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6G-RUPA: A Flexible, Scalable, and Energy-Efficient User Plane Architecture for Next-Generation Mobile Networks

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Abstract: As the global deployment of Fifth Generation (5G) is being well consolidated, the exploration of Sixth Generation (6G) wireless networks has intensified, focusing on novel Key Performance Indicators (KPIs) and Key Value Indicators (KVIs) that extend beyond traditional metrics like throughput and latency. As 5G begins transitioning to vertical-oriented applications, 6G aims go beyond, providing a ubiquitous communication experience by integrating diverse Radio Access Networks (RANs) and fixed-access networks to form a hyper-converged edge. This unified platform will enable seamless network federation, thus realizing the so-called *network of networks* vision. Emphasizing energy efficiency, the present paper discusses the importance of reducing telecommunications' environmental impact, aligning with global sustainability goals. Central to this vision is the proposal of a novel user plane network protocol architecture, called 6G Recursive User Plane Architecture (6G-RUPA), designed to be scalable, flexible, and energy-efficient. Briefly, 6G-RUPA offers superior flexibility in network adaptation, federation, scalability, and mobility management, aiming to enhance overall network performance and sustainability. This study provides a comprehensive analysis of 6G's potential, from its conceptual framework to the high-level design of 6G-RUPA, addressing current challenges and proposing actionable solutions for next-generation mobile networks.

Keywords: 6G; energy efficiency; network architecture; network scalability; programmable networks; recursive networking; user plane protocols

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1. Introduction

With the initial commercial deployments of 5G technology already surpassing 1.5 billion at the end of 2023 [1], both industry professionals and academic researchers have begun to explore potential use cases and KPIs for the next generation of mobile networks: 6G. Anticipated for implementation around 2030, these new KPIs that go beyond traditional metrics like throughput and latency have driven an expanded set of technological advancements and use cases.

Figure 1 shows the typical deployment of mobile networks throughout history. The primary goal in previous mobile network generations was to route traffic to the data network, namely the Internet, as fast as possible, a target well met since Fourth Generation (4G). The introduction of 5G expanded the range of use cases to also encompass Enhanced Mobile Broadband (eMBB), massive Machine Type Communications (mMTC), and Ultra-Reliable Low-Latency Communications (URLLC), pushing the boundaries one step further. Not only that, 5G also started to transition from a Public Land Mobile Network Operator (PLMNO)-centric perspective to a vertical-oriented one, thus supporting new use cases like Non-Public Networks (NPNs).

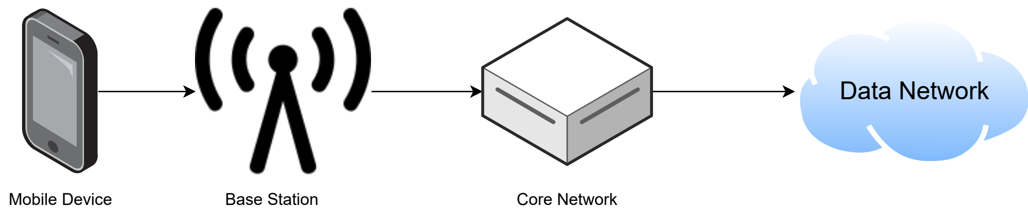

Figure 1. Typical mobile communications network topology.

However, the spectrum of envisioned 6G use cases broadens even further than in previous generations. The goal of 6G is to offer users a ubiquitous and seamless communication experience that caters for a wide range of devices and services, while also being highly energy-efficient and eco-friendly. Specifically, the fundamental challenge in achieving this goal is the integration of diverse RANs and fixed-access networks.

To this end, 6G envisions a hyper-converged edge that offers a unified platform for access networks, incorporating all forms of network access, including cellular, Wi-Fi, Non-Terrestrial Networkss (NTNs), and others. This will form an ecosystem composed of a dynamic federation of 6G network operators. This federation will allow User Equipments (UEs) to roam freely across different domains with session continuity, without the need to relay traffic through external data networks such as the Internet, thus effectively creating an inter-network of 6G domains providing seamless connectivity to billions or trillions of devices [2]. In the literature, this vision is named as *network of networks* [3].

Moreover, 6G networks are expected to be powered by cutting-edge Artificial Intelligence (AI)/Machine Learning (ML) techniques, featuring self-aware capabilities that will enhance their ability to adapt, optimize, learn, and evolve. This will enable networks to provide more personalized and context-aware services to users. However, for 6G networks to truly harness this intelligence, they must not only offer programmability in the control plane, as in traditional Software Defined Networking (SDN) approaches, but also in the data plane. It is then crucial to move towards flexibly programmable architectures, allowing network protocols to be seamlessly adapted to the applications and services they support.

It is worth mentioning as well that the energy usage of telecommunications has a serious impact on climate change, contributing approximately one percent of worldwide CO_2 emissions (this is roughly equivalent to the emissions of the UK in 2021: https://ourworldindata.org/co2/country/united-kingdom, accessed on 11 May 2024). Hence, there is a clear need for 6G to reduce the energy usage of telecommunications, thereby reducing the green house gas emissions that are connected to it, primarily targeting United Nations Sustainable Development Goal 13: "Take urgent action to combat climate change and its impacts".

Figure 2 showcases the evolution of the latest layers of user plane protocols since Third Generation (3G) to 5G, showing that the fundamental architecture of user plane protocols has maintained a similar framework from 3G through to 5G. Protocols such as the Packet Data Convergence Protocol (PDCP) and GPRS Tunneling Protocol—User Plane (GTP-U) have been foundational across previous generations, emphasizing stable continuation rather than drastic changes in user plane protocols across generations. Nevertheless, if in future generations, such as 6G, the network is expected to be more flexible, scalable, and energy-efficient, the user plane protocols should be redesigned in order to meet the aforementioned requirements. Addressing the 6G vision's challenge of being energy-efficient and at the same time programmable, scalable and high-performing requires a redesign of 5G's current protocol architecture, particularly of its user plane. Despite the evolution of mobile network use cases from generation to generation, user plane protocols, particularly GTP-U, have remained largely unchanged. As a result, the current user plane protocol architecture cannot support the related 6G network of networks use cases, such as Device to Device (D2D) communication or 6G domain federation, without requiring an intermediate data network. Moreover, the virtual circuit switching approach adopted by all previous generations requires storing a considerable state in the User Plane Functions (UPFs), which makes GTP-U hard to scale to the level anticipated for 6G.

