forwarding hardware to become softwarized and deployed onto standard DC servers, which then lead into the decomposition of the architecture of complex routers into software modules called Virtual Network Functions (VNFs) and Network Forwarding Virtualization (NFV). This has allowed more modular overlay and edge-network architectures to evolve. This has also opened the door to much faster development of new network protocols for such software network forwarders.

Secondly, the ASICs of high speed forwarders for data-center switches, LANs and WANS, with speeds into the terabits did evolve in the past decade to become more programmable, not only to the few vendors that developed them, but also to third parties. This raised interest especially in the research community to work on better next-generation network protocols and network designs.

Network automation: With networks becoming faster and larger and their services becoming more varied and challenging, network management and operations have become a core aspect of development and research. In 2007, a concept called Software Defined Networking (SDN) evolved. It encompasses today the aforementioned softwarized network components as well as automated provisioning and operations of softwarized and hardware network equipment and of the service instances running on them. These SDN management architectures themselves are becoming so complex that they need to be rebuilt from complex and often fragile hierarchical command and control architectures to so-called “Intent Based Networking” [6]. Intent-based networking provides different levels of abstractions to express goals (Intent) in high-level terms. Then the system attempts to converge the operational state to meet that intent.

In many cases though, the best way to deal with complexity is to avoid it in the first place. Building the components of a network to embody the desired properties is preferred to layering them through complex management solutions. This is what research and standardization into more secure forwarding planes (such as SCION) and self-automation in the network is about. Next-generation network protocols can help such simplification goals by providing more monitoring (telemetry), security and self-managing service quality mechanisms.

3. NON-IP TECHNOLOGIES AND PROTOCOLS

In this section, we turn our attention to efforts to standardize new networking protocols in ETSI (NGP in Section 3.1 and NIN in Section 3.2), in IETF (ICN in Section 3.3) and in 3GPP (satellite networks in Section 3.4).

3.1 NGP

Next Generation Protocol (NGP) was the project in ETSI that investigated and analyzed the problem for the current TCP/IP-based communication protocols for the Internet. It also tried to study and propose the next generation protocols.

 ©International Telecommunication Union, 2022

For NGP, the project has defined scenarios [7], requirements [8] and Key Performance Indicators (KPIs) [9].

There are two completely different technical road maps for NGP: IP-based and non-IP-based solutions. For the IP-based solutions, supporters believe that future network protocols for the Internet will evolve from the current TCP/IP technologies; on the contrary, the non-IP supporters think that there are too many problems and challenges in the current TCP/IP, and using a newly designed protocol suite is a better choice.

For the evolutionary direction or TCP/IP-based solutions, the basic principle for NGP is to keep the most important characteristics of IP. That includes (but is not limited) to the following:

1. The Internet protocol suite or TCP/IP model: The Internet protocol stack consists of the physical layer, link Layer, IP layer, transport Layer and application Layer.
2. IPv4 and IPv6 packet header format: The IP packet header is extensible in IPv6.
3. IGP and BGP-based routing protocols: IGP is for the routing within an administrative domain, and BGP is for the routing between different administrative domains.
4. IP forwarding mechanism: The IP packet is forwarded based on Longest Prefix Match (LPM).

Based on these principles, NGP has focused on new services that the current TCP/IP technologies cannot provide. The new services have the following criteria:

1. More automation and intelligence in the network control and management.
2. Better Quality of Service (QoS), in terms of bandwidth, latency, jitter and packet loss ratio.
3. Better efficiency to utilize the network resource and capacity.
4. More flexibility to deliver user traffic through a network to satisfy the user's expectation.

NGP has proposed the following work items:

1. GS-NGP-002 [10]: "NGP: Self-Organizing Control and Management Planes." This is to enhance the IP network control and management by introducing self-organizing automation.
2. GR-NGP-006 [11]: "Intelligence-Defined Network (IDN)." This is about the new network architecture with intelligence from AI or machine learning.
3. GR-NGP-008 [12]:"Mobile Deterministic Networking." This work item analyzed the current issues to realize ultra-Reliable Low Latency Communications (uRLLC, as defined in 3GPP), and proposed a solution based on time synchronization and deterministic transmissions.
4. GR-NGP-010 [13]: "Recommendation for New Transport Technologies." This work item tries to provide better service than best-effort, in terms of guaranteed QoS (bandwidth, latency and jitter), by introducing a sublayer in the network layer to control the transport layer. The transport control is achieved by programming hardware based on the customer expected service info embedded in the user's packet.
5. GR-NGP-011 [14]: "E2E Network Slicing Reference Framework and Information Model." This work item conducted the gap analysis for the current virtualization, cloud-centric, NFV and SDN technologies, and then specified the common requirements in information and modeling for network resource used for end-to-end network slicing services.
6. GR-NGP-014 [15]: "Preferred Path Routing (PPR) for Next Generation Protocols." This work item proposed a method to support the customer preferred path in an IGP domain by enhancing the IGP protocol to populate the preferred path programming information to network devices.
7. GR-NGP-015 [16]: "Recommendation for Network Layer Multi-Path Support." This work item studied the possibility and different technical aspects to support multi-path at the IP layer for Internet where multiple administrative domains exist, and BGP is used.
8. GR-NGP-016 [17]: "Large-Scale Deterministic Network." This work item proposed to use a new queuing mechanism to support bounded latency and jitters for the IP network. The new techniques will be suitable to large-scale networks such as a service provider's network.
9. GR-NGP-004 [18]: "NGP: Evolved Architecture for mobility using Identity Oriented Networks." This work item proposed Identity Oriented Networks (ION) for 5G and beyond; the identifier and temporal location information are dissociated. The underlayer of the network is still IP, but a non-IP format of the identifier is supported in the new architecture.

For non-IP directions, NGP has worked on two categories. One is RINA, another is FLEXLINK.

Recursive Inter-Network Architecture (RINA) [19] is an alternative architecture to the current TCP/IP-based Internet protocol suites. RINA attempts to solve the following problems of Internet protocols: Transmission complexity and performance issues caused by separation of

TCP and IP, and TCP overhead; multi-homing and mobility issues caused by IP address and port number at the same low level; management and security vulnerability caused by IP address.

The key concept of RINA is that every layer for a communication protocol stack can be represented by inter-process communications or *IPCs*. Different layers in the stack should be a recurring set of protocols used for different scopes and scales, rather than based on a specified function and specialized protocols like in TCP/IP.

Fig. 2 illustrates the architecture for RINA. In the architecture, the Distributed IPC Facilities (DIF) is repeating in every layer for the communication between different entities. The scope of each layer (DIF) is configured to handle communications between specified entities with a given range of bandwidth, QoS and scale. Each DIF consists of "IPC Processes" (IPCPs); different IPCPs at different entities collaborate together to provide and manage an IPC service over a certain scope.

For example, the new LTE architecture instantiated in RINA, and the corresponding traditional LTE architecture defined by 3GPP, are illustrated in Fig. 3. For RINA, two fundamental DIFs are used: one is the radio DIF used between the user equipment (UE) and the wireless access device. Another is the Point-to-Point (PtP) DIF used between devices in the backhaul network. On top of these two DIFs, there are several upper layer DIFs, such as the metro DIF, the backbone DIF, the mobile network top level DIF and the public Internet DIF. Fig. 3 shows the streamlined architecture simplicity brought in by RINA.

FLEXILINK [20] is a technology for packet switching for network devices. Its purpose is to provide both basic and guaranteed QoS services for a network. FLEXILINK proposes that the user's packet header should be minimized and only carries a "label," which is an index into the routing table. Each entry in the routing table will contain the output port number and the label for the next hop. All other control information is carried in control plane messages and is sent once for each flow instead of in every packet. FLEXILINK can support different user packet formats. User packets can be either encapsulated with FLEXILINK label like MPLS, or can be stripped on entry and added back on exit of the FLEXILINK network. The controller is responsible for the routing table content establishment and for the installation into hardware.

The reports for RINA and FLEXILINK are:

1. GR-NGP-003 [22]: "NGP: Packet Routing Technologies." This document introduces the RINA basics in architecture for packet routing.

2. GS-NGP-007 [23]: "NGP Reference Model." This document specifies a reference model for the existing protocol enhancement and new protocol design.

3. GR-NGP-009 [21]: "An example of a non-IP network protocol architecture based on RINA design principles." This document is about the RINA architecture and design guidance for different types of networks, such as wireless access and core network, virtual private LAN service, data center network, etc.

4. GS-NGP-013 [24]: "Flexilink: efficient deterministic packet forwarding in user plane for NGP; Packet formats and forwarding mechanisms." This document discusses the basics about FLEXILINK to achieve QoS expectations.

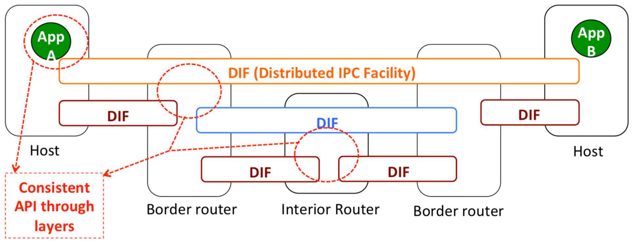


Fig. 2 – A repeating layer (the DIF) for different scopes is the basic structural pattern of RINA [21]

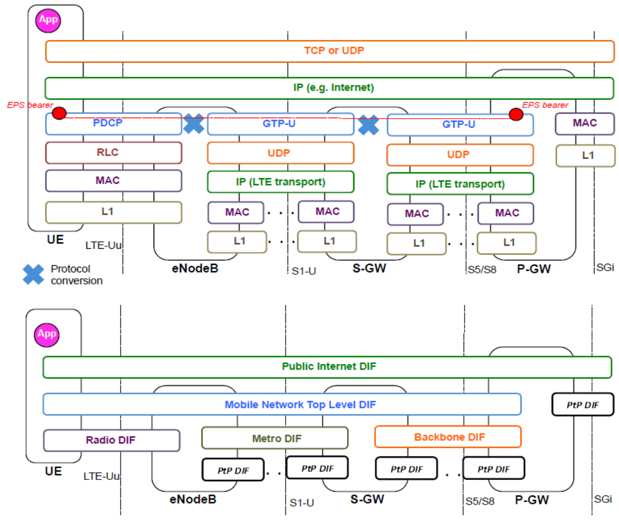


Fig. 3 – Comparison of the architecture of LTE (up) and RINA (down) [21]

3.2 NIN

Non-IP Networking (NIN) is an active project in ETSI as of this writing. It is actually the continuation of the non-IP technologies in NGP and it excludes all IP-based solutions. NIN emphasizes that its proposed technology is not dependent on IP packet formats or protocols; however, it still supports the different protocol suites including TCP/IP, Information Centric Networking (ICN, see below) and RINA.

NIN's scope focuses on further research and standardization for FLEXILINK, and its application to cellular networks. The following technical reports have been pub-

 ©International Telecommunication Union, 2022

lished by the NIN project so far:

1. GR-NIN-001 [25]: "NIN: Problem statement: networking with TCP/IP in the 2020s."
2. GR-NIN-002 [26]: "NIN: Implementing Non-IP networking over 3GPP cellular access." It uses FLEXILINK for the realization of wireless access networks defined by 3GPP such as LTE and 5G.
3. GR-NIN-003 [27]: "NIN: Flexilink network model." This document discusses the details of a Flexilink network including layering, control plane, packet format (see Figure 4), etc.

NIN is still working on two items: "Signaling messages and protocols" and "Carriage of Flexilink flows over DECT 2020 New Radio."

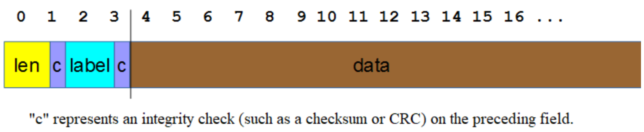


Fig. 4 – Flexilink packet format [27]

3.3 ICN

The Information-Centric Networking (ICN) architecture attempts to reinvent the Internet, with the explicit goal of replacing RFC 793. IP sets up a connection by connecting two hosts (typically a client and a server) over a UDP or TCP session. These hosts then provide the content that is being requested, as the Internet has evolved to allocating most of its resources to delivering content. Video streaming accounts for over 80% of the Internet [2], thanks to the success of video sharing platform such as Netflix, Hulu, Disney+, etc.

The Internet has evolved to accommodate this shift in the traffic patterns, most notably with the deployment of an overlay infrastructure for content distribution. Content Distribution Networks (CDNs), such as Akamai and others [28], have been successfully deployed and most of the Internet traffic now goes over such a network. CDNs replicate the content to multiple servers so that clients can access a copy of the content that is placed in a cache near the users. This avoids overwhelming the origin server for the content, and the network in between. This also reduces the latency for the client to retrieve the content, and improves the Quality of Experience (QoE) of the users.

