**Article:**

Alberti, A.M. orcid.org/0000-0002-0947-8575, Pivoto, D.G.S., Rezende, T.T. et al. (5 more authors) (2024) Disruptive 6G architecture: Software-centric, AI-driven, and digital market-based mobile networks. Computer Networks, 252. 110682. ISSN 1389-1286

https://doi.org/10.1016/j.comnet.2024.110682

# Disruptive 6G Architecture: Software-Centric, AI-Driven, and Digital Market-Based Mobile Networks

Antônio M. Alberti[a], Diego G. S. Pivoto[a], Tibério T. Rezende[a], Alexis V. A. Leal[d], Cristiano B. Both[d,*], Michelle S. P. Facina[b], Rodrigo Moreira[c], Flávio de Oliveira Silva[c]

[a]*Instituto Nacional de Telecomunicações (INATEL), Santa Rita do Sapucaí, MG, 37540-000, Brazi*
[b]*Fundação Centro de Pesquisa e Desenvolvimento em Telecomunicações (CPQD), Campinas, SP, 13086-902, Brazil*
[c] *Federal University of Uberlândia (UFU), Uberlândia, MG, 38408-100, Brazil*
[d]*Applied Computing Graduate Program (PPGCA), Av. Unisinos, 950, 93020-190, São Leopoldo - RS - Brazil*

**Abstract**

Mobile communications have followed a progression model detailed by the Gartner hype cycle, from a proof-of-concept to widespread productivity. As fifth-generation (5G) mobile networks are being deployed, their potential and constraints are becoming more evident. Although 5G boasts a flexible architecture, enhanced bandwidth, and data throughput, it still grapples with infrastructure challenges, security vulnerabilities, coverage issues, and limitations in fully enabling the Internet of Everything (IoE). As the world experiences exponential growth in Internet users and digitized devices, relying solely on evolutionary technologies seems inadequate. Recognizing this, global entities such as the 3rd Generation Partnership Project (3GPP) are laying the groundwork for 5G Advanced, a precursor to 6G. This article argues against a mere evolutionary leap from 5G to 6G. We propose a radical shift towards a disruptive 6G architecture (D6G) that harnesses the power of smart contracts, decentralized Artificial Intelligence (AI), and digital twins. This novel design offers a software-centric, AI-driven, and digital market-based redefinition of mobile technologies. As a result of an integrated collaboration among researchers from the Brazil 6G Project, this work identifies and synthesizes fifty-one key emerging enablers for 6G, devising a unique and holistic integration framework. Emphasizing flexibility, D6G promotes a digital market environment, allowing seamless resource sharing and solving several of 5G's current challenges. This article comprehensively explores these enablers, presenting a groundbreaking approach to 6G's design and implementation and setting the foundation for a more adaptable, autonomous, digitally monitored, and AI-driven mobile communication landscape. Finally, we developed a queuing theory model to evaluate the D6G architecture. Results show that the worst-case delay for deploying a smart contract in a 6G domain was 23 seconds. Furthermore, under high transaction rates of ten transactions per minute, the delay for contracting a 6G slice was estimated at 53.7 seconds, demonstrating the architecture's capability to handle high transaction volumes efficiently.

*Keywords:* 6G, Disruptive Architecture, Enabling Technologies, Mobile Networks, Network Architecture, System Architecture, D6G.

*Corresponding author.
*Email addresses:* alberti@inatel.br (Antônio M. Alberti), diegopivoto@gea.inatel.br (Diego G. S. Pivoto), tiberio.rezende@inatel.br (Tibério T. Rezende), alexis.leal@ifmt.edu.br (Alexis V. A. Leal), cbboth@unisinos.br (Cristiano B. Both), michelle.facina@gmail.com (Michelle S. P. Facina), rodrigo@ufv.br (Rodrigo Moreira), flavio@ufu.br (Flávio de Oliveira Silva)

## 1. Introduction

According to the Gartner hype cycle methodology, every technology follows five main stages of evolution. It could not be different concerning mobile communications [1]. An initial proof-of-concept is developed in a trigger phase. In the peak phase of inflated expectations, the technology starts to be implemented and gains much notoriety. Research intensifies in the next step, known as the trough of disillusionment, in which developers encounter problems and disadvantages. Consequently, there is a great disappointment regarding the technology. Some disappear or are even forgotten due to significant issues [2]. On the slope of enlightenment, some problems are solved, and the potential of technology becomes broader and more understood. In the plateau stage of productivity, the technology is more widely implemented, the mainstream industry starts to adopt it, standardization is considered, and the technology grows continuously [2]. This methodology fits so well for mobile communications that we are witnessing the transition of two technological waves.