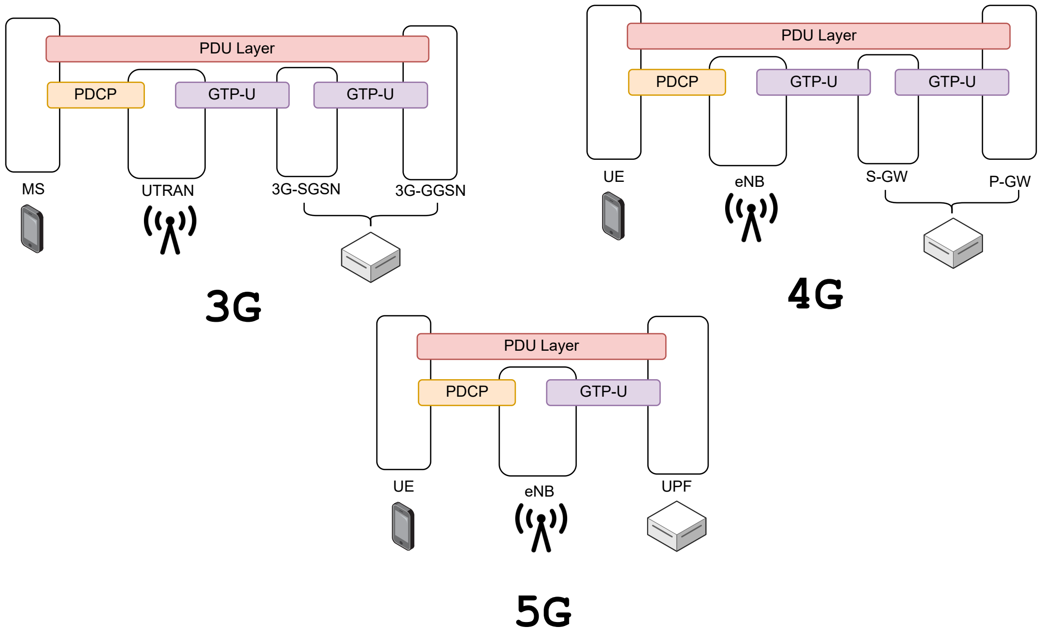

Figure 2. Evolution of user plane protocols from 3G (first commercial deployment: 2001) to 5G (first commercial deployment: 2018).

In light of this, the present paper introduces 6G-RUPA, a novel user plane network protocol architecture appropriately designed to meet the demands of 6G and beyond. Briefly, 6G-RUPA is a streamlined yet flexible architecture that seeks to overcome the limitations imposed by the existing GTP-U protocol. As will be thoroughly detailed, 6G-RUPA provides the flexibility required for networks to adjust to diverse use cases and demands by optimizing protocol resources for specific scenarios. For instance, it offers the ability to choose whether to use encryption or not, or to provide services over unreliable backhauls. Moreover, it allows us to choose between tunnel-based or packet-switched communication approaches for enhanced scalability, or to adapt the amount of addresses needed to suit smaller network deployments. Indeed, with a well-defined addressing scheme, e.g., following the addressing principles described in [4], 6G-RUPA can improve mobility management, reducing the resources needed to support it, hence fostering resource utilization and energy efficiency. Additionally, 6G-RUPA's recursive nature enhances scalability, allowing networks to segment into smaller, independently operated units with their tailored user plane protocols, all interconnected via a unified layer.

The remainder of the paper serves to position 6G-RUPA as a viable proposal to effectively realize the upcoming 6G-enabled network panorama. To this goal, Section 2 reviews the related state of the art as well as background for some concepts, presenting different visions of 6G from relevant stakeholders. Section 3 identifies the current deficiencies of mobile networks and suggests necessary enhancements. Section 4 provides a detailed overview of 6G-RUPA, its principles, its adaptable data plane protocol, and its potential to meet the architectural needs identified earlier. Finally, Section 6 summarizes our key contributions and concludes the paper.

2. State of the Art

As we approach the 6G of mobile networks, several publications have tackled what 6G will look like and what the use cases that will support are. This section delves into the foundational principles, visions, and technological advancements that are shaping the trajectory toward 6G, while highlighting the collaborative efforts between academia and industry to address the complex challenges of the future digital society.

The exploration of 6G networks within academia has resulted in a rich body of literature that examines potential use cases, while pointing out their requisites and enablers. To the best of the authors' knowledge, although there exist proposals for specific modifications at the system architectural level already, there is a lack of them from relevant bodies regarding such specific modifications to be applied to network protocol architecture.

The European 6G flagship project Hexa-X [5,6], involving both European academia and industry partners, represents an effort to lead the development of 6G by establishing a well-defined set of guiding principles [3]. These principles advocate for a 6G architecture that can support minor-scale deployments and accommodate large-scale operations seamlessly. Moreover, the emphasis on resilience and availability highlights the strategic move toward eliminating single points of failure through multi-connectivity and other robust infrastructure provisions. Furthermore, flexibility emerges as a critical principle in adapting to diverse network topologies, ensuring optimal performance and resource utilization across various scenarios, including emerging traffic demands and environments with different access networks. The push for network simplification also seeks to streamline the next-generation network architecture, reducing operational complexity through cloud-native technologies and minimizing the need for extensive parameter configurations and external interfaces. Finally, the principle of exposing network capabilities to end-to-end applications introduces a paradigm shift, allowing for predictive orchestration and the leveraging of analytic information for performance optimization. All these principles will be discussed in Sections 3 and 4, as they are the basis for the 6G-RUPA proposal.

The integration of AI and ML into mobile networks is increasingly recognized as pivotal, with worldwide organizations such as 5G Infrastructure Public Private Partnership (5GPPP) [7], Hexa-X project [8], and Next Generation Mobile Networks (NGMN) Alliance [9] advocating for an AI-powered 6G network ecosystem. The adoption of AI and ML enhances network programmability, enabling external systems to dynamically alter network states. This advancement extends beyond the control plane, influencing the data plane and guiding in a new era of network architecture characterized by enhanced data plane programmability. The NGMN Alliance's vision for 6G includes a strong emphasis on embedding native AI and Network as a Service (NaaS) technologies into network infrastructures, making future networks inherently AI-driven [10,11]. In these envisioned networks, AI is not merely an add-on but a core component that significantly enhances network management, service lifecycle, and user experience. AI-driven networks will autonomously learn from traffic data, adapt to varying conditions and demands, and proactively optimize performance.

Furthermore, the NGMN Alliance underscores the importance of expanding network coverage, particularly through integrating NTNs with terrestrial networks to enhance accessibility, especially in rural areas. This integration aims to provide seamless transitions and consistent access across different network types. Lastly, it also prioritizes energy efficiency, advocating for improved protocol efficiency and intelligent resource management. These measures are intended not only to minimize energy consumption but also to support a more sustainable and environmentally friendly network infrastructure.

Advancements in Radio Access Technology (RAT) and network infrastructure are crucial for achieving the ambitious latency and throughput goals of 6G [12]. Tataria et al. advocate for a transformation towards fully virtualized network slices, utilizing SDN to surpass the constraints of traditional transport networks. Corici et al. introduce the concept of organic networks, which propose enhancements including the strengthening of backhaul capabilities to support both dedicated and less reliable infrastructures, like the Internet [13]. They also suggest an innovative extension to the 5G core designed for seamless NPN federation over these unreliable backhauls [14].

This evolving landscape also prompts a re-evaluation of the core network architecture, where researchers consider a shift towards coreless cellular systems to meet future demands [15]. These systems highlight the increasing necessity for network programmability across both control and user planes. The emergence of data plane programmability through technologies such as smart Network Interface Card (NIC)s and Programming Protocol-Independent Packet Processors (P4)-enabled hardware underscores their significant impact on the future of mobile networks [16].