ICN is an attempt to generalize CDNs and to replace the traditional host-server connection by a connection directly to the content. There were several such proposals, such as Content-Centric Networking (CCN [29]), Data-Oriented Network Architecture (DONA [30]), Publish/Subscribe Internet Technology (PURSUIT [31]) or Networks of Information (NetInf [32]). We refer to [33] for a survey on information-centric networks and briefly present the key ideas of the architecture below.
We focus now on CCN, as it is one of the most visible research efforts. The Named-Data Networking project [34, 35], which evolved out of CCN, was one of the Future Internet Architecture (FIA) programs funded by NSF and CCN has been pushed towards standardization as a suite of informational RFCs in the IRTF [36, 37, 38].

Fig. 5 shows the key abstraction of CCN, namely that the central part of the architecture, the "new narrow waist" of a future Internet, would be to address content directly. This means the client would request content directly by its name, without specifying the IP address of a host that holds the content. The network forwards that request directly to such a host. The network thus performs name-based forwarding directly on the content name.

Fig. 6 (from PARC) shows the processing of such a content request in a node. The client issues its request as an "Interest" message. Each node that receives this interest then looks up its content store to see if it holds a copy of the content locally. If it does, then the content is being returned to the client. If not, then it looks up its Forwarding Information Base (FIB) to find out if it knows how to forward this interest. The FIB does not hold IP address prefixes, but name prefixes. Once it locates the next hop to forward the request, it sends the interest to that node and keeps in a "Pending Interest Table" (PIT) a list of the interests that have been forwarded and are expecting a response. This PIT keeps a pointer towards the interface that received the interest initially. Once it receives the content as a response to an interest in the PIT, it can then forward that response back to that interface, and remove the entry from the PIT.

There are several important considerations in such an architecture, namely that there is no address for the clients nor the servers. The content is sent back to the client who issued the interest by following the trail of breadcrumbs placed in the PIT of the intermediate nodes. The content is found by looking up the FIB.

Obviously, such a forwarding architecture introduces many issues, including lack of backward compatibility, scaling issues while dealing with content names vs IP addresses, overhead issues in maintaining the FIB up to date to locate local content, etc. There are also some incentive issues, as this architecture requires that the operators deploy a whole new network. It is unclear what the business model is for such a new network: CDN overlays provide a similar function (albeit with a contractual relationship between the CDN and the content providers to disseminate their content) and they only generate a fraction of the ISP revenues or that of the Over-The-Top (OTT) content providers.
However, some research effort has gone into studying and fixing some of these issues [39, 40].

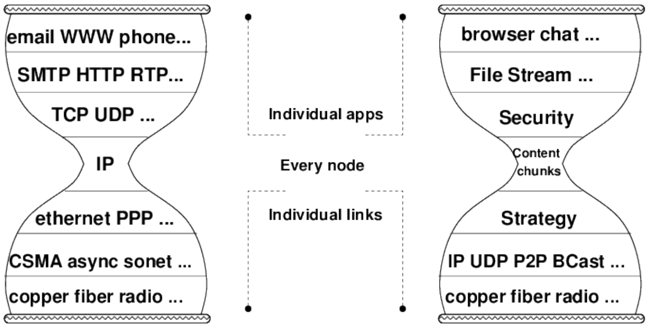


Fig. 5 – CCN stack

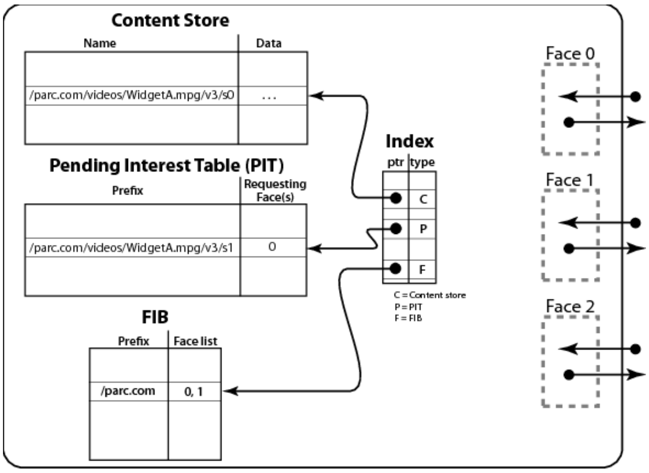


Fig. 6 – CCN forwarding engine model

3.3.1 Cisco hybrid ICN

One attempt to commercially deploy ICN was proposed by Cisco, namely hybrid ICN (hICN) [41, 42]. The main idea of hICN is to provide a network protocol that integrates ICN in IPv6 by embedding a data identified (using 64 bits) into the IPv6 address. Because the first 64 bits of the address provide a routable prefix, this address is understood by regular IP routers. However, hICN routers on the path are able to look up the data identifier and to provide the name-based functions of ICN.

hICN was a valuable attempt to deploy ICN in existing commercial networks, and demonstration at Mobile World Congress and others showed some appreciable gains for video distribution. However, the effort seems to be dormant as of this writing, with no further updates to the IETF draft and no recent contributions to research papers or the code base at https://wiki.fd.io/view/HICN.

3.4 Satellite

3GPP is a major SDO that contributes to satellite networking from several angles, including physical signaling, radio spectrum, radio network, use cases, deployment, and system architecture.

Initially, a satellite network was treated as an extension to the terrestrial network and was considered only to provide service to areas where no regular terrestrial network is available, and also should provide services that are more efficient than a terrestrial network, such as broadcasting services, delay-tolerant services, etc. After 5G however, the importance of satellites has grown in the 3GPP community. 5G has proposed to use a Non-Terrestrial Network (NTN) to represent all networks that involve non-terrestrial flying objects, such as satellite network, High Altitude Platform Systems (HAPS), and air-to-ground networks. Of all those networks, satellite networks are the major case, and others are special cases of satellite networks.

Since Rel-15, 3GPP has proposed different Study items or Working Items in different Technical Specification Groups (TSGs): Radio Access Network (RAN), Service & System Aspects (SA), Core Network & Terminals (CT). The following Technical Reports (TRs) were published:

1. TR 38.811 [43]: “Study on NR to support non-terrestrial networks”, Rel-15
2. TR 38.821 [44]: “Study on solutions for NR to support non-terrestrial network”, Rel-16
3. TR 36.763 [45]: “Study on NB-IoT/eMTC support for NTN”, Rel-17
4. TR 22.822 [46]: “Study on using satellite access in 5G”, Rel-16
5. TR 23.737 [47]: “Study on architecture aspects for using satellite access in 5G”, Rel-17
6. TR 28.808 [48]: “Management and orchestration aspects with integrated satellite components in a 5G network”, Rel-17
7. TR 22.926 [49]: “Guidelines for extra-territorial 5G systems”, Rel-18
8. TR 24.821 [50]: “CT aspects of 5GC architecture for satellite networks”, Rel-17

3GPP expects the satellite network to directly connect to mobile devices with acceptable bandwidth. Obviously this is a visionary feature and needs a lot of research and engineering work. The current regular mobile device (cell phone) cannot provide enough power to directly connect to satellites at an altitude of a couple of hundreds kilometers. The research will focus on the physical layer: how to design a radio receiver on mobile devices and satellite that is super-sensitive to the weak signal, and a design transmitter that can transmit stronger signals under limited power supply. This may need revolutionary innovation in components, antennas, and semiconductors, etc.

Since Rel-15, 3GPP has started the study for the NTN with New Radio (NR) technologies developed for 5G. In TR 38.811, different aspects of NR for the use of satellite were studied. This includes:

 ©International Telecommunication Union, 2022

1. Channel modeling for satellites when considering different user environments and atmospheric conditions.
2. Satellite-specific constraints associated with satellite networks: propagation channel; frequency plan and channel bandwidth; link budget; cell pattern generation; propagation delay characteristics and impacts; mobility of transmission equipment and terminals; service continuity crossing 5G and NTN; radio resource management.

Meanwhile, 3GPP also proposed architectures for the integration of NTN with terrestrial networks under the assumption that the mobile device can connect with satellites directly. TR 38.821 for Release 16 described a satellite-based NG-RAN architectures. In this proposal, the 5G architecture is used directly and satellites are treated as a complete or partial replacement for a base station (e.g. gNB). There are three types of satellite in the report:

1. Satellite with transparent payload;
2. Satellite with regenerative payload (gNB on board, with and without ISL - see below);
3. Satellite with regenerative payload (gNB-DU on board, gNB-CU on ground, see below).

The first type of satellite (see Fig. 7) represents the current work model for LEO satellite constellation such as StarLink: the satellite only does the signal relaying between ground stations. The only difference is that StarLink only uses its own ground station for the terminal and gateway, and uses its own proprietary technology instead of 5G NR for radio. For this type of architecture, there is no packet processing in a satellite except the signal processing, such as radio frequency filtering, frequency conversion and amplification. So, the base station functions are provided by devices on the ground behind the ground station. The corresponding control plane and data plane are shown in Fig. 8.

For the second type of satellite, in addition to the signaling processing function provided by transparent payload, the satellites also provide demodulation/decoding, switching and/or routing, coding/modulation. This is effectively equivalent to having all or part of the base station functions (e.g. gNB) on board the satellite (or UAS platform)m, as shown in Fig. 9. This is a general architecture for a satellite constellation integrated with 5G and the Internet. Each satellite is functioning as a flying base station and the satellite constellation functions as backhaul network, or core network. The satellite constellation connected by ISL will form an IP network and will be a carrier for the NG or Xn interfaces [51]. For this architecture, the AMF, UPF functions [51] are provided by devices on the ground (see Fig. 10).

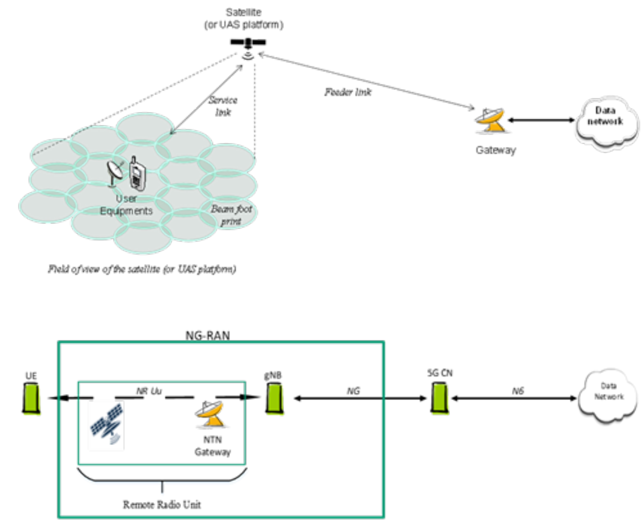


Fig. 7 – Satellite with transparent payload [44]

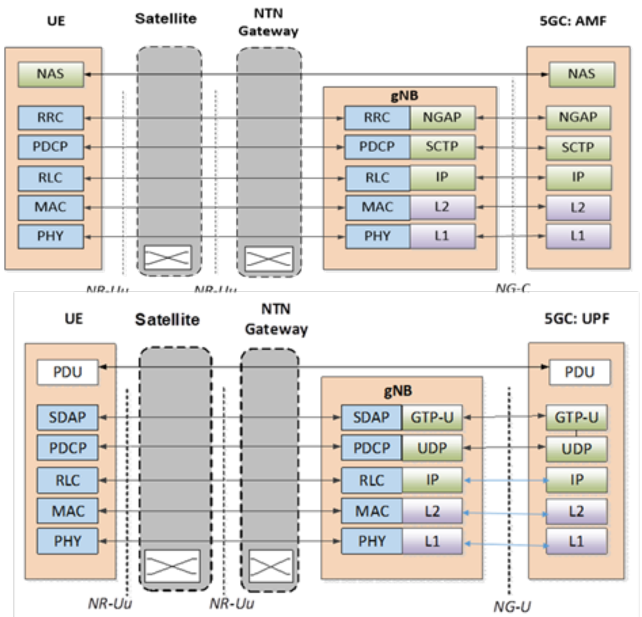


Fig. 8 – Control plane and user plane for satellite with transparent payload [44]

The third type of satellite is similar to the second type and is shown in Fig. 11, but each satellite will only provide part of the functions of a base station. For this architecture, the control unit (gNB-CU) and data unit (gNB-DU) of the base station (gNB) are separated. The control unit of the gNB is provided by devices on the ground; the satellite only does the data unit work. The user plane of gNB is also separated between the satellite and device on the ground (see Fig. 12).