The current landscape illustrates the advancements in deploying fifth generation cellular mobile network (5G), focusing on standardization and the scenarios it supports [3–10]. 5G aims to establish an architecture with enhanced flexibility and support for low-latency requirements, higher bandwidth, and increased data throughput. However, some shortcomings and drawbacks are already becoming apparent. For example, our society is undergoing a digitization revolution, with a substantial increase in Internet users and connected devices [11]. In this context, evolutionary technologies alone could not be enough [5, 12, 13]. The innovative features of 5G, such as the infrastructure and antenna densification and frequency bands in the millimeter wave (mmWave), cannot achieve the desired requirements [5, 13]. Its constant implantation exposes some limitations, and the original premise of 5G as an enabler for the Internet of everything (IoE) needs to be stronger [14].

As the first phase of 5G consolidates in several countries around the world [7], the 3rd generation partnership project (3GPP), other standardization bodies, and several companies are already planning and designing 5G Advanced [3] as the next step in the evolution towards sixth generation cellular mobile network (6G) [8]. The literature is rich [6, 7, 9, 10, 15–17] in examples of how 5G is limited and which services and applications can motivate the advance to the next generation. However, in these references, the transition to 6G follows the same approach from fourth generation cellular mobile network (4G) to 5G, employing an evolutionary process. Should we follow the same path, or is it time for a change?

In many countries, to deliver speeds over 1 Gbit/sec and millisecond latencies, a significant amount of work is being done to adjust optical networks, including installing new fiber optic cables. This change is a complex and time-consuming process [18]. Moreover, infrastructure sharing is the way to make deployment less costly. However, the best technology for this purpose in 5G is network slicing, usually restricted to the domain of a single carrier [19]. The network slicing and programmability of resources across domains is challenging for operators and their operations support system (OSS) and business support system (BSS). Sharing in an architecture that does not allow easy coexistence of suppliers, developers, and providers in the same environment, with the automation of digital contracts, causes enormous difficulty [20].

5G operates on frequencies higher than 4G, which requires 5-10 times more antennas to provide the same coverage. In addition, even if a city has 5G coverage, this does not necessarily mean that the 5G signal is available throughout the city's territory. Dead zones or areas without signals remain a problem. Investments to achieve the same coverage as 4G are too high for most operators [18]. This aspect is essential for the financial viability of 5G and 6G, especially in developing countries, as an operator cannot bear all infrastructure costs alone. The path is to create a multi-stakeholder digital marketplace that allows elastic sharing of devices, equipment, resources, services, data, intelligence, and much more [20].

Multidisciplinary innovations that jointly advance technology, the digital economy, business, and human resources are needed. It is becoming evident that the current model, without sharing, collaboration, automation, representation, intelligence, digital market, intention, and security, will not be able to deliver what is expected in 5G. Consequently, new approaches are needed in 6G. Multi-operator efforts are required [21]. There is no doubt that 5G is a remarkable evolution. However, its design is based on a communications point of view. The degree of softwarization, i.e., using software to solve problems at all points where hardware can be replaced, servitization (service-centric business and solutions), digital monetization, and required immutability, have increased significantly [12, 22–24], especially after the COVID-19 pandemic [25].

Another limitation of 5G is the security of virtual functions. There is no support for the immutability of services and decentralized storage of perennial data in the control, management, knowledge, and inference planes [26]. 5G does not support the creation of distributed ledger technologies (DLT) based on digital markets with virtual functions, digital twin (DT), and artificial intelligence (AI)-based services. The resolution of names depends on the domain name system (DNS), with limited namespaces and name resolution support. DT only inhabits the application layer [27]. However, they have a fundamental role in architecture, representing everything physical and not virtualizable. 5G does not support architecture-level intent-based network (IBN) [28], AI-based assistants, facilitators, autopilots, and other critical enablers for future mobile networks. Only a disruptive 6G can fully address these limitations using a novel smart contract software-engineered approach.