At the heart of the 6G architectural vision emerges the so-called *network of networks* framework, proposed under the Hexa-X project umbrella. This paradigm envisions a digital ecosystem comprising interconnected subnetworks, each serving distinct purposes and use cases. The *network of networks* framework aims to cater to a diverse array of connectivity needs, ensuring efficient and flexible operation across an expansive digital landscape. This necessitates significant architectural modifications, particularly at the user plane protocol level, so as to address challenges related to scalability, flexibility, and energy consumption efficiently [3].

This examination of the state of the art in 6G network development showcases the multifaceted nature of the challenges and innovations that define the path towards the next generation of mobile networks. As the industry progresses, the collaborative endeavors of academia and industry stakeholders will continue to play a crucial role in realizing the transformative potential of 6G technology.

3. Requirements and Deficiencies at the Architectural and Functional Level in the Core Network

The UPF is the network function responsible for handling the user plane connectivity in 5G. As illustrated in Figure 3, the UPF in current 5G network handles tasks such as packet routing, session management, and mobility anchoring. While it supports essential network functions effectively, the UPF faces challenges that may hinder the transition to 6G networks, which demand greater scalability, flexibility, and energy efficiency.

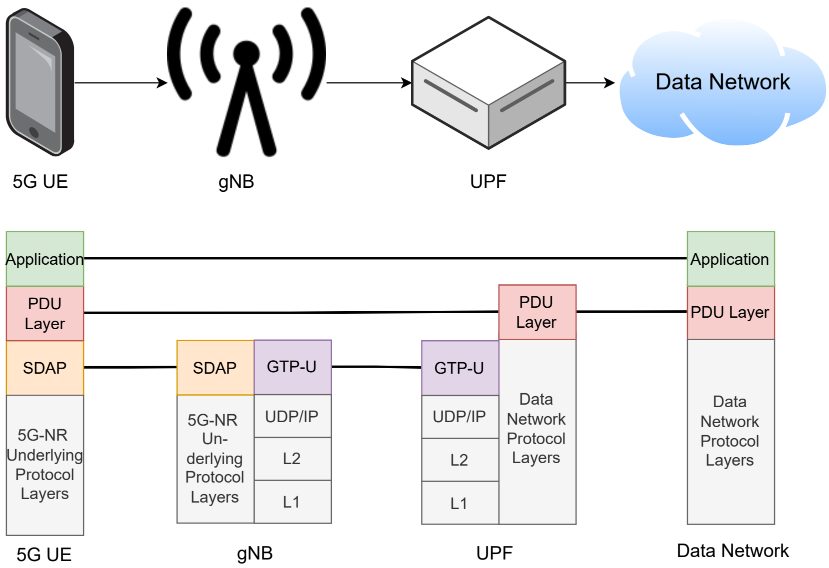

Figure 3. The 5G user plane protocol stack for a typical mobile network deployment.

Historically, the core focus of user plane mobile network architectures has been centered on KPIs. As shown in Figure 1, the primary goal has been to route traffic as efficiently as possible from the UE to the data network, i.e., the Internet. However, from 5G, the requirements have not only been centered on traditional KPIs, but also KVIs. Moreover, 5G UEs are no longer only smartphones, but a variety of devices expanded to include those connecting via non-3rd Generation Partnership Project (3GPP) access like Wi-Fi. In turn, 6G use cases have also evolved drastically. Despite such advancements, underlying user plane protocols, particularly GTP-U, have remained essentially unchanged since 3G, whose initial commercial deployment dates back to 2001. This static aspect of the user plane architecture is illustrated in Figure 2.

3.1. Current Limitations in the User Plane

During previous generations, all access networks such as 5G New Radio (5G-NR) or NTN were integrated into a unified flat transport network that employed GTP-U to manage traffic using Internet Protocol (IP) tunnels for each UE. Hence, every connection from a UE to the core implied allocating a new IP tunnel, which is essentially a virtual circuit that requires state to be stored in the core. This leads to scalability and mobility management issues, especially during scenarios like handovers where a UE's point of attachment changes, creating the need to re-allocate the whole virtual circuit.

Furthermore, GTP-U presents a flat structure. It identifies tunnel endpoints using IP addresses and Tunnel Endpoint Identifiers (TEIDs), leading to a scenario where each UE connected to the core requires one or more GTP-U tunnels depending on the Quality of Service (QoS) required per application running in the UE. This approach not only scales poorly, but also results in large forwarding tables at network switches. Related to this issue, in [17], the authors implemented a UPF using P4 switches and remarked upon the importance of reducing the amount of state kept by the UPF, since switches have a limited amount of memory. Moreover, in [18], the authors modeled the power consumption of Ternary Content Addressable Memory (TCAM) memories used in high-performance switches, and showcased that power consumption is directly proportional to the number of rows in the forwarding tables. Hence, in order to reduce the power consumption of the network, it is necessary to address the amount of state kept by the UPF, thus necessitating a novel user plane protocol that scales better than GTP-U.

Interestingly, available works in the literature also reveal that the current IP tunneling approach may not be the most effective solution for supporting existing 5G use cases [19,20]. These studies showcase that Segment Routing over IPv6 (SRv6) could address some of GTP-U's scalability issues by reducing the state maintenance required, while leveraging IPv6's larger address space, which inherently performs better than that of IPv4. Furthermore, in [21], alternative network technologies such as Transparent Interconnection of Lots of Links (TRILL) and Provider Backbone Bridging (PBB) were also identified as more suitable for the requirements posed by time-sensitive industrial uses, due to their better performance for deterministic traffic requirements.

Despite the technical limitations and the existence of alternative solutions, GTP-U remains widely used in 3GPP Release 16 due to its extensive deployment and the significant investment in existing infrastructure. The continued use of GTP-U is supported by the operational familiarity and compatibility it offers, which are highly valued by major equipment vendors and operators.

3.2. Inter-Network Federation Mechanisms

In particular, the *network of networks* vision for 6G includes supporting a broad spectrum of use cases. Those use cases begin to exist due to the transition from nationally administered mobile networks to a vastly multi-administered ecosystem encompassing setups like campus networks, industrial deployments, smart cities, small local networks, etc. To make this a reality, 6G envisions a wide number of access networks that need to be integrated, enabling seamless mobility between them, thus building 6G on a core-centric perspective, instead of a radio-centric one as in previous generations.

In current mobile networks, the only existing mechanism for network federation is roaming. However, roaming is designed to provide network federation with two national-administered PLMNOs, so the physical and logistical infrastructure required to support seamless roaming in such a fragmented network landscape poses significant challenges. Especially in those scenarios with unreliable backhaul connections, typically found in remote or rapidly deployable networks like those used in emergency responses or temporary installations. However, the predominant mechanism for inter-networking remains rooted in traditional roaming agreements, which are static, lack neighbor network discovery capabilities, and depend on contractual methods for authentication and authorization. This limitation is further limited by GTP-U's design, which does not support core-to-core communication mechanisms without relying on an external data network. In this regard, in [14], the authors propose a solution to this problem by extending the 5G core to support NPN federation over unreliable backhauls.

In summary, traditional roaming mechanisms and user plane protocols might be insufficient for 6G networks due to their inability to dynamically manage numerous specialized networks, each with distinct and complex requirements, as posed by the *network of networks* vision. Additionally, 6G should be able to provide enhanced network federation solutions addressing these specific challenges, aiming to ensure seamless, secure, and efficient connectivity across a diverse and fragmented network landscape.