Since the satellite network moves so fast (with the speed more than 7 km/s [52]), it impacts how NR is used. TR 38.821 also has done the detailed analysis and potential solutions. The analysis includes:

1. Radio layer issues: it analyzed the satellite parame-

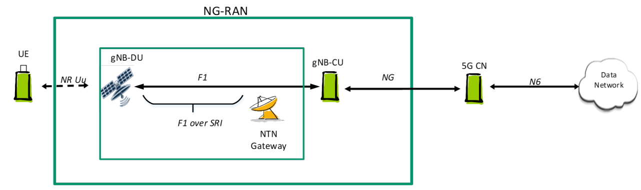


Fig. 9 – Satellite with regenerative payload (gNB on board, with and without ISL) [44]

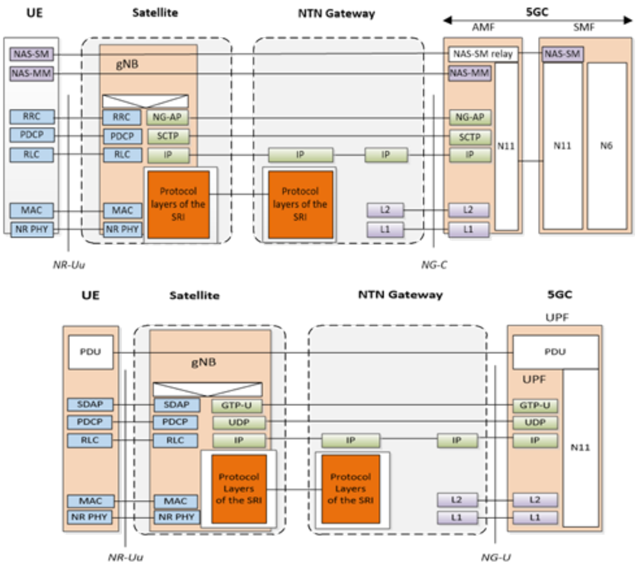


Fig. 10 – Control plane and user plane for satellite with regenerative payload (gNB on board, with and without ISL) [44]

ters and UE characteristics for system level simulator calibration; and beam layout parameters for single satellite and multiple satellites simulation. It also discussed about the link level simulation, link budget analysis. For physical control procedures, analysis for timing relationship, power control, beam management are done. Also the DL synchronization and random access are discussed for uplink timing procedures.

2. Radio protocol issues: the report has analyzed the user plane enhancement for radio protocols like Media Access Control (MAC), Radio Link Control (RLC), Packet Data Convergence Protocol (PDCP), Service Data Adaptation Protocol (SDAP). It also analyzed the enhancement for control plane in the areas: idle model mobility, connected model mobility, paging, radio link monitoring, public land mobile network (PLMN) identities deployment and ephemeral data for NTN.

3. Architecture level and interface protocols issues: Tracking area management; registration update and paging handling, connected model mobility.

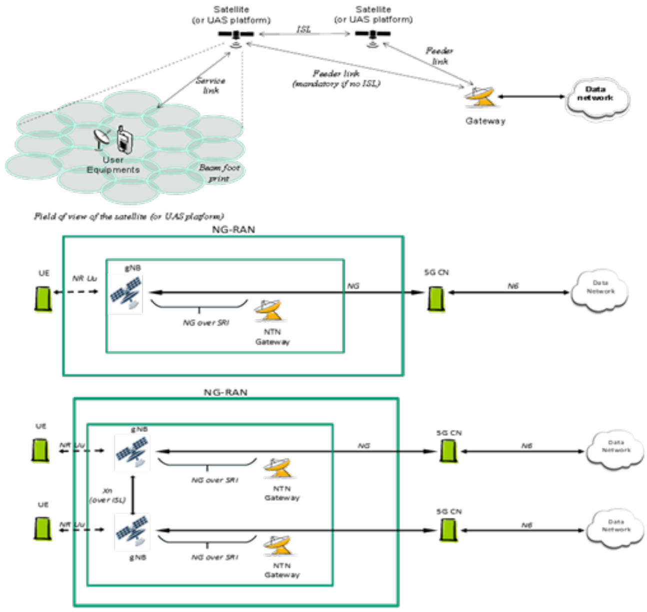


Fig. 11 – Satellite with regenerative payload (gNB-DU on board, gNB-CU on ground) [44]

4. NETWORK LAYER TECHNOLOGIES AND PROTOCOLS

In this section, we discuss work on new network layer technologies outside of the SDOs. Namely, Section 4.1 discusses new protocols for satellite networks; Section 4.2 and Section 4.3 discuss SCION and NewIP respectively; Section 4.4 mentions the potential of network programmability for network layer innovation. Section 4.5 briefly discusses the "Extensible Internet" (EI) proposal.

4.1 Satellite

For network layer or IP technology, IETF has not done too much work dedicated to satellite networking. Its historic work related to satellites only focused on the transport (L4) area: TCP Over Satellite (TCPSAT WG). This WG handled issues for TCP over different satellite links (geostationary, GEO, medium earth orbit, MEO, low earth orbit, LEO). RFC 2488 [**RFC2488**] (Enhancing TCP Over Satellite Channels using Standard Mechanisms) was published in 1999; RFC 2760 [53] (Ongoing TCP Research Related to Satellites) was published in 2000. There was another individual draft RFC 8975 [54] (Network Coding for Satellite Systems), published in 2021.

Delay/Disruption Tolerant Networking (DTN WG) has some relationship with high altitude satellites such as GEO or MEO, since the network composed of GEO or MEO satellites normally has high link delay and low bandwidth. But LEO satellite networks normally have shorter latency than terrestrial network and do not belong to this category, and the RFCs generated in DTN are not expected to apply.

Currently, there is ongoing work related to Satellite:

 ©International Telecommunication Union, 2022

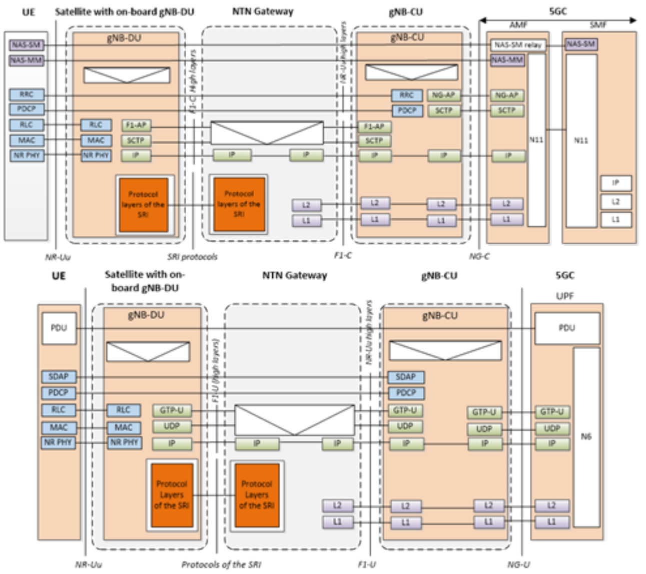


Fig. 12 – Control plane and user plane for satellite with regenerative payload (gNB-DU on board, gNB-CU on ground) [44]

1. Enhancing Transport Protocols over Satellite Networks [55].
2. Problems and Requirements of Satellite Constellation for Internet [52].
3. Satellite Semantic Addressing for Satellite Constellation [56].
4. Semantic Address Based Instructive Routing for Satellite Network [57].

The documents [52, 56, 57] try to analyze the problems and requirements of satellite networks when Inter-Satellite Link (ISL) and L3 routing are used. They also provide a routing solution for satellite networking that uses a new semantic address to identify satellites and to route user packets by instructions. ISL is a very important leap for the LEO constellations like StarLink to extend its coverage globally, and to improve service quality. Also, this is a mandatory requirement for the regenerative mode for 3GPP NG RAN described in Section 3.4.

4.2 SCION

Another architecture has been proposed with SCION [58, 59, 60]. SCION stands for *Scalability, Control and Isolation in next-generation Networks*. The project started in 2009, initially as part of the XIA [61] project and is still ongoing: it recently hosted a SCION day on 1/26/22 in Zürich, and some outreach activity to the IETF community at the IETF 113 meeting in March 2022.

SCION addresses some issues of IP, namely: 1) a lack of separation between routing and forwarding that makes paths brittle; 2) a lack of transparency and control, that prevents the sender from choosing a preferred path; and 3) stateful routers that rely on expensive and energy-hungry TCAMs.

SCION also tackles issues arising out of BGP (namely outages, lack of fault isolation, scalability, single path) a lack of authentication and trust within the network, migration towards a new architecture, as well as vulnerability to all sorts of attacks: prefix hijacking, spoofing, DDoS attacks, forged certificates, etc.

SCION is built upon the current administrative and economic boundaries of the current Internet, and leverages the Autonomous Systems (ASs). In SCION, ASs are grouped into Isolation Domains (ISDs) where the ASs share trust and security parameters. In an ISD, ASs pick a set of trust roots (namely, the Trust Root Configuration, TRC). Routing is based on (ISD,AS) numbers and is independent of the local addresses with an AS. SCION assumes that an AS gets to keep its current AS number, but allows for new SCION AS numbers by expanding the namespace to 48 bits. Each ISD contains some core ASs, that is a subset of ASs within the ISD which govern and manage the trust roots.

Each host has a local address and is uniquely identified by a 3-tuple (ISO, AS, local address). The local address is only used for intra-domain routing and does not have to be globally unique. It can be an IPv4 or IPv6 address (or any other scheme within an AS).

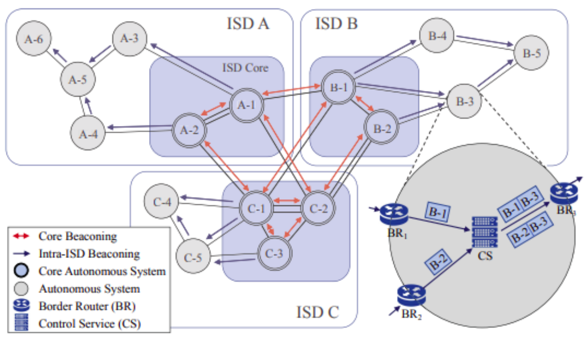


Fig. 13 – ASs form ISDs within SCION architecture (Figure from [62])

Paths are established as AS-level path segments. A path segment describes the inter-domain interfaces connecting ASs on the path. The path between end hosts is built of three distinct path segments: a path from the AS of the source host to the core, a path within the core, a path from the core to the AS of the destination host (recall that SCION does not deal with paths within an AS). These are respectively the up-path, core-path and down-path. The core-path only contains core-ASs. If it is more practical to avoid core-ASs, the path may bypass this step to find potential shortcuts.

Routing (that is: building the paths) happens at the level of the core, to build the core-paths; and within each ISD to build the up and down paths. Each AS beacons its position to the other ASs within the ISD. This replaces BGP and has a similar function. However, the process is secured and

©International Telecommunication Union, 2022

happens within the limited scope of the ISD, thereby providing better scalability. Beaconing happens at the level of the ISD and at the level of the core, to create a scalable hierarchy.

In the data plane, the name resolution service in SCION provides the 3-tuple composed of (ISD,AS,local address). Using the (ISD,AS) pair enables the retrieval of the core-path and the down-path. The up-path is known to the AS and can be combined to make a whole path. The path may be optimized if some of the nodes are within the same ASs or if a peering link is available. The path needs to be authenticated to avoid unauthorized path combinations. The path segments specify which interface to use to enter/leave an AS, and is protected to prevent path modifications. Routers do not keep local state as all the necessary information is securely carried by the packet.

[62] provides a thorough analysis of the architecture, answering questions regarding incentives for deployment, migration strategy alongside BGP, and scalability issues.

4.3 New IP

New IP is a term often attached to attempts to evolve the hop-by-hop network functionalities beyond what is possible for IPv4 and IPv6, so as to meet requirements by the variety of networks, and current and future applications requiring more than best-effort services, as outlined in Section 2.

New IP is designed to evolve, upgrade, improve the Internet to implement and support future and emerging applications, in particular, applications enabled by 5G/B5G/6G, and convergence with operational technology networks so as to offer connectivity to networks that have not been or cannot be connect to the current Internet. It is not being standardized as a single proposal, but a broad range of enhancement technologies with the goal to culminate in a new version of IP. This subsection gives an overview of several of the core motivations and technology aspects that have been explored so far for new IP research.

4.3.1 Evolution instead of revolution

In contrast to non-IP efforts such as those outlined in Section 3, the goal of the "New IP" proposals is to provide an evolutionary path from the IPv4/IPv6 protocols. Given the large installed base of IP, it is important to maintain backward compatibility and interoperability with both protocols, and to allow for the future to easier evolve the protocol without hard versioning breaks. This was not the goal when introducing IPv6 in the 1990s, as it was planned to quickly and completely replace IPv4. This never happened though. Instead, we have today an order of magnitude more IPv4/IPv6 networks, and more than 26 IPv4/IPv6 transition mechanisms [3].

4.3.2 New IP for private networks and the Internet

While the needs and benefits of a New IP will easily be first applicable to private or limited-domain networks, a protocol can only claim to be an evolution of IP when its architecture supports and improves the Internet. Likewise, the Internet is intended to support multi-protocol operations, as laid out by RFC 1726 [63]. Through the co-existence of IPv4 and IPv6, the Internet is already a multi-network-protocol network. New IP (for parts of the Internet where it adds value) can be the next logical stage of testing, experimentation and development.

Compared to (most) private networks, the Internet has several additional challenges, including so-called inter-domain network paths across the networks of more than one operator; and large-scale networks with potentially millions of parallel traffic flows. Challenges of these network paths have to also be addressed by New IP, but with the observed "Death of Transit" [64], most Internet paths today do not include a pure transit carrier, which is a provider without a business relationship to either endpoint of the communications. This can significantly change and simplify the feasible economic models to support more than the best-effort model of the Internet.

4.3.3 IP and service differentiation

To support IP service level differentiation beyond best effort, the IETF developed for IP networks first the "Integrated Services" (IntServ) architecture [65]. In IntServ, every traffic flow could be given separate treatments from other traffic flows through per-flow state at each hop. Managing this state is enabled through a per-flow control plane such as the "Resource reSerVation Protocol" (RSVP [66]).

For large-scale networks with (more than) hundreds of thousand of flows in need of better service, neither the control plane nor the forwarding plane could scale to this per-hop, per-flow state model.

To overcome this challenge, the IETF developed the Differentiated Services (DiffServ) [67] architecture. There, packets are treated as a member of a class through a per-packet marking, the so-called "DiffServ Code Point" (*DSCP*). DiffServ has fundamental limitations that render it insufficient for demanding applications and large-scale service provider networks: Even with only a few DSCPs, it can be very complex to operate, and it cannot provide absolute or relative service experiences, such as bounded latency between flows of the same class. For more background about challenges of IntServ and DiffServ, see [68],

[3] See for instance https://en.wikipedia.org/wiki/IPv6_transition_mechanism.

©International Telecommunication Union, 2022

or [69] specifically for issues with bounded latency.

SCTP [70, 71] was also defined to support the setup of telephony signaling over IP and offer multi-homing and multi-streaming.

4.3.4 *Scaling services through stateless operations*

As a result of these scalability challenges, research began to explore how to provide better per-hop, per-flow stateless service differentiation and guarantees through additional in-packet header fields. For example in 2002, "Per Hop Behaviors Based on Dynamic Packet State" (DPS) [72] proposed to use a "weight" packet header to indicate in each packet the relative bandwidth weight to be given to packets of the flow relative to the bandwidth of other flows, eliminating the need for per-flow weighted queuing.

Stateless operation through additional packet header information was popularized in IPv6 for traffic steering via the IPv6 instance of source routing, which is called "Segment Routing" (SR) and defined in [73, 74].

Supporting deterministic bounded latency without per-hop, per-flow state in wide-area networks is another service that ideally requires new network packet header parameters, such as those proposed in the 2018 "Large-Scale Deterministic Network" (LDN) proposal [75, 76].

4.3.5 *IP packet header extensions and challenges*

Mechanisms for stateless operations through extension headers except for SR/SRH (such as DPS), have thus far failed to gain traction. As of this writing, the "Low Latency, Low Loss, Scalable Throughput" (L4S) architecture [77] intends to improve Internet congestion control by adding additional semantics to two pre-existing "Early Connection Notification" (ECN) bits to avoid the need to extend or change the IPv4/IPv6 headers.

In reflection of these existing IPv4/IPv6 extension header challenges, "A New Framework and Protocol for Future Networking Applications" [78], proposed a flexible protocol header framework that supports both stateful operation without relying on transport protocol headers (which IP IntServ has to rely on for its operations), as well as stateless operation through flexible and extensible parameters. It also proposed mechanisms to share parameters across multiple services indicated in the header, and to explicitly indicate dependencies and execution order of services as well as the ability to execute services in parallel.

4.3.6 *Latency services*

Latency management has in recent years been a core area of interest for future networks with trends such as "ultra-Reliable Low Latency Communications" (uRLLC). New IP packet headers help latency management with "Latency Based Forwarding" (*LBF*). It utilizes the framework of BPP [78] to introduce a service in which the hop-by-hop latency is controlled with high precision through in-packet latency parameters and programmable scheduling of packets at the switch.

One set of parameters are so-called "Service Level Objective" (SLO) parameters set by the sender and not changed by the network. Another set of parameters are processing parameters such as the latency experienced by the packet as it traverses every hop. These parameters are updated by the network while it processes the packet. With SLO parameters of minimum and maximum end-to-end latency, the LBF concept provides benefits such as providing controlled latency ranges independent of path latency (within physical limits, of course); equalizing latencies of packets traversing paths of different RTT; distributing buffer load more equally across hops; or making packets that experienced congestion on a prior hop catch up and be processed faster on the following hops, reducing the flow jitter.

4.3.7 *New communication service paradigms*

Through the work of the ITU-T Focus Group on Technologies for Network 2030 (FGNET2030), more controlled communication services and their respective use case drivers were identified. [79] identifies "High Precision Communications" as the means by which latency, throughput, and congestion can be controlled. It introduces specifically for latency a distinction between "on-time" service for low-jitter delivery and "in-time" delivery with uncontrolled jitter. It identifies "Qualitative Communications" as a mean to take the quality of data into account for the network forwarding layer (see below). It identifies "Coordinated Services" as a means through which multiple traffic flows (for example, in group communications) can achieve relative performance goals such as simultaneous arrival times of traffic between more than two parties.

Likewise, loss reducing technologies without added latency through packet duplication, forwarding across failure-disjoint paths, and duplication elimination, have been called zero-Loss network services.

All these communication paradigms require specific network layer forwarding service functions, and various hop-by-hop network packet header parameters, especially when the service function is also intended to be supported in a stateless fashion.

4.3.8 Addressing headers

Whereas these new QoS services are still at least theoretically possible to add to IPv4/IPv6 via extension headers, the elements of the IPv4/IPv6 base header are immutable without defining a new version of IP. This means that the 8 bits of existing QoS parameters, DSCP + ECN cannot be eliminated when not needed (because no or better parameters are required), but it primarily means that addressing in IPv4 is fixed to 32 bit and in IPv6 to 128 bit.

Various research and standardization efforts have pointed out the shortcomings of these IPv4/IPv6 addressing options: The ISO/OSI network layer "ConnectionLess Network Protocol" (CLNP [80]) already provides addressing up to, but not fixed to 128 bit, avoiding the waste of addressing bits where not needed. [81] describes various benefits of using shorter addresses including energy savings in low bit rate networks. [82] describes how IPv6 makes it operationally harder than IPv4 to compose industrial networks due to its focus on only a single global (Internet) address space, including the support of only heuristically private addresses via [83] as opposed to actual private addresses in IP via [84] and NAT.

Due to the fixed 128 bit addressing in IPv6, additional complexity had to be added to IPv6, for example header compression for IPv6 over IoT, such as [85] to eliminate the overhead of long addressing (and other unnecessary header elements). The statefulness of these solutions and their computational complexity prohibit their use in large-scale networks. In high speed IPv6 networks, where Segment Routing (SR) has to indicate a steering sequence of IPv6 addresses, similar compression efforts are under way, such as SRHC [86].

The decision to make IPv6 addressing fixed-length was valid (even in hindsight) for high speed forwarding hardware when IPv6 was designed in the 1990s. Fixed address lengths are not necessary for today's networking hardware. Instead, it is stifling and slowing down adoption of IP networking to even more areas, such as industrial networking or other federated networks composed over time from non-global networks, as in transportation, cities or commercial B2B settings.

4.3.9 ManyNets

[87] observes that TCP/IP networking is already evolving from the One(Net) Internet to a multitude of ManyNets that are only partially connected. These ManyNets often reuse TCP/IP even if their requirements such as addressing would prefer modification; but with no flexibility to extend the IPv4IPv6 addressing, they have to live with the constraints introduced by the IPv6 OneNet (Internet) addressing structure.

Allowing more flexibility in addressing is therefore one key aspect of New IP. This same observation also leads to the representation of the already evolving view of ManyNets in Fig. 14.

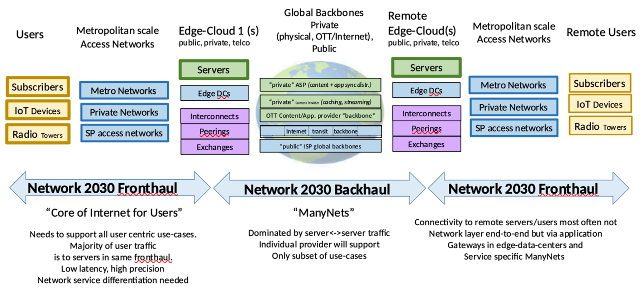


Fig. 14 – ManyNets evolution (figure from [68])

In Fig. 14, the majority of the end-user traffic travels only across the Network 2030 front haul, either between users or between a user and an edge-cloud instance. In both cases, the network path will most often only include WAN networks of metropolitan or smaller scale with a direct business relationship to one or both ends of the communication, but no pure transit networks. This allows us to more easily create business and accounting models to offer more than an Internet best-effort service only.

The Network 2030 backhaul that is also shown in that picture equally benefits from New IP. It would most often terminate between the edge-cloud instances of the owner of that global backbone, as seen today already with many global, so-called "Over The Top" (OTT) service providers that also own global backbones, but do not offer IP transit across those backbones. Instead, they use it only for Edge-2-Edge application traffic of their edge-cloud applications or other non-Internet traffic. From the perspective of a New IP, this would be another ManyNet instance, separate from the one used on the user edge and end-to-end traffic would be limited to those from cloud instances of that operator.

4.3.10 The thin waist

When New IP technologies are proposed, (legacy) IP proponents often warn about violations to the "hourglass" design principle of networking, as described in [88, 89]. In this principle, the inter-network layer has to be a "thin waist" with as little functionality as possible to ensure maximum interoperability and connectivity. This is a sound principle, and any service supported hop-by-hop has to show that it offers more value than attempts to support the service through only end-to-end mechanisms. This is already happening for functions around congestion control, as explained for computational multiplexing below, and does equally apply to the other New IP mechanisms described below.

What thin-waist restatements often ignore is the flip side

 ©International Telecommunication Union, 2022

to the argument, as written in the original RFC 1726 [63], for IPng, which became IPv6: *"When IPng does not perform a particular function or provide a certain service, it should not get in the way of the other elements of the protocol stack which may well wish to perform the function."*

Unfortunately, the one ongoing problem with IP is, that it in fact does block the variety of sub-IP network technologies to be easily absorbed/utilized by TCP/IP applications because these services cannot be passed through the IP layer. Alternatively, they are reinvented within IP in a fashion that duplicates effort unnecessarily.

For example, the widely used Ethernet 802.1p mechanism of "Class Of Service" (COS) cannot be passed through to TCP/IP applications or across IP routers, because IP has no option for header element to allow carrying such sub-IP service parameters. Instead IP duplicates the concept with its DSCP parameter and requires network operators utilizing COS to provide complex configuration and mapping between COS and DSCP.

Similarly, the standards of the "Time Sensitive Networking" (TSN) group of the IEEE[4] and several other IEEE standards offer a wide range of wired and wireless (WiFi) service level options that all are made difficult or impossible to be used by TCP/IP applications and across TCP/IP routers because of the same interpretation of the "thin waist" design principle. When the problem is recognized, such as in IETF DetNet for IP, then the proposed solutions again consist of duplicating efforts of the lower layer: DetNet proposes IP services comparable to those offered by TSN.

Through its ease of extensibility, New IP in contrast could avoid duplicate functionality and instead allows us to make lower layer parameters easier to access at the internetwork and application levels, while preserving the thin waist. The New IP header allows parameters to be defined from sub-IP services/functionality.