3.3. Network Flexibility

Each preceding mobile generation has been designed on the foundation of performance-based requirements, a need given the rapid evolution of applications and their associated network demands. However, 6G is envisioned to transition from a performance-centric approach to a one more focused on KVIs. As such, the key values should be assessed with respect to the outcome of economic, social, and ecological values associated with measurable metrics and adopted in the network design of 6G [22]. The network must be able to support the varying needs of different verticals, such 0as terrestrial and NTNs, and public and NPNs. Not only that, 6G should be built upon a network architecture that supports seamless mobility between them. Despite 5G having already standardized the deployment of NTNs and low-performance devices like NarrowBand Internet of Things (NB-IoT), these implementations are suboptimal due to their late introduction in the 5G development cycle [22]. In order to avoid mistakes from past generations, the 6G network protocol architecture should be designed to support a wide range of access methods, existing and non-existing ones, while also being able to adapt to the requirements of each use case.

However, the current user plane protocol architecture at the core, based on GTP-U, is not designed to support the flexibility required by 6G networks. For instance, the rigid and flat structure of GTP-U does not allow for the dynamic allocation of resources across the network, which is essential for supporting the diverse range of use cases envisioned for 6G networks. Furthermore, the virtual circuit switching approach adopted by GTP-U might in fact be unnecessary for such network deployments that do not need the reliability provided by virtual circuits.

GTP-U has served past generations of mobile networks effectively. However, as the paradigm is shifting from a performance-centric perspective, the evolving landscape of 6G and beyond presents new challenges. Those challenges require the rethinking and potentially redesigning of core network elements to ensure efficiency, and suitability for a wide range of current and emerging use cases.

3.4. Scalability Issues

While RANs within 5G are already operating at high capacities, the bottleneck has shifted towards the transport network. This shift is critical, especially as computers are moving closer to the edge to meet stringent latency requirements. The transport network, historically over-dimensioned and rigid, now requires a more dynamic architectural approach to accommodate new use cases, like coverage extension through convergence with NTNs. It becomes a need to dynamically allocate resources not just within the access network but across the transport network, selecting the most suitable backhaul based on the specific characteristics of the available transport links.

The current user plane protocol architecture, based on GTP-U, is not designed to support the scalability requirements of 6G networks. The virtual circuit switching approach adopted by GTP-U requires storing considerable state in the UPFs, which makes GTP-U hard to scale to the level anticipated by 6G.

4. 6G-RUPA: A Scalable and Flexible User Plane Network Protocol Architecture

Briefly, 6G-RUPA enhances the user plane protocol architecture, making it more flexible, scalable, and energy-efficient to meet the requirements of envisioned 6G networks. 6G-RUPA offers a highly efficient and adaptable network protocol architecture that maximizes commonality and interoperability across diverse network segments. Specifically, 6G-RUPA is built upon the following principles:

- **A flexible amount of layers**. In contrast to the single user plane protocol layer model of previous generations, 6G-RUPA empowers network architects to determine the number of layers necessary. Unlike the current user plane protocol framework, which employs a single user plane protocol layer, 6G-RUPA allows for stacking an unconstrained number of layers. Inspired by the Recursive InterNetwork Architecture (RINA) [23], 6G-RUPA features a recursive user plane with a programmable and common flexible protocol across all layers. These flexible layers serve as a tool for network architects to enhance scalability, security, or flexibility. Hence, 6G-RUPA can be viewed as a superset of current user plane protocols. In other words, utilizing a single user plane protocol layer in 6G-RUPA would make it functionally equivalent to current 3GPP standards.
- **Multilayer QoS framework**. Additionally, 6G-RUPA enables the network to adapt to the specific requirements of diverse applications and physical media, dynamically allocating resources to meet those demands. Each user plane protocol layer provides flows to applications or other user plane protocol layers above it, allowing them to signal their desired QoS for each flow. These quality requirements are communicated in a technology-independent manner: applications and upper-user plane layers request flow characteristics in terms of performance, security, or other service-level attributes. This is a relevant feature for 6G, as it enables more granular control over network resources.
- **Agnostic about Protocol Data Unit (PDU) Layers and transport network protocols**. Currently, in 5G networks, GTP-U provides UE-to-core connectivity using a virtual circuit approach, leveraging IP tunneling. While this approach performs well in most current use cases, it may not suffice for certain scenarios envisioned by 6G, such as Time-Sensitive Networking (TSN). To address this, Gebert et al. [21] propose PBB and TRILL (Ethernet over Ethernet). This decision is primarily due to the limitations of GTP-U's single layer in handling deterministic networking traffic and the unnecessary reliance on GTP-U's transport protocols (IP and User Datagram Protocol (UDP)) for this specific use case. However, 6G-RUPA aims to surpass this by proposing a flexible solution that can be used with any transport network or link layer protocol, not just IP and UDP.
- **Programmable protocol layers**. Moreover, 6G-RUPA layers share common functions—mechanisms— which are customizable through well-defined extension points—policies. Key functions like addressing, forwarding, congestion control, and routing can be tailored to specific use cases. This adaptability enables 6G-RUPA to meet the diverse demands of various public and non-public networks, subnetworks, and topologies, such as D2D and NTN. Furthermore, SDN is envisioned as a key enabler for the programmability of 6G networks, allowing for a dynamic configuration of network resources and services. A network architecture designed for programmability is crucial for integrating AI and in particular ML into the network. This enables the network to be dynamically reconfigured to meet the specific requirements of the applications and services it supports.
- **Support for multiple control planes**. Furthermore, 6G-RUPA aims to support the integration of existing and future control planes, such as the 5G Service Based Architecture (SBA). It allows for the seamless composition of different control planes, using the as-a-service paradigm to facilitate control plane integration.
- **AI for 6G and 6G for AI**. AI is crucial to 6G-RUPA, enhancing its adaptability and intelligence. AI enables predictive analytics for network optimization, intelligent

resource management, and automated handling of dynamic network conditions. However, all these AI capabilities are only possible if the network is programmable. In turn, 6G-RUPA provides the necessary programmability to integrate AI into the network, enabling the network to adapt to the specific requirements of the applications and services it supports.

4.1. Error and Flow Control Protocol (EFCP), A Flexible User Plane Protocol

Since 6G-RUPA is designed as a flexible user plane protocol architecture adaptable to various network scenarios, it requires a customizable user plane protocol to meet the unique requirements of each network segment. To this end, 6G-RUPA leverages the EFCP protocol in all its layers. EFCP, originating from the RINA architecture [24], is a data transfer protocol that provides all the mechanisms necessary to implement user plane protocols. It offers mechanisms for addressing, QoS management, flow control, forwarding, error recovery, and security. These can be customized by using policies, which complement and adapt the protocol's behavior to the operational requirements of the 6G network it operates within. For instance, forwarding can be configured to utilize a virtual circuit approach—similar to GTP-U—as well as the longest-prefix match or any other suitable method.