4.3.11 (Towards) a New IP framework

In consideration of these and several other insights, "New IP: A Data Packet Framework to Evolve the Internet" [87] proposed a coalesced framework for evolving IP. As a framework, it is not a specification of all details, but instead of the key aspects that a New IP should achieve. It also gives examples of how they can be achieved. According to [87] a New IP packet is built from four main functional components:

1. "Shipping Specification": An extensible and ideally IPv4/IPv6 backward compatible header comparable to the envelope of physical mail packets, which contains the addressing necessary to deliver the packet as well as for error diagnostics. Like a mail packet, additional information may be attached or modified to support shipping services when traversing the ManyNets.
2. "Contract Specification": An extensible header to indicate the services desired for the traffic, including aforementioned service types such as "High Precision Communications," "Coordinated Communications," or services for "Very Large Volumetric" (VLV) data services as found in, say, holographic communications.
3. "User payload": Instead of a single flat payload that can at best be fragmented without knowing its semantics (as in IPv4/IPv6), the New IP payload can choose to indicate a structure to support "Qualitative Communication" options as explained below.
4. "Header Specification": The complete New IP packet is preceded with a header specification that is indicating the offsets of the above three components in the packet to allow for parallel examination instead of the serial processing required by IP's sequential (extension) header chaining parsing.

[4]Please refer to: https://1.ieee802.org/tsn/

When services are realized via New IP, their parameters are appropriately split across the different components. In LBF for example, the SLO parameters "minimum and maximum latency" are (immutable) part of the contract header, whereas the hop-by-hop "experienced latency" of the packet is part of the shipping header.

4.3.12 New IP addressing

Addresses in the shipping spec have different types. Types for pre-existing addresses such as IPv4/IPv6 or MPLS (labels) are supported, making New IP backward compatible with those networks. Likewise, the variable length of addresses allows us to efficiently design New IP addressing for various ManyNets and services, such as 16 bit or shorter addresses for embedded IoT networks, or 128 byte or longer addresses for bit strings in multicast that indicate a subset of receivers or ICN content name addressing.

4.3.13 Structured addressing

Through types, new semantics for addresses are easily added without having to go through the current approach of having to fit within the existing structure of the IPv6 address.

For example, [90] is an ingenious and deployed mechanism to significantly simplify Internet IP multicast services by use of a structured address consisting of a unicast address prefix, a separate unicast address identifier part of a so-called Rendez-vous Point (RP), and a multicast group identifier. The use of a unicast address prefix makes it possible to acquire this type of address from address registries, as these registries would only register unicast addresses, but not multicast addresses. The RP address identifier allows us to reconstruct a full unicast RP address, which avoids an Internet-wide control plane to coordinate these basic IP multicast service functions.

Encoding these address components into an IPv6 multicast address prefix on the other hand was, and still is seen (rightfully) as an ugly hack against the original IPv6 specification and was only accepted when it could be shown that any other solution to the service delivery problem would be orders of magnitude more complex, less scalable and more fragile.

4.3.14 Other aspects of New IP

[87] also recognizes and architecturally labels other fundamental hop-by-hop forwarding aspects as follows.

Computational multiplexing: Best-effort forwarding can be seen as stochastic multiplexing of packets. The management of bandwidth sharing and of latency and loss management in the IP Internet architecture is outsourced to the endpoints, resulting in an ongoing search for ever better end-to-end congestion control in transport protocols such as TCP or now QUIC [91].

Since the inception of IP, it has been clear that packet multiplexing on every network hop had to support congestion control. This is commonly called "Active Queue Management" (*AQM*). "Random Early Detection" (RED) [92] was an early instance. Recent mechanisms include "Controlled Delay Active Queue Management" (CoDel) [93] and "Proportional Integral Controller Enhanced" (PIE) [94]. PIE attempts to be scalable by being unaware of which flow a packet belongs to. CoDel is often claimed to achieve better results, by being flow aware but therefore also less scalable.

What these AQM mechanisms exhibit is a more controlled and calculated method of multiplexing packets, but still with (only) the goal of maintaining some limited degree of fairness for congestion control, but not more elaborate service delivery goals.

New IP recognizes the procedures of per-hop management of the scheduling of packets as "Computational Multiplexing". It does not limit itself to supporting best-effort congestion control as these typical Internet AQM mechanisms. Instead, New IP sees it as the fundamental mechanism to support any service aspects related to the high-precision management of bandwidth, latency, congestion and potentially even loss.

In programmable networking, computational multiplexing can be achieved through a combination of programmable schedulers such as "Push In First Out" (PIFO) or "Push In Extract Out" (PIEO) (see for example [95], where the computation is driven by the parameters of a New IP packet carried in the shipping or contract specs). The validation implementation of LBF is an instance of such a programmable scheduler-based approach for using computational multiplexing to achieve high-precision latency services.

Value added services: As in physical mail/package shipping, a variety of value added services are being asked from networks, especially those requiring specific SLO: "Service Accountability", "Measurement of Services" or "Charging and Billing" of services delivered by the network. [87] gives examples of value-added services including exception handling, progress tracing or degree of SLO compliance. These can be encoded in the contract and/or shipping specification in an easily extensible, and application-programmable fashion.

Qualitative communications: Not all data has the same value to applications. When there is temporarily or ongoing a change in available resources, it is highly desirable that the network foremost delivers what is most important.

The common example given for contextual/motion encoded video streams is that so-called "I)ntra coded" frames are more important than "B)idirectional predicted" frames because loss in their data reduces the quality after decoding further. If packets for a frame have to be discarded, it should therefore be those of B-frame. IP has no option/extension to indicate the quality impact of the packet payload, but attempts such as [96] were made to introduce them.

Assigning importance/type or quality impact only at the packet level creates for each individual application traffic flow only a very coarse and undesirable method for the network to react. Consider that instead of reducing the temporal resolution through discarding of the packets of a B-frame, a video (or even more so some VLV data) stream would want to reduce the spatial and/or color resolution under resource constraints. With more intelligent encoding, it is possible to break up encoded data easily by those quality dimensions, and to packetize the data accordingly.

The *qualitative communication* mechanism of New IP proposes to include the ability for applications to indicate for their payload the qualitative importance of chunks of the payload. This allows the hop-by-hop forwarding to perform on (larger) packets more intelligent qualitative operations. One example is the tail-chop of the last (and lowest priority) chunk of the packet under temporary congestion, but not of the whole payload. Another one is quality-based weighted congestion control, for example using the principles of DPS. For more proposed details on qualitative communications, see [97, 98, 99, 100].

 ©International Telecommunication Union, 2022

4.3.15 Summary

New IP work covers a broad set of aspects, from service abstractions over generalized methods of programmable services to flexible, extensible and scalable packetization of service delivery mechanisms in hop-by-hop network packet headers. The evolution from IP to IPv6 started after twenty years, and IPv6 has been around for at least another 25 years. New IP proposes to be the next incremental generation of IP, taking into account all that was learned in the past 25 years. Practical deployment experimentation would help to take the ideas to the next stage of adoption. This is made much easier than it was in past decades through the evolution of more programmable networking hardware.

4.4 Programmability

As seen in the previous section, network programmability is an important tool to deploy new protocols. Active Networks [101, 102] attempted this in the 90s, but it was not until SDN [103] that practical solutions were deployed, especially in the data center.

At the origin of SDN was the idea that the entrenchment of IP as *the* network architecture had a detrimental impact on innovation. Indeed, [104] states: "*We argue that the biggest problem with the current Internet architecture is not a particular functional deficiency, but its inability to accommodate innovation.*"

One solution to enable innovation was to offer an experimental platform of the scale of the Internet. PlanetLab [105] or GENI [106] tried to fill that need. Another solution was to partition existing networks, devoting some *slice* of the network to experimental protocols. This would allow us test innovating network protocols at scale using an actual infrastructure.

SDN was a tool to apply per-flow policies in a programmable manner. This could be used to partition and isolate a slice of the network. 5G networks are supposed to support network slicing, defined as "a network architecture that enables the multiplexing of virtualized and independent logical networks on the same physical network infrastructure."

SDN has been used to support Service Function Chaining (SFC [107, 108]), namely a mechanism to override the basic destination-based forwarding of IP networks. In a nutshell, SFC allows network packet flows to route through a network via a different path from that a routing table lookups on the packet's destination IP address would select. The flow can then be routed through a predefined set of nodes that perform some services (such as security services/firewalling).

While in theory SDN would allow deploying new architectures on a virtualized infrastructure, in practice the purpose is often to deploy some virtual private networks over a legacy architecture.

One issue is that the network needs to be programmable within each slice, and this is not supported in practice. However, with the deployment of protocols to support programmable switches (say, POF [109] for an early proposal), and the availability of hardware supporting P4 [110], it may be possible to experiment with network innovation at scale.

Infrastructure Processing Units (IPUs [111]) for instance allow us to cleanly separate the network layer infrastructure from the other functions associated with that network in the data center and realize some network partitioning and isolation. DC innovation tends to leak in the WAN in a future phase.

4.5 Extensible Internet

Slices enable in theory a partitioning of the network end to end. Overlays allow us to insert new functionality at some well-defined points within the network, leveraging the traditional network in between these points. This is the approach taken in Extensible Internet (EI [112]) to develop new features at a network scale.

EI is a Layer 3.5 approach that allows us to insert new functions, such as caching or path-aware routing, without overhauling the underlying network. EI does allow new network architecture within a limited domain, and provides an interconnection layer in between such domains.

However, the scope of the new functionality enabled by EI is restricted to whatever is supported by the protocol used within a domain. If it is best-effort IP, then for instance, more elaborate guarantees for, say low latency services, cannot be provided. However, with the death of transit [64] mentioned earlier, it may be sufficient to deploy new services in limited-domain to demonstrate enough of a proof of concept for a new architecture.

5. CONCLUSION

We have provided a perspective on the future of IP and the research work done to identify and design a path forward. All protocols become obsolete at some point, and IP will not be an exception. However, IP has been so successful that any successor will have to meet enormous challenges to succeed. Namely, a successor to IP would have to provide a significant improvement over the status quo while at the same time supporting and scaling for billions of users and being compatible, in some way, with a wide range of devices, protocols, applications, business models and interactions with a myriad of government policies.

It is well known in human psychology that there is bias towards the status quo [113]. Further, the Internet is such a sensitive and important platform that national security issues have cropped up, and ideas from other countries are viewed with suspicion due to the critical nature of the network.

The path to deployment for such a solution, as described in Section 2, will be to find a niche market, or a *limited domain* to deliver benefits and get acceptance. Once this is achieved, then standardization via SDOs such as IETF and expansion of the initial market to other areas will gradually happen, until an island of the new protocol surrounded by a sea of IP becomes an ocean of the new protocol with shrinking legacy islands of IP remaining.

Section 3 has described some non-IP protocols, while Section 4 considered network layer solutions. It seems humbling that most of the Future Internet Architecture (FIA) grants from the NSF[5] have gained little traction in actual deployments and markets, despite promising initial results for some applications. We hope that the architectures described in this article have better success.

[5]See here for instance: http://www.nets-fia.net/

REFERENCES

[1] *Transmission Control Protocol*. RFC 793. Sept. 1981. DOI: 10.17487/RFC0793. URL: https://www.rfc-editor.org/info/rfc793.

[2] Cisco Annual Internet Report (2018–2023) White Paper. 2020. URL: https://www.cisco.com/c/en/us/solutions/collateral/executive-perspectives/annual-internet-report/white-paper-c11-741490.pdf.

[3] Brian E. Carpenter and Bing Liu. *Limited Domains and Internet Protocols*. RFC 8799. July 2020. URL: https://www.rfc-editor.org/info/rfc8799.

[4] C. Westphal. “Challenges in Networking to Support Augmented Reality and Virtual Reality”. In: *IEEE ICNC*. San Jose, CA, Jan. 2017.

[5] D He, C Westphal, and JJ Garcia-Luna-Aceves. “Network Support for AR/VR and Immersive Video Application: A Survey”. In: *Proceedings of the 15th International Joint Conference on e-Business and Telecommunications, ICETE 2018, 1*. 2018.

[6] Engin Zeydan and Yekta Turk. “Recent Advances in Intent-Based Networking: A Survey”. In: *IEEE 91st Vehicular Technology Conference (VTC2020-Spring)*. 2020.

[7] ETSI. *NGP: Scenario Definitions*. GS 1.3.1. ETSI, Jan. 2019. URL: https://www.etsi.org/deliver/etsi_gs/NGP/001_099/001/01.03.01_60/gs_NGP001v010301p.pdf.

[8] ETSI. *NGP: Next Generation Protocol Requirements*. GS 1.1.1. ETSI, Apr. 2017. URL: https://www.etsi.org/deliver/etsi_gs/NGP/001_099/005/01.01.01_60/gs_NGP005v010101p.pdf.