Figure 4 illustrates the abstract syntax of an EFCP data transfer PDU. Notably, the length of the fields—address, qos-id, cepid, length, and sequence number—is unspecified. This is because the field lengths are determined by the EFCP policies specific to each network. For instance, small private networks might not require a 32-bit address field, as in the IP protocol, but a 16-bit field might suffice. The same applies to QoS. Some networks might only need a few QoS classes with their own implementations, not necessarily based on 3GPP QoS classes. The EFCP supports this level of customization, allowing for tailored protocol implementation that optimizes network performance across different segments. In practice, the core traffic is tagged with the QoS identifier, and the layer applies appropriate policies—ranging from forwarding strategies like virtual circuit or statistical multiplexing to flow control methods such as congestion and retransmission control.

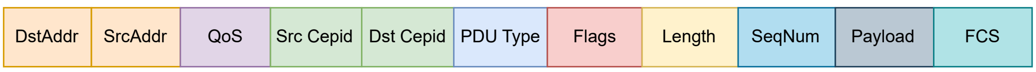

Figure 4. Abstract syntax of an EFCP data transfer PDU.

4.2. Addressing 6G Needs and Lacks Leveraging 6G-RUPA

This subsection analyzes how 6G-RUPA can be an effective solution to solve the 6G needs and lacks pointed out in Section 3. This section addresses the lack of appropriate inter-network federation mechanisms, as well as the flexibility and scalability issues stemming from legacy GTP-U.

4.2.1. Inter-Network Federation Mechanisms

One of the primary goals of 6G is to provide extensive coverage. This inevitably necessitates the seamless integration of diverse access and core networks, encompassing NTNs, public and NPNs, non-3GPP accesses, and more. Consequently, the future 6G network envisions dynamic federations of 6G domains, each comprising numerous heterogeneous RANs and cores interconnected with other 6G domains and external data networks. This vision encompasses various wired and wireless networks, such as copper, fiber, 3GPP cellular, Bluetooth, and Wi-Fi, spanning different frequency bands. This is known as the *network of networks* vision [3]. Therefore, the evolution of the core network emerges as a key area for 6G research.

Briefly, 6G-RUPA leverages recursivity by employing the EFCP protocol in its the layers. By allowing the stacking of multiple user plane protocol layers, 6G-RUPA can support the diverse requirements of different network segments, ensuring seamless connectivity across the 6G ecosystem. Moreover, 6G-RUPA allocates flows for applications by name, instead of using addresses, as happens with IP-based networking. This has an intrinsic advantage, since the applications can connect to each other no matter where they are located. This approach not only simplifies mobility management but also enhances the overall flexibility and efficiency of the network architecture, as detailed further in [25].

All in all, given the diverse range of access networks, ensuring seamless mobility between them poses a significant challenge. While roaming is currently utilized in 5G networks to achieve network federation, it might not be sufficient to fully support the *network of networks* vision, as discussed in Section 3. Therefore, to effectively address these challenges, a re-architecting of the user plane network protocols, which have remained largely unchanged since 3G, may be necessary.

4.2.2. Network Flexibility

It should be noted that 6G-RUPA protocol layers can be optimized to align with the specific characteristics of the radio layers required by each RAT. Given the objective of supporting multiple types of RANs and non-radio access networks, different protocols will operate between base stations—or access routers—and UEs connecting to the network. Consequently, an instance of the 6G-RUPA protocol will always be present as an overlay on top of these RAN-specific protocols.

Furthermore, the separation between mechanisms—fixed protocol elements—and policies—changeable protocol elements—within EFCP enables 6G-RUPA to readily adopt SDN principles. This allows the user plane to offer well-defined Application Programming Interfaces (APIs) for reconfiguring its mechanisms, encompassing not only forwarding but also flow control, retransmission control, addressing, and security. This feature is crucial for the required dynamism of 6G networks, particularly for the integration of AI and ML, as it facilitates dynamic network reconfiguration to meet the evolving demands of supported applications and services.

4.2.3. Scalability Issues

To minimize the number of forwarding table entries at the UPFs and base stations, and achieve a more efficient resource allocation policy, 6G-RUPA proposes using statistical multiplexing instead of virtual circuit switching whenever possible. This approach enables more efficient network resource utilization, as it eliminates the need to store state in the UPF for each flow provided to each UE, thereby reducing the number of forwarding table entries in the UPF. The use of virtual circuits is reserved for scenarios where they are strictly necessary, such as when the network must provide a specific QoS level that cannot be achieved through statistical multiplexing. This approach allows the network to be both more energy-efficient and scalable simultaneously.

Additionally, 6G-RUPA employs an addressing scheme that contributes to enhanced scalability. The core idea behind this scheme is twofold. First, addresses are assigned to reflect the logical location of each node within the network. Second, since addresses in 6G-RUPA are ephemeral, nodes can change addresses without disrupting ongoing flows [26]. This is achieved through two types of names: application process names and node addresses. Application process names are fixed identifiers for applications, similar to Domain Name System (DNS) names, while node addresses indicate the current location of a node, changing as the node moves.

This approach offers several advantages. Firstly, forwarding tables in the UPFs are reduced, as each node can generate default routes to all other nodes in the layer by just storing the addresses of their direct neighbors. Secondly, since nodes themselves can change addresses without disrupting existing flows, addressing schemes can evolve as the network grows. Last but not least, changing the address of a node, e.g., when it joins a different subnetwork after a handover, keeps the address of the node aggregate within the layer. Hence, the UPFs and the base stations do not need to add new entries in their forwarding tables.

5. Illustrative Use Cases of 6G-RUPA User Plane Designs

Figure 5 showcases a 6G-RUPA user plane protocol stack for typical Mobile Network Operator (MNO) deployment, as depicted in Figure 1. The figure illustrates the user plane protocol stack for a 6G network, comprising a single core and a 6G RAN. In this deployment, it can be noted that there is no protocol conversion between the 6G RAN and the core, as there is a *Local MNO Layer* that spans across all the operator domains. This layer is responsible for managing the interaction between the 6G RAN and the core, and can be implemented on top of any underlying technology, depending on the requirements of the operator. This layer's flexibility allows it to support operations ranging from small private networks with few devices to large national operators managing millions of devices.

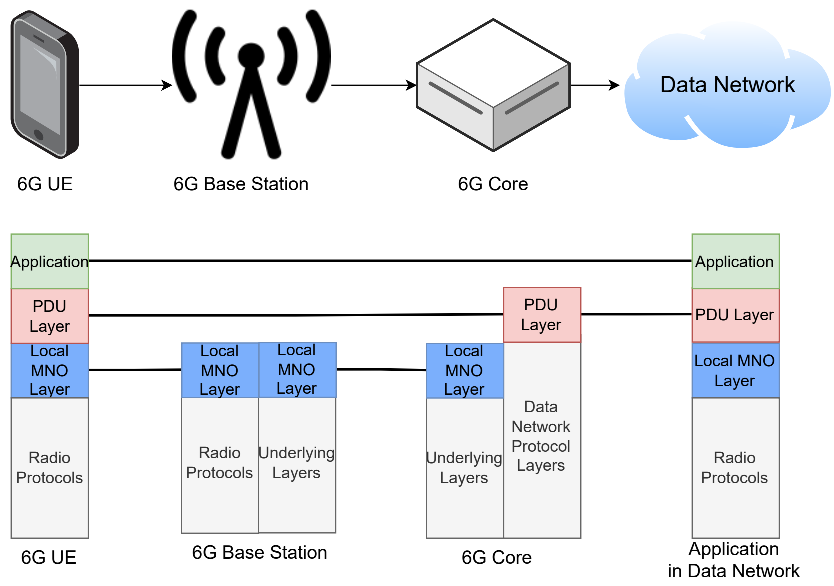

Figure 5. A 6G-RUPA user plane protocol stack for typical mobile network deployment.

In addition to simplifying the user plane network architecture, 6G-RUPA introduces significant improvements to existing verticals through enhanced features like network slicing, edge computing, and support for emerging technologies such as quantum computing and tactile internet. These advancements are relevant for operators aiming to optimize network efficiency and performance, particularly in scenarios requiring robust latency management and innovative communication flows.

- **Network slicing**. With 6G-RUPA, every operator could have layers running in parallel, each with certain characteristics, such as different QoS profiles, different amounts of addresses, different congestion control policies, etc. Furthermore, these concurrent layers could be designed by AI algorithms thanks to the programmability of the user plane that 6G-RUPA provides.
- **Edge computing**. In edge computing deployments, latency is a key KPI. Having protocols that are aware of these latency requirements is a must.
- Quantum computing. Quantum computing is a promising technology that will require a new set of protocols to be able to communicate with the rest of the network. In fact, in [27] the authors provide an initial proposal of a very similar protocol architecture to that o6G-RUPA in order to support a future quantum internet.
- **Tactile internet and haptic communications**. Similarly, as in edge computing, latency is a key KPI in the tactile internet; 6G-RUPA can provide mechanisms to ensure that protocols used in tactile internet network segments help to achieve the required latency.

- **Optical Wireless Communication (OWC)**. Briefly, 6G-RUPA could optimize the deployment and performance of OWC systems, which are relevant in environments where traditional radio communications are unsuitable.
- **Fronthaul and backhaul networks**. Moreover, 6G-RUPA envisions the use of unreliable backhauls to provide connectivity between different 6G domains. This is particularly relevant in scenarios where the backhaul is not reliable, such as in emergency responses or temporary installations; 6G-RUPA can provide mechanisms to ensure that the network can operate efficiently in these challenging scenarios.

Figure 5 showcases how 6G-RUPA may be applied in a common mobile network scenario. However, the potential of 6G-RUPA is shown in complex cases where current 5G user plane protocols struggle to optimize. In this regard, the following subsections will explore how 6G-RUPA can be applied in a *network of networks* scenario and in Low Earth Orbit (LEO) constellation deployment, since these scenarios are particularly challenging for current user plane protocols.

5.1. Network of Networks Scenario

The *network of networks* vision for 6G conceives a digital ecosystem comprising interconnected subnetworks, each serving distinct purposes and use cases. This paradigm aims to cater to a diverse array of connectivity needs, ensuring efficient and flexible operation across an expansive digital landscape. Figure 6 illustrates a scenario where multiple 6G domains are interconnected, each consisting of a multiple cores and multiple RANs. Today, the only mechanism at user plane level to federate these different network domains is based on roaming network techniques. As briefly discussed in Section 3, current roaming mechanisms are not designed to manage the dynamic interactions among a multitude of small networks with varying reliability and policy requirements.

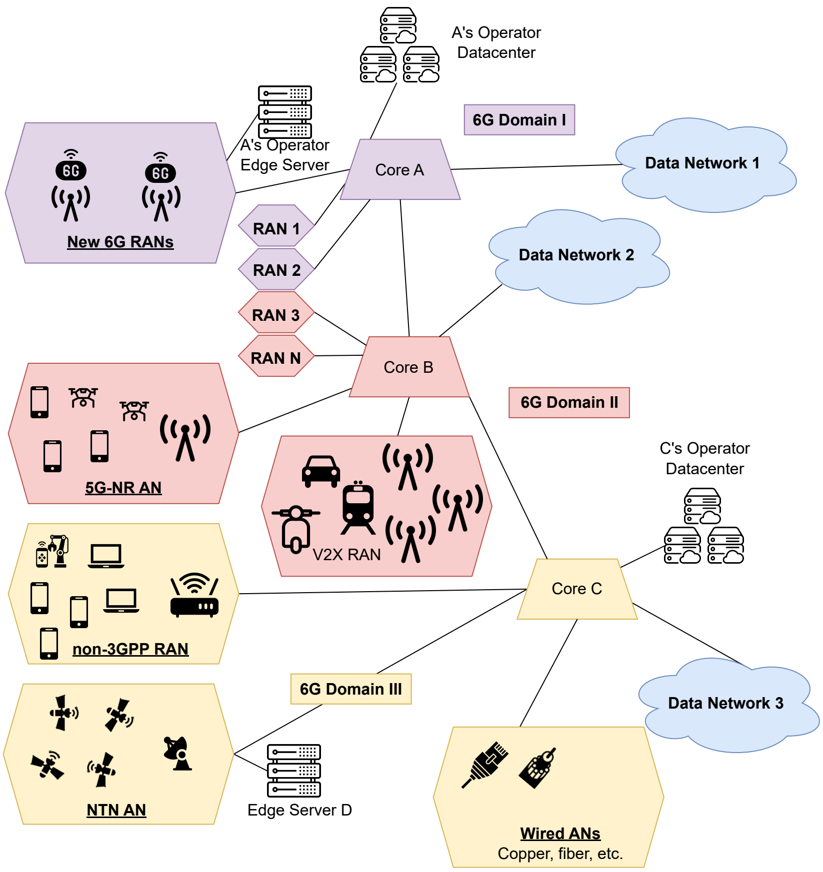

Figure 6. A *network of networks* conceptual scenario.

Until the emergence of 5G, mobile networks were primarily designed to rapidly forward PDUs from UEs to the data network. Even when a UE was located within another operator's domain, existing inter-networking mechanisms like roaming aimed to reach the data network through the visited operator's domain.

Figure 7 depicts the user plane protocols involved in roaming scenarios, particularly utilizing the home-routed approach, and contrasts it with an example configuration of the 6G-RUPA user plane protocol stack. It illustrates a home-routed scenario where the UE connects to the visited network, but data are routed through the home network. This is common in roaming due to subscription management occurring within the home operator.