[9] ETSI. *NGP: Basis for measuring benefits of NGP*. GS 1.1.1. ETSI, Dec. 2018. URL: https://www.etsi.org/deliver/etsi_gs/NGP/001_099/012/01.01.01_60/gs_NGP012v010101p.pdf.

[10] ETSI. *NGP: Self-Organizing Control and Management Planes*. GS 1.1.1. ETSI, May 2017. URL: https://www.etsi.org/deliver/etsi_gs/NGP/001_099/002/01.01.01_60/gs_NGP002v010101p.pdf.

[11] ETSI. *NGP: Intelligence-Defined Network (IDN)*. GR 1.1.1. ETSI, June 2018. URL: https://www.etsi.org/deliver/etsi_gr/NGP/001_099/006/01.01.01_60/gr_NGP006v010101p.pdf.

[12] ETSI. *NGP: Mobile Deterministic Networking*. GR 1.1.1. ETSI, Jan. 2019. URL: https://www.etsi.org/deliver/etsi_gr/NGP/001_099/008/01.01.01_60/gr_NGP008v010101p.pdf.

[13] ETSI. *NGP: Recommendation for New Transport Technologies*. GR 1.1.1. ETSI, Sept. 2018. URL: https://www.etsi.org/deliver/etsi_gr/NGP/001_099/010/01.01.01_60/gr_NGP010v010101p.pdf.

[14] ETSI. *NGP: E2E Network Slicing Reference Framework and Information Model*. GR 1.1.1. ETSI, Sept. 2018. URL: https://www.etsi.org/deliver/etsi_gr/NGP/001_099/011/01.01.01_60/gr_NGP011v010101p.pdf.

[15] ETSI. *NGP: Preferred Path Routing (PPR) for Next Generation Protocols*. GR 1.1.1. ETSI, Oct. 2019. URL: https://www.etsi.org/deliver/etsi_gr/NGP/001_099/014/01.01.01_60/gr_NGP014v010101p.pdf.

[16] ETSI. *NGP: Recommendation for Network Layer Multi-Path Support*. GR 1.1.1. ETSI, Nov. 2019. URL: https://www.etsi.org/deliver/etsi_gr/NGP/001_099/015/01.01.01_60/gr_NGP015v010101p.pdf.

[17] ETSI. *NGP: Large-Scale Deterministic Network*. GR 1.1.1. ETSI, Nov. 2019. URL: https://www.etsi.org/deliver/etsi_gr/NGP/001_099/016/01.01.01_60/gr_NGP016v010101p.pdf.

[18] ETSI. *NGP: Evolved Architecture for mobility using Identity Oriented Networks*. GR 1.1.1. ETSI, Jan. 2018. URL: https://www.etsi.org/deliver/etsi_gr/NGP/001_099/004/01.01.01_60/gr_NGP004v010101p.pdf.

[19] John Day. *Patterns in Network Architecture: A Return to Fundamentals (paperback)*. 1st ed. Prentice Hall, Jan. 2008. ISBN: 0137063385.

©International Telecommunication Union, 2022

[20] Yonghao Wang, John Grant, and Jeremy Foss. "Flexilink: A unified low latency network architecture for multichannel live audio". In: *Audio Engineering Society Convention 133*. Audio Engineering Society. 2012.

[21] ETSI. *NGP: An example of a non-IP network protocol architecture based on RINA design principles*. GR 1.1.1. ETSI, Feb. 2019. URL: https://www.etsi.org/deliver/etsi_gr/NGP/001_099/009/01.01.01_60/gr_NGP009v010101p.pdf.

[22] ETSI. *NGP: Packet Routing Technologies*. GR 1.1.1. ETSI, Mar. 2017. URL: https://www.etsi.org/deliver/etsi_gr/NGP/001_099/003/01.01.01_60/gr_NGP003v010101p.pdf.

[23] ETSI. *NGP: NGP Reference Model*. GS 1.1.1. ETSI, May 2017. URL: https://www.etsi.org/deliver/etsi_gs/NGP/001_099/007/01.01.01_60/gs_NGP007v010101p.pdf.

[24] ETSI. *NGP: Flexilink: efficient deterministic packet forwarding in user plane for NGP; Packet formats and forwarding mechanisms*. GS 1.1.1. ETSI, Sept. 2018. URL: https://www.etsi.org/deliver/etsi_gs/NGP/001_099/013/01.01.01_60/gs_NGP013v010101p.pdf.

[25] ETSI. *NIN: Problem statement: networking with TCP/IP in the 2020s*. GR 1.1.1. ETSI, Mar. 2021. URL: https://www.etsi.org/deliver/etsi_gr/NIN/001_099/001/01.01.01_60/gr_NIN001v010101p.pdf.

[26] ETSI. *NIN: Implementing Non-IP networking over 3GPP cellular access*. GR 1.1.1. ETSI, Mar. 2021. URL: https://www.etsi.org/deliver/etsi_gr/NIN/001_099/002/01.01.01_60/gr_NIN002v010101p.pdf.

[27] ETSI. *NIN: Flexilink network model*. GR 1.1.1. ETSI, Mar. 2021. URL: https://www.etsi.org/deliver/etsi_gr/NIN/001_099/003/01.01.01_60/gr_NIN003v010101p.pdf.

[28] J. Dilley, B. Maggs, J. Parikh, H. Prokop, R. Sitaraman, and B. Weihl. "Globally distributed content delivery". In: *IEEE Internet Computing* 6.5 (2002), pp. 50–58. DOI: 10.1109/MIC.2002.1036038.

[29] Van Jacobson, Diana K. Smetters, James D. Thornton, Michael F. Plass, Nicholas H. Briggs, and Rebecca L. Braynard. "Networking named content". In: *Proceedings of the 5th international conference on Emerging networking experiments and technologies*. CoNEXT '09. Rome, Italy: ACM, 2009, pp. 1–12. URL: http://dx.doi.org/10.1145/1658939.1658941.

[30] Teemu Koponen, Mohit Chawla, Byung G. Chun, Andrey Ermolinskiy, Kye H. Kim, Scott Shenker, and Ion Stoica. "A data-oriented (and beyond) network architecture". In: *Proceedings of the 2007 conference on Applications, technologies, architectures, and protocols for computer communications*. SIGCOMM '07. Kyoto, Japan: ACM, 2007, pp. 181–192. ISBN: 978-1-59593-713-1. DOI: 10.1145/1282380.1282402. URL: http://dx.doi.org/10.1145/1282380.1282402.

[31] Dirk Trossen, George Parisis, Kari Visala, Borisalva Gajic, Janne Riihijarvi, Paris Flegkas, Pasi Sarolahti, Petri Jokela, Xenofon Vasilakos, Christos Tsilopoulos, and Somaya Arianfar. "PURSUIT Conceptual Architecture: Principles, Patterns and sub-Components Descriptions". In: *Publish Subscribe Internet Technology FP7-INFSO-ICT-257217 Deliverable D2.2*. May 2011.

[32] Christian Dannewitz, Dirk Kutscher, Börje Ohlman, Stephen Farrell, Bengt Ahlgren, and Holger Karl. "Network of Information (NetInf) – An information-centric networking architecture". In: *Computer Communications* 36.7 (2013), pp. 721–735. ISSN: 0140-3664. DOI: https://doi.org/10.1016/j.comcom.2013.01.009. URL: https://www.sciencedirect.com/science/article/pii/S0140366413000364.

[33] Bengt Ahlgren, Christian Dannewitz, Claudio Imbrenda, Dirk Kutscher, and Borje Ohlman. *A Survey of Information-Centric Networking (Draft)*. Schloss Dagstuhl, Germany, 2011.

[34] Lixia Zhang, Deborah Estrin, Jefrey Bruke, Van Jacobson, James Thornton, Diana Smetters, Beichuan Zhang, Gene Tsudik, Kc Claffy, Dmitri Krioukov, Dan Massey, Christos Papadopoulos, Tarek Abdelzaher, Lan Wang, Patrick Crowley, and Edmund Yeh. "Named Data Networking (NDN) Project". In: (Oct. 2010).

[35] L. Zhang, A. Afanasyev, J. Burke, V. Jacobson, KC. claffy, P. Crowley, C. Papadopoulos, L. Wang, and B. Zhang. "Named Data Networking". In: *ACM SIGCOMM Comput. Commun. Rev.* 44.3 (2014), pp. 66–73.

[36] Bastiaan Wissingh, Christopher A. Wood, Alex Afanasyev, Lixia Zhang, David R. Oran, and Christian Tschudin. *Information-Centric Networking (ICN): Content-Centric Networking (CCNx) and Named Data Networking (NDN) Terminology*. RFC 8793. June 2020. DOI: 10.17487/RFC8793. URL: https://www.rfc-editor.org/info/rfc8793.

[37] Marc Mosko, Ignacio Solis, and Christopher A. Wood. *Content-Centric Networking (CCNx) Semantics*. RFC 8569. July 2019. DOI: 10.17487/RFC8569. URL: https://www.rfc-editor.org/info/rfc8569.

[38] Marc Mosko, Ignacio Solis, and Christopher A. Wood. *Content-Centric Networking (CCNx) Messages in TLV Format*. RFC 8609. July 2019. DOI: 10.17487/RFC8609. URL: https://www.rfc-editor.org/info/rfc8609.

[39] Dirk Trossen, Mikko Sarela, and Karen Sollins. "Arguments for an information-centric internetworking architecture". In: *SIGCOMM Comput. Commun. Rev.* 40.2 (Apr. 2010), pp. 26–33.

[40] Van Jacobson, Diana K. Smetters, Nicholas H. Briggs, Michael F. Plass, Paul Stewart, James D. Thornton, and Rebecca L. Braynard. "VoCCN: voice-over content-centric networks". In: *Proceedings of the 2009 workshop on Re-architecting the internet*. ReArch '09. Rome, Italy: ACM, 2009, pp. 1–6. ISBN: 978-1-60558-749-3. DOI: 10.1145/1658978.1658980. URL: http://dx.doi.org/10.1145/1658978.1658980.

[41] Luca Muscariello, Giovanna Carofiglio, Jordan Auge, Michele Papalini, and Mauro Sardara. *Hybrid Information-Centric Networking*. Internet-Draft draft-muscariello-intarea-hicn-04. Work in Progress. Internet Engineering Task Force, May 2020. URL: https://datatracker.ietf.org/doc/html/draft-muscariello-intarea-hicn-04.

[42] Giovanna Carofiglio, Luca Muscariello, Jordan Augé, Michele Papalini, Mauro Sardara, and Alberto Compagno. "Enabling ICN in the Internet Protocol: Analysis and Evaluation of the Hybrid-ICN Architecture". In: *Proceedings of the 6th ACM Conference on Information-Centric Networking*. ICN '19. Macao, China, 2019.

[43] 3GPP. *Study on New Radio (NR) to support non-terrestrial networks*. TS 38.811. 3rd Generation Partnership Project (3GPP), Oct. 2020. URL: https://www.3gpp.org/ftp//Specs/archive/38_series/38.811/38811-f40.zip.

[44] 3GPP. *Solutions for NR to support Non-Terrestrial Networks (NTN)*. TS 38.821. 3rd Generation Partnership Project (3GPP), June 2021. URL: https://www.3gpp.org/ftp/Specs/archive/38_series/38.821/38821-g10.zip.

[45] 3GPP. *Study on Narrow-Band Internet of Things (NB-IoT) / enhanced Machine Type Communication (eMTC) support for Non-Terrestrial Networks (NTN)*. TS 38.763. 3rd Generation Partnership Project (3GPP), June 2021. URL: https://www.3gpp.org/ftp/Specs/archive/36_series/36.763/36763-h00.zip.

[46] 3GPP. *Study on using satellite access in 5G*. TS 22.822. 3rd Generation Partnership Project (3GPP), July 2018. URL: https://www.3gpp.org/ftp//Specs/archive/22_series/22.822/22822-g00.zip.

[47] 3GPP. *Study on architecture aspects for using satellite access in 5G*. TS 23.737. 3rd Generation Partnership Project (3GPP), Mar. 2021. URL: https://www.3gpp.org/ftp/Specs/archive/23_series/23.737/23737-h20.zip.

[48] 3GPP. *Study on management and orchestration aspects of integrated satellite components in a 5G network*. TS 28.808. 3rd Generation Partnership Project (3GPP), Apr. 2021. URL: https://www.3gpp.org/ftp/Specs/archive/28_series/28.808/28808-h00.zip.

[49] 3GPP. *Guidelines for extraterritorial 5G Systems (5GS)*. TS 22.926. 3rd Generation Partnership Project (3GPP), Dec. 2021. URL: https://www.3gpp.org/ftp/Specs/archive/22_series/22.926/22926-i00.zip.

[50] 3GPP. *Study on PLMN selection for satellite access*. TS 24.821. 3rd Generation Partnership Project (3GPP), Sept. 2021. URL: https://www.3gpp.org/ftp/Specs/archive/24_series/24.821/24821-h00.zip.

[51] ETSI. *5G; System architecture for the 5G System (5GS) (3GPP TS 23.501 version 15.3.0 Release 15)*. GS 15.3.0. ETSI, Sept. 2018. URL: https://www.etsi.org/deliver/etsi_ts/123500_123599/123501/15.03.00_60/ts_123501v150300p.pdf.

[52] Lin Han, Richard Li, Alvaro Retana, chenmeiling, Li Su, and Ning Wang. *Problems and Requirements of Satellite Constellation for Internet*. Internet-Draft draft-lhan-problems-requirements-satellite-net-02. Work in Progress. Internet Engineering Task Force, Feb. 2022. 37 pp. URL: https://datatracker.ietf.org/doc/html/draft-lhan-problems-requirements-satellite-net-02.

[53] Jim Griner, Dr. Dan Glover, Spencer Dawkins, Dr. Joseph D. Touch, Mark Allman, Diepchi Tran, Hans Kruse, John Heidemann, Jeff Semke, Shawn Ostermann, Keith Scott, and Tom Henderson. *Ongoing TCP Research Related to Satellites*. RFC 2760. Feb. 2000. DOI: 10.17487/RFC2760. URL: https://www.rfc-editor.org/info/rfc2760.

[54] Nicolas Kuhn and Emmanuel Lochin. *Network Coding for Satellite Systems*. RFC 8975. Jan. 2021. DOI: 10.17487/RFC8975. URL: https://www.rfc-editor.org/info/rfc8975.

[55] Tom Jones, Gorry Fairhurst, Nicolas Kuhn, John Border, and Stephan Emile. *Enhancing Transport Protocols over Satellite Networks*. Internet-Draft draft-jones-tsvwg-transport-for-satellite-02. Work in Progress. Internet Engineering Task Force, Oct. 2021. 29 pp. URL: https://datatracker.ietf.org/doc/html/draft-jones-tsvwg-transport-for-satellite-02.

 ©International Telecommunication Union, 2022

[56] Lin Han, Richard Li, Alvaro Retana, chenmeiling, and Ning Wang. *Satellite Semantic Addressing for Satellite Constellation*. Internet-Draft draft-lhan-satellite-semantic-addressing-01. Work in Progress. Internet Engineering Task Force, Mar. 2022. 21 pp. URL: https://datatracker.ietf.org/doc/html/draft-lhan-satellite-semantic-addressing-01.

[57] Lin Han, Alvaro Retana, and Richard Li. *Semantic Address Based Instructive Routing for Satellite Network*. Internet-Draft draft-lhan-satellite-instructive-routing-00. Work in Progress. Internet Engineering Task Force, Mar. 2022. 25 pp. URL: https://datatracker.ietf.org/doc/html/draft-lhan-satellite-instructive-routing-00.

[58] Xin Zhang, Hsu-Chun Hsiao, Geoffrey Hasker, Haowen Chan, Adrian Perrig, and David G. Andersen. "SCION: Scalability, Control, and Isolation on Next-Generation Networks". In: *2011 IEEE Symposium on Security and Privacy*. 2011, pp. 212–227. DOI: 10.1109/SP.2011.45.

[59] David Barrera, Raphael M. Reischuk, Pawel Szalachowski, and Adrian Perrig. "SCION Five Years Later: Revisiting Scalability, Control, and Isolation on Next-Generation Networks". In: *CoRR* abs/1508.01651 (2015). arXiv: 1508.01651. URL: http://arxiv.org/abs/1508.01651.

[60] Adrian Perrig, Pawel Szalachowski, Raphael M. Reischuk, and Laurent Chuat. *SCION: A Secure Internet Architecture*. Springer International Publishing AG, 2017. ISBN: 978-3-319-67079-9. DOI: 10.1007/978-3-319-67080-5. URL: /publications/papers/SCION-book.pdf.

[61] Dongsu Han, Ashok Anand, Fahad Dogar, Boyan Li, Hyeontaek Lim, Michel Machado, Arvind Mukundan, Wenfei Wu, Aditya Akella, David G. Andersen, John W. Byers, Srinivasan Seshan, and Peter Steenkiste. "XIA: Efficient Support for Evolvable Internetworking". In: *9th USENIX Symposium on Networked Systems Design and Implementation (NSDI 12)*. USENIX Association, Apr. 2012, pp. 309–322.

[62] Cyrill Krähenbühl, Seyedali Tabaeiaghdaei, Christelle Gloor, Jonghoon Kwon, Adrian Perrig, David Hausheer, and Dominik Roos. "Deployment and Scalability of an Inter-Domain Multi-Path Routing Infrastructure". In: *Proceedings of the 17th International Conference on Emerging Networking EXperiments and Technologies*. CoNEXT '21. Virtual Event, Germany: Association for Computing Machinery, 2021.

[63] Frank Kastenholz and Dr. Craig Partridge. *Technical Criteria for Choosing IP The Next Generation (IPng)*. RFC 1726. Dec. 1994. DOI: 10.17487/RFC1726. URL: https://www.rfc-editor.org/info/rfc1726.

[64] Geoff Houston. *The Death of Transit and Beyond*. 2018. URL: https://hknog.net/wp-content/uploads/2018/03/01_GeoffHuston_TheDeath_of_Transit_and_Beyond.pdf.

[65] Yoram Bernet, Robert T. Braden, Lixia Zhang, Dr. Raj Yavatkar, John T. Wroclawski, Michael F. Speer, Eyal Felstaine, Fred Baker, Dr. Bruce S. Davie, and Peter S. Ford. *A Framework for Integrated Services Operation over Diffserv Networks*. RFC 2998. Nov. 2000. DOI: 10.17487/RFC2998. URL: https://www.rfc-editor.org/info/rfc2998.

[66] Robert T. Braden, Lixia Zhang, Steven Berson, Shai Herzog, and Sugih Jamin. *Resource ReSerVation Protocol (RSVP) – Version 1 Functional Specification*. RFC 2205. Sept. 1997. DOI: 10.17487/RFC2205. URL: https://www.rfc-editor.org/info/rfc2205.

[67] David L. Black, Zheng Wang, Mark A. Carlson, Walter Weiss, Elwyn B. Davies, and Steven L. Blake. *An Architecture for Differentiated Services*. RFC 2475. Dec. 1998. DOI: 10.17487/RFC2475. URL: https://www.rfc-editor.org/info/rfc2475.

[68] FG-NET2030. *Network 2030 – Architecture Framework*. Technical Report. 2020. URL: https://www.itu.int/pub/T-FG-NET2030-2020-3.

[69] Toerless Eckert and Stewart Bryant. *Problems with existing DetNet bounded latency queuing mechanisms*. Internet-Draft draft-eckert-detnet-bounded-latency-problems-00. Work in Progress. Internet Engineering Task Force, July 2021. 29 pp. URL: https://datatracker.ietf.org/doc/html/draft-eckert-detnet-bounded-latency-problems-00.

[70] Shaojian Fu and M. Atiquzzaman. "SCTP: state of the art in research, products, and technical challenges". In: *IEEE Communications Magazine* 42.4 (2004), pp. 64–76.

[71] Randall R. Stewart, Michael Tüxen, and Karen Nielsen. *Stream Control Transmission Protocol*. RFC 9260. June 2022. URL: https://www.rfc-editor.org/info/rfc9260.

[72] Ion Stoica, Hui Zhang, Fred Baker, and Yoram Bernet. *Per Hop Behaviors Based on Dynamic Packet State*. Internet-Draft draft-stoica-diffserv-dps-02. Work in Progress. Internet Engineering Task Force, Oct. 2002. 16 pp. URL: https://datatracker.ietf.org/doc/html/draft-stoica-diffserv-dps-02.

©International Telecommunication Union, 2022

[73] Clarence Filsfils, Stefano Previdi, Les Ginsberg, Bruno Decraene, Stephane Litkowski, and Rob Shakir. *Segment Routing Architecture*. RFC 8402. July 2018. DOI: 10.17487/RFC8402. URL: https://www.rfc-editor.org/info/rfc8402.

[74] Clarence Filsfils, Darren Dukes, Stefano Previdi, John Leddy, Satoru Matsushima, and Daniel Voyer. *IPv6 Segment Routing Header (SRH)*. RFC 8754. Mar. 2020. DOI: 10.17487/RFC8754. URL: https://www.rfc-editor.org/info/rfc8754.

[75] Li Qiang, Xuesong Geng, Bingyang Liu, Toerless Eckert, Liang Geng, and Guangpeng Li. *Large-Scale Deterministic IP Network*. Internet-Draft draft-qiang-detnet-large-scale-detnet. Work in Progress. Internet Engineering Task Force, 2018. URL: https://datatracker.ietf.org/doc/html/draft-qiang-detnet-large-scale-detnet.

[76] Bingyang Liu, Shoushou Ren, Chuang Wang, Vincent Angilella, Paolo Medagliani, Sebastien Martin, and Jeremie Leguay. "Towards Large-Scale Deterministic IP Networks". In: *2021 IFIP Networking Conference (IFIP Networking)*. 2021, pp. 1–9. DOI: 10.23919/IFIPNetworking52078.2021.9472798.

[77] Bob Briscoe, Koen De Schepper, Marcelo Bagnulo, and Greg White. *Low Latency, Low Loss, Scalable Throughput (L4S) Internet Service: Architecture*. Internet-Draft draft-ietf-tsvwg-l4s-arch-17. Work in Progress. Internet Engineering Task Force, Mar. 2022. 45 pp. URL: https://datatracker.ietf.org/doc/html/draft-ietf-tsvwg-l4s-arch-17.

[78] Richard Li, Alexander Clemm, Uma Chunduri, Lijun Dong, and Kiran Makhijani. "A New Framework and Protocol for Future Networking Applications". In: *Proceedings of the 2018 Workshop on Networking for Emerging Applications and Technologies*. NEAT '18. Budapest, Hungary: Association for Computing Machinery, 2018, pp. 21–26. ISBN: 9781450359078. DOI: 10.1145/3229574.3229576. URL: https://doi.org/10.1145/3229574.3229576.

[79] FG-NET2030. *Network 2030 - New Services and Capabilities for Network 2030: Description, Technical Gap and Performance Target Analysis*. Technical Report. 2019. URL: https://www.itu.int/pub/T-FG-NET2030-2019-SUB.G2.

[80] International Organization for Standardization. *Information processing systems - Data Communications - "Protocol for providing the Connectionless-mode Network Service and Provision of Underlying Service"*. May 1987.

[81] Haoyu Song, Zhaobo Zhang, Yingzhen Qu, and James Guichard. "Adaptive Addresses for Next Generation IP Protocol in Hierarchical Networks". In: *2020 IEEE 28th International Conference on Network Protocols (ICNP)*. 2020, pp. 1–6. DOI: 10.1109/ICNP49622.2020.9259354.

[82] Toerless Eckert and Nirmala Shenoy. *Functional Addressing (FA) for internets with Independent Network Address Spaces (IINAS)*. Internet-Draft draft-eckert-intarea-functional-addr-internets-01. Work in Progress. Internet Engineering Task Force, Oct. 2021. 30 pp. URL: https://datatracker.ietf.org/doc/html/draft-eckert-intarea-functional-addr-internets-01.

[83] Brian Haberman and Bob Hinden. *Unique Local IPv6 Unicast Addresses*. RFC 4193. Oct. 2005. DOI: 10.17487/RFC4193. URL: https://www.rfc-editor.org/info/rfc4193.

[84] Robert Moskowitz, Daniel Karrenberg, Yakov Rekhter, Eliot Lear, and Geert Jan de Groot. *Address Allocation for Private Internets*. RFC 1918. Feb. 1996. DOI: 10.17487/RFC1918. URL: https://www.rfc-editor.org/info/rfc1918.

[85] Pascal Thubert and Jonathan Hui. *Compression Format for IPv6 Datagrams over IEEE 802.15.4-Based Networks*. RFC 6282. Sept. 2011. DOI: 10.17487/RFC6282. URL: https://www.rfc-editor.org/info/rfc6282.