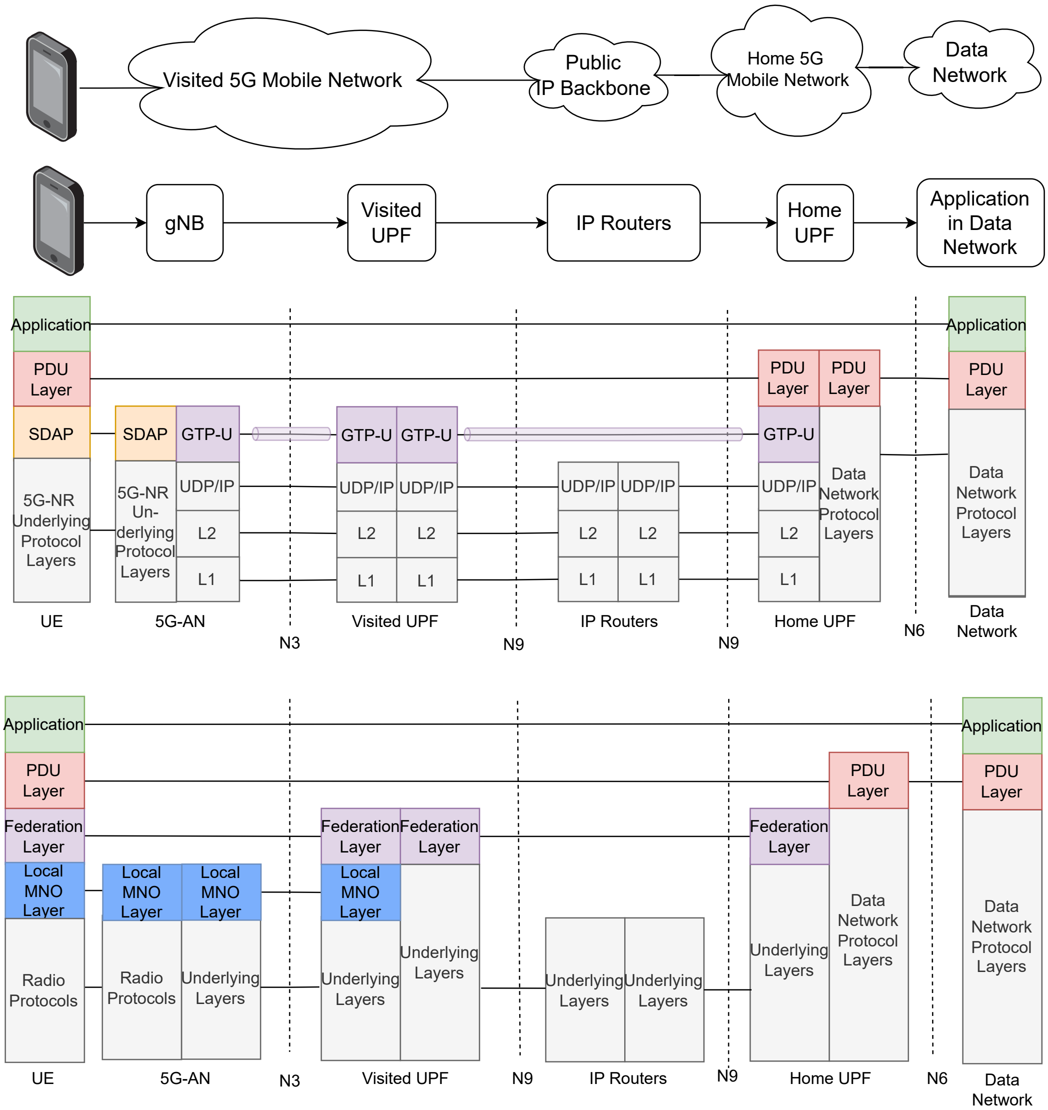

Figure 7. Home-routed roaming 5G protocol stack scenario vs. 6G-RUPA approach.

Notably, 6G-RUPA deployment takes a different approach, with the UE connecting to the visited UPF through an MNO federation layer. This approach offers several advantages. Firstly, the MNO federation layer isolates network complexities from lower layers, ensuring flexibility regardless of the *Local MNO layer*'s implementation—e.g., NTN, Vehicle to Everything (V2X). Secondly, multiple MNO federation layers can operate concurrently, facilitating adaptable and scalable network federation. For instance, there could be a federation optimized for Extended Reality (XR) services and another tailored for TSN services, both supported by the internal user planes of different providers, i.e., the *Local MNO layer* in Figure 7.

Moreover, the MNO federation layer can transport PDUs beyond just the data network. Given the evolving need for seamless network federation, it can route PDUs to another local MNO layer, and so on. This approach offers greater flexibility than traditional roaming mechanisms and aligns better with the requirements of the 6G *network of networks* scenario.

5.2. LEO Constellation as an Access Network

This section aims to explain how 6G-RUPA can overcome existing challenges in network federation while simultaneously satisfying the requirements of specific network segments in terms of scalability, flexibility, energy efficiency, and performance. To achieve this, this subsection investigates how 6G-RUPA can address current challenges related to user plane protocols in NTN deployments.

Figure 8 illustrates the system architecture and user plane protocols employed in a potential LEO NTN deployment. This scenario incorporates a minimal core and base stations integrated within the satellites, an approach anticipated to effectively transport PDUs traversing the satellite constellation. Referred to as regenerative payload architectures, this integration of core functions within satellites is well documented. Conversely, deployments lacking core functions in satellites are known as transparent payload architectures, where the LEO constellation functions as a relay between ground stations and end-users.

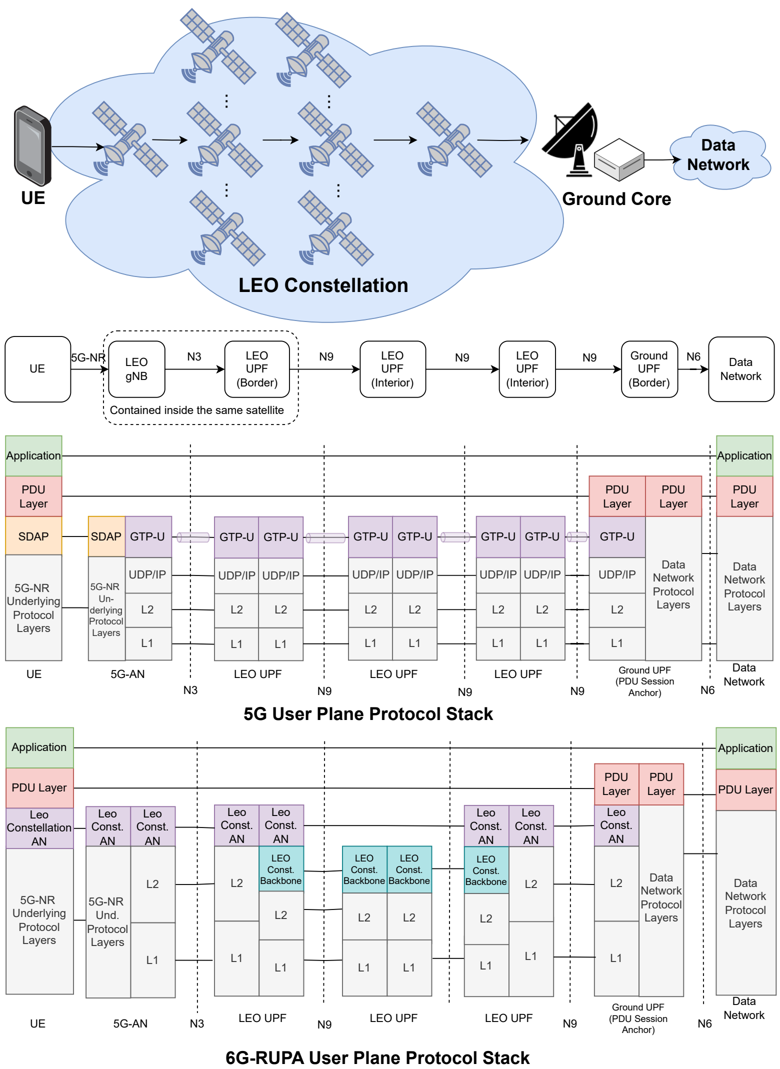

Figure 8. User plane protocols of a regenerative architecture LEO constellation deployment.