[86] Weiqiang Cheng, Clarence Filsfils, Zhenbin Li, Bruno Decraene, Dezhong Cai, Daniel Voyer, Francois Clad, Shay Zadok, Jim Guichard, Aihua Liu, Robert Raszuk, and Cheng Li. *Compressed SRv6 Segment List Encoding in SRH*. Internet-Draft draft-ietf-spring-srv6-srh-compression-00. Work in Progress. Internet Engineering Task Force, Feb. 2022. 20 pp. URL: https://datatracker.ietf.org/doc/html/draft-ietf-spring-srv6-srh-compression-00.

[87] Richard Li, Kiran Makhijani, and Lijun Dong. "New IP: A Data Packet Framework to Evolve the Internet : Invited Paper". In: *2020 IEEE 21st International Conference on High Performance Switching and Routing (HPSR)*. 2020, pp. 1–8. DOI: 10.1109/HPSR48589.2020.9098996.

[88] Walter Willinger and John Doyle. "Robustness and the Internet: Design and evolution". In: *Robust Design: A Repertoire of Biological, Ecological, and Engineering Case Studies (Santa Fe Institute Studies on the Sciences of Complexity)*. Ed. by Erica Jen. Oxford: Oxford University Press, 2004, pp. 231–272.

[89] David Meyer and Randy Bush. *Some Internet Architectural Guidelines and Philosophy*. RFC 3439. Dec. 2002. DOI: 10.17487/RFC3439. URL: https://www.rfc-editor.org/info/rfc3439.

 ©International Telecommunication Union, 2022

[90] Brian Haberman and Pekka Savola. *Embedding the Rendezvous Point (RP) Address in an IPv6 Multicast Address*. RFC 3956. Nov. 2004. DOI: 10.17487/RFC3956. URL: https://www.rfc-editor.org/info/rfc3956.

[91] Jana Iyengar and Martin Thomson. *QUIC: A UDP-Based Multiplexed and Secure Transport*. RFC 9000. May 2021. DOI: 10.17487/RFC9000. URL: https://www.rfc-editor.org/info/rfc9000.

[92] Fred Baker and Gorry Fairhurst. *IETF Recommendations Regarding Active Queue Management*. RFC 7567. July 2015. DOI: 10.17487/RFC7567. URL: https://www.rfc-editor.org/info/rfc7567.

[93] Kathleen Nichols, Van Jacobson, Andrew McGregor, and Jana Iyengar. *Controlled Delay Active Queue Management*. RFC 8289. Jan. 2018. DOI: 10.17487/RFC8289. URL: https://www.rfc-editor.org/info/rfc8289.

[94] Rong Pan, Preethi Natarajan, Fred Baker, and Greg White. *Proportional Integral Controller Enhanced (PIE): A Lightweight Control Scheme to Address the Bufferbloat Problem*. RFC 8033. Feb. 2017. DOI: 10.17487/RFC8033. URL: https://www.rfc-editor.org/info/rfc8033.

[95] Oliver Michel, Roberto Bifulco, Gábor Rétvári, and Stefan Schmid. "The Programmable Data Plane: Abstractions, Architectures, Algorithms, and Applications". In: *ACM Comput. Surv.* 54.4 (May 2021).

[96] Ken Carlberg and Toerless Eckert. *A Real-time Transport Protocol (RTP) Classifier Header Extension*. Internet-Draft draft-carlberg-avtext-classifier-01. Work in Progress. Internet Engineering Task Force, Oct. 2013. 5 pp. URL: https://datatracker.ietf.org/doc/html/draft-carlberg-avtext-classifier-01.

[97] R. Li, K. Makhijani, H. Yousefi, C. Westphal, L. Dong, Tim Wauters, and Filip De Turck. "A framework for Qualitative Communications using Big Packet Protocol". In: *Proceedings Of The 2019 ACM Sigcomm Workshop On Networking For Emerging Applications And Technologies*. 2019.

[98] Cedric Westphal, Dongbiao He, Kiran Makhijani, and Richard Li. "Qualitative Communications for Augmented Reality and Virtual Reality". In: *2021 IEEE 22nd International Conference on High Performance Switching and Routing (HPSR)*. 2021.

[99] Abdulazaz Albalawi, Hamed Yousefi, Cedric Westphal, Kiran Makhijani, and J.J. Garcia-Luna-Aceves. "Enhancing End-to-End Transport with Packet Trimming". In: *GLOBECOM'20 - IEEE Global Communications Conference*. 2020.

[100] Richard Li, Lijun Dong, Cedric Westphal, and Kiran Makhijani. "Qualitative Communications for Emerging Network Applications with New IP". In: *17th International Conference on Mobility, Sensing and Networking (MSN)*. Dec. 2021.

[101] K.L. Calvert, S. Bhattacharjee, E. Zegura, and J. Sterbenz. "Directions in active networks". In: *IEEE Communications Magazine* 36.10 (1998), pp. 72–78.

[102] David L. Tennenhouse and David J. Wetherall. "Towards an Active Network Architecture". In: *ACM SIGCOMM Comput. Commun. Rev.* 37.5 (Aug. 2007), pp. 81–94.

[103] Nick McKeown, Tom Anderson, Hari Balakrishnan, Guru Parulkar, Larry Peterson, Jennifer Rexford, Scott Shenker, and Jonathan Turner. "OpenFlow: Enabling Innovation in Campus Networks". In: *SIGCOMM Comput. Commun. Rev.* 38.2 (Mar. 2008), pp. 69–74.

[104] Teemu Koponen, Scott Shenker, Hari Balakrishnan, Nick Feamster, Igor Ganichev, Ali Ghodsi, P. Brighten Godfrey, Nick McKeown, Guru Parulkar, Barath Raghavan, Jennifer Rexford, Somaya Arianfar, and Dmitriy Kuptsov. "Architecting for Innovation". In: *ACM SIGCOMM Comput. Commun. Rev.* 41.3 (July 2011), pp. 24–36.

[105] Larry Peterson, Andy Bavier, Marc E. Fiuczynski, and Steve Muir. "Experiences Building PlanetLab". In: *7th USENIX Symposium on Operating Systems Design and Implementation (OSDI 06)*. Nov. 2006.

[106] Chip Elliott. "GENI-global environment for network innovations." In: *LCN*. 2008, p. 8.

[107] Deval Bhamare, Raj Jain, Mohammed Samaka, and Aiman Erbad. "A survey on service function chaining". In: *Journal of Network and Computer Applications* 75 (2016), pp. 138–155.

[108] Joel M. Halpern and Carlos Pignataro. *Service Function Chaining (SFC) Architecture*. RFC 7665. Oct. 2015. DOI: 10.17487/RFC7665. URL: https://www.rfc-editor.org/info/rfc7665.

[109] Haoyu Song. "Protocol-Oblivious Forwarding: Unleash the Power of SDN through a Future-Proof Forwarding Plane". In: *Proceedings of the Second ACM SIGCOMM Workshop on Hot Topics in Software Defined Networking*. HotSDN '13. Hong Kong, China, 2013, pp. 127–132.

[110] Pat Bosshart, Dan Daly, Glen Gibb, Martin Izzard, Nick McKeown, Jennifer Rexford, Cole Schlesinger, Dan Talayco, Amin Vahdat, George Varghese, and David Walker. "P4: Programming Protocol-Independent Packet Processors". In: *SIGCOMM Comput. Commun. Rev.* 44.3 (July 2014), pp. 87–95.

©International Telecommunication Union, 2022

[111] Brad Burres, Dan Daly, Mark Debbage, Eliel Louzoun, Christine Severns-Williams, Naru Sundar, Nadav Turbovich, Barry Wolford, and Yadong Li. “Intel’s Hyperscale-Ready Infrastructure Processing Unit (IPU)”. In: *2021 IEEE Hot Chips 33 Symposium (HCS)*. IEEE. 2021, pp. 1–16.

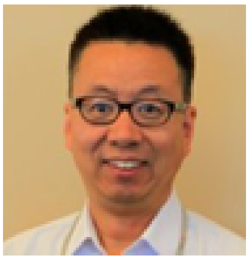
[112] Hari Balakrishnan, Sujata Banerjee, Israel Cidon, David Culler, Deborah Estrin, Ethan Katz-Bassett, Arvind Krishnamurthy, Murphy McCauley, Nick McKeown, Aurojit Panda, Sylvia Ratnasamy, Jennifer Rexford, Michael Schapira, Scott Shenker, Ion Stoica, David Tennenhouse, Amin Vahdat, and Ellen Zegura. “Revitalizing the Public Internet by Making It Extensible”. In: *SIGCOMM Comput. Commun. Rev.* 51.2 (Apr. 2021).

[113] W. Samuelson and R. Zeckhauser. “Status quo bias in decision making”. In: *J Risk Uncertainty* (1988), pp. 7–59.

AUTHORS

Toerless Eckert Since 2016, Toerless Eckert is a distinguished engineer at Futurewei USA’s Future Network Research Lab where he works on programmable networks, network layer evolution and high precision network services. From 1986 to 1998 he worked at his university as a student and staff member on computer networking and distributed system research, planning, deployment, operations and teaching. Toerless received his MSCS (Diplom Informatiker) in 1992. His projects included the first TCP/IP network for the research community in Bavaria, network consulting for RARE and DFN as well as research and validation for technologies and systems including tele-teaching, scalable video codecs, FDDI, ATM, IP multicast and IPv6. Toerless joined Cisco Systems in 1999, where he worked in the Cisco IOS software development team on network and systems architecture, customer deployment and education for a multitude of networking technologies. He is a renowned SME on multicast technologies and has received 2 Cisco Pioneer Awards for his work on the integration of multimedia application with advanced networks and on autonomous networking. Toerless holds more than 50 patents and is a co-chair of the IETF ANIMA working group. He is coauthor of 11 IETF RFCs and various IETF drafts. He has also worked on standardization in CableLabs, ETSI and ITU-T and co-authored research papers and research book chapters.

Lin Han is a distinguished engineer in Futurewei Technologies, Inc. USA. His interest is to explore new network technologies for the future Internet, including 5G, New IP technologies, IP-based in-vehicle networking, etc. His current work is on the LEO satellite networking for NTN integration for 5G and beyond. He has worked in the networking industry for more than 20 years including at Huawei in the USA, Cisco System in the USA and New Bridge in Canada. He also worked as the rapporteur of ETSI NGP project for “Network Layer Multi Path” and “ New Transport Technology” in 2017 and 2018. He has published papers in ACM and IEEE conferences and holds more than twenty US patents.



Richard Li is Chief Scientist and Vice President of Network Technologies at Futurewei, USA. Dr Li served as the chair of the ITU-T FG Network 2030 from 2018 to 2020, and as the vice-chair for the Europe ETSI ISG NGP (Next-Generation Protocols) from 2016 to 2019. He has also served as co-chair of steering committees and technical program committees of many academic and industrial conferences. Dr Li is extremely passionate about advancing ICT infrastructure technologies and solving problems in their entirety, thus creating a bigger and long-term impact on the networking industry. During his career, Dr Li spearheaded network technology innovation and development in routing and MPLS, mobile backhaul, metro and core Networks, data center, cloud and virtualization. Currently he leads a team of scientists and engineers to develop technologies for next-generation network architectures, protocols, algorithms, and systems in the support of emerging and forward-looking applications and industry verticals in the context of New IP and Network 2030.

Cedric Westphal is a principal research architect with Futurewei. He was an adjunct assistant, then associate professor with the University of California, Santa Cruz from 2009 to 2019. Prior to Futurewei, he was with DOCOMO Innovations from 2007 to 2011 and at Nokia Research Center (now Nokia Bell Labs) from 2000 to 2006. He has received an MSEE in 1995 from Ecole Centrale Paris, and an MS (1995) and PhD (2000) in EE from the University of California, Los Angeles. Cedric Westphal has authored and coauthored over a hundred journal and

©International Telecommunication Union, 2022

conference papers, including several best paper awards at conferences such as IEEE ICC'11, IEEE ICNC'18, IEEE MuSIC'16 and others. He has been awarded over thirty patents. He has received the IEEE Communication Society IINTC 2018 Technical Achievement Award to "*recognize a lifelong set of outstanding technical contributions in the area of information infrastructure and networking*." He was an area editor for the ACM/IEEE Transactions on Networking, an assistant editor for (Elsevier) Computer Networks journal, and a guest editor for Ad Hoc Networks journal, ACM/IEEE JSAC and others. He has served as a reviewer for the NSF, GENI, the EU FP7, INRIA, and other funding agencies; he has chaired the technical program committee of several conferences, including IEEE ICC (NGN symposium), IEEE NFV-SDN or IEEE IPCCC, and he was the general chair for IEEE INFOCOM 2016. He is a senior member of the IEEE.

©International Telecommunication Union, 2022