For instance, in [28], a novel architecture is proposed to enable store and forward mechanisms within the often unreliable satellite–ground link. This enhancement involves integrating a core into the satellite and implementing corresponding extensions. While regenerative payload architectures offer greater flexibility, they introduce the challenge of incorporating a mobile core into resource-constrained satellites. Several research efforts have focused on addressing this challenge. For example, in [29], the authors assess the utilization of SDN in satellite constellations to mitigate the complexity of the satellite-based core.

Figure 8 showcases the aforementioned deployment with the user plane protocols of 5G and 6G-RUPA. Some points to note in the 5G deployment of Figure 8 are as follows:

1. The UE connects to the NTN access network via the 5G-NR protocols. For simplicity's sake, only the Service Data Adaptation Protocol (SDAP) layer is depicted in Figure 8. These protocols, 5G-NR protocols, are mainly designed for terrestrial RANs; hence, they are not optimized for satellite feeder links. The 5G-NR protocol needs to be adapted in order to operate in the Earth—satellite segment, mainly due to high propagation delays [30].
2. Once the UE reaches the base station on the satellite, the onboarded gNodeB (gNB) encapsulates the PDUs over the $N3$ interface. The encapsulation consists of a GTP-U header and an IP tunnel to the UPF onboarded at the same satellite.
3. The PDUs is forwarded over one or more interior UPFs through the $N9$ interface. In this interface, each satellite hop translates into a new GTP-U tunnel. In Figure 8, three hops are depicted (border UPF → interior UPF → border UPF → ground UPF). Note that, in big constellations, there might be numerous hops through multiple satellites, leading to the need to maintain numerous tunnels per UE connection. Not only is this the case, but if the satellites belong to different operators, roaming mechanisms will be needed in the $N9$ interfaces.
4. The traffic is sent back to the ground segment, again creating a new GTP-U tunnel over the $N9$ interface. This time, however, the physical layer is the feeder link, not the inter-satellite link, unlike in the previous bullet.
5. Finally, the traffic is sent to the data network over the $N6$ interface, removing the GTP-U headers and leaving only the underlying transport network protocols and the upper PDU layers.

Now, let us analyze Figure 8; it consists of the same deployment as before, but leveraging 6G-RUPA in the user plane:

1. The UE connects to the NTN access network via 5G-NR protocols. The PDU to the satellite is encapsulated in the LEO constellation access layer, which is in charge of providing flows with a given quality of service between the UE and a ground UPF. This is an example of how 6G-RUPA can be customized to meet the requirements of the network segment.
2. The LEO gNB forwards the PDU over the $N3$ interface within the LEO constellation access layer. In this network segment, the LEO constellation access layer is located on top of the intra-satellite comms layer, which is optimized for the local communication inside the satellite—i.e., since the communication is local, it does not require the use of UDP/IP protocols. In generative payload-based satellites, light-weight minimal gNBs and UPFs could coexist in the satellites. In the considered architecture, the LEO satellite has both the base station and the core onboard; hence, the physical link might be just a wire, or even a shared memory region if the base station and the core are virtualized in the satellite's computing board.
3. The PDU is forwarded through one or several UPFs from different satellites, over the $N9$ interface. The PDU flows through the LEO constellation access layer, which in turn goes on top of the LEO constellation backbone layer. The latter is a network layer that goes over the LEO satellite constellation. The LEO constellation backbone layer deals with mobility and handovers between the satellites, isolating the complexity of satellite constellation mobility management from the flow between UE and the

ground UPF within the LEO constellation access layer. It is important to note that the LEO constellation backbone user plane layer is deployed on top of an Inter-Satellite Link (ISL), and is specifically tailored for ISL particularities at the link level.

4. The traffic is sent back to the ground segment, following the same approach as that in item 1.
5. Finally, the traffic is sent to the data network over the *N*6 interface, removing the LEO constellation access layer, leaving only the underlying transport network protocols and the above PDU layers.

Some key benefits extracted from the comparison of the 5G and 6G-RUPA deployments are as follows:

- It can be noted that 6G-RUPA does not constrain how the upper PDU layers or the underlying transport network protocols are implemented. This allows for a more flexible approach to network design, allowing the network architect the possibility choose the most suitable policies for each network segment.
- Furthermore, 6G-RUPA clearly groups network functionalities in layers. This means that the LEO constellation access layer is responsible for the data transmission from the UE until the last UPF at the ground segment. Therefore, the layer defines the needed QoS per flow within this layer. On the other hand, the LEO constellation backbone layer is responsible for the inter-satellite communications; thus, network functionalities such as mobility management—i.e., handovers between satellites—within the satellite constellation are managed in this layer, making it transparent to upper layers.
- It is noteworthy that the LEO constellation backbone layer could hide a multi-layer satellite constellation. At peak points, the LEO constellation links might be saturated. Therefore, the traffic could be forwarded to a Medium Earth Orbit (MEO) or Geostationary Earth Orbit (GEO) constellation. Nevertheless, this approach is suitable for non time-sensitive applications.

6. Conclusions and Future Work

In this paper, we introduced 6G-RUPA, an innovative user plane network protocol architecture tailored to meet the evolving demands of 6G. As the telecommunications industry advances toward the realization of 6G, a scalable, flexible, and energy-efficient user plane architecture becomes a need. We show that 6G-RUPA addresses these requirements by offering a versatile protocol framework that enhances network scalability, optimizes resource utilization, and promotes sustainability.

The high-level analysis presented in this paper demonstrates that traditional user plane protocols, such as GTP-U, encounter substantial challenges in supporting envisioned 6G use cases, particularly concerning network scalability, flexibility, and energy efficiency. We also show that 6G-RUPA addresses these limitations by introducing key features like a flexible number of user plane layers, multi-layer QoS management, user plane protocol layer programmability, and support for various underlying network protocols.

These features enable 6G-RUPA to seamlessly integrate diverse access and core networks, encompassing a wide range of access networks, as envisioned in the *network of networks* paradigm. The implementation of 6G-RUPA within a *network of networks* scenario demonstrates its potential to facilitate inter-network federation, offering flexible mechanisms for uniting heterogeneous network domains. By enabling the introduction of novel enhancements, such as advanced addressing schemes or statistical multiplexing techniques, 6G-RUPA significantly reduces forwarding state requirements at the 6G core, thus improving network scalability and decreasing energy consumption.

Future work will focus on specific designs for the NTN use case, the high-level design of which is preliminary presented in Section 5.2. This includes proposing detailed policies for addressing, forwarding, and mobility management tailored to the various user plane layers, both in access and backbone networks. Conducting simulations to obtain numerical results is crucial for comparing the performance of 6G-RUPA with that of existing protocols like GTP-U. Such simulations will provide insights into the efficiency and practicality of 6G-RUPA in real-world deployments at a scale, helping to refine and optimize the protocol further.

The future of mobile networks lies in their ability to adapt and evolve in response to emerging technologies and use cases. Finally, 6G-RUPA stands as a promising solution for the user plane, laying the groundwork for scalable, flexible, and sustainable 6G networks.

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