A disruptive design centered on the synergistic integration of smart contracts, AI, and DTs could revolutionize the landscape of mobile technologies. Moreover, this design can focus on monetized service-based ingredients and integrate enablers from several areas with a flexible, cohesive, and synergistic approach. We argue that 6G is the next opportunity, and it is time to take this revolutionary choice of a software-centric, AI-driven, digital-market-based redesign. This technological synergy is the meaning of the term disruptive 6G (D6G) in the context of this article. The ever-increasing demand for information leads not only to the acceleration of evolutionary technologies but also to giving room to disruptive ones. Therefore, our objective is to address the trigger phase of mobile communications. We propose a D6G architecture powered by smart contracts, decentralized AI, and DTs that can take full advantage of other emerging enablers without being stuck with the limitations of previous mobile generations. We define a whole set of design principles to guide this effort. Enablers have been extrapolated to maximize their support for others.

This work results from a joint effort developed by some Brazil 6G Project researchers. Definition and inspiration for design principles took into account previous work on concurrent and synergistic architectures. For example, the multi-strategy information architecture called NovaGenesis (NG) is an alternative to the Internet-based transmission control protocol (TCP)/Internet protocol (IP) stack [12, 24, 29]. Moreover, another relevant effort has been the development of data and control plans for a future Internet exchange point (FIXP) based on a programming protocol-independent packet processor (P4) [30]. In this work, an NG controller orchestrates an autonomous system with FIXP to allow name-based content distribution applications between hosts. This orchestration contributes to the design of the 6G programmable network since it implements a contract-based self-organizing control plane. In this context, our main contributions are as follows:

- Fifty-one key emerging enablers have been identified, selected, discussed, and analyzed. To our knowledge, D6G provides a unique, synergistic, flexible, programmable, digitally monetized, autonomous, and AI-driven integration of key 6G ingredients;
- Standardize a meta-architecture based on DLT with interfaces defined at runtime via digital smart contracts. Including disruptive

technologies such as DLT and others in our D6G architecture is vital to address emerging challenges and the growing demands of future communication systems;

- Automation of resource sharing by different stakeholders through smart contracts to improve the representation of physical entities; self-organization of all entities; relation to the intent of operators, providers, and users; the security, immutability, and trust of computing and networking; programmability, elasticity, efficiency, and flexibility of physical and virtual infrastructures.

In summary, this work reviews 6G enablers while proposing a novel approach to the design and implementation of 6G. This disruptive design, driven by key emerging enablers, aims to overcome 5G constraints and sets the path for a more flexible, autonomous, digitally monetized, and AI-driven mobile communication architecture. The remainder of this article is organized as follows. Section 2 points to the related work on disruptive architecture for 6G. Section 3 positions the 6G enablers in three strata based on the related work. Section 4 presents the proposed D6G architecture, approaching the functionalities distributed in layered strata. Next, Section 5 introduces a use case focused on drone connectivity, with a detailed sequence diagram of the proposed 6G components. Section 6 provides a queuing theory model for this use case, encouraging results to continue with 6G research in this direction. Finally, Section 7 summarizes our contributions and possible future work on the subject.

## 2. Related Work

This section reviews the main work related to disruptive 6G architectures. A strategy based on two objectives was adopted to compare the related work: (i) to define the level of disruptiveness, consolidation, and completeness of the proposed architectures; and (ii) to analyze whether the approach model supports key roles to be performed within a 6G architecture. To achieve the first objective, we defined a set of five architecture depth levels (ADLs) that allow us to assess the level of depth presented by the researched works. Conversely, we classified enablers into different families to accomplish the second objective, each responsible for performing a specific key role of a 6G architecture.

Concerning the five proposed architecture depth levels (from ADL1 to ADL5), the ADL1 requirement is met (by inserting the value "✓") when a 6G proposal introduces an architecture with new enablers and disruptive concepts to idealize an emerging structure independent of the known models in previously cellular generations, for example. ADL2 is related to the organizational structure level. It shows whether a related work is represented by a 6G architecture model based on an overall illustration (OI), structured into layers (LA), levels (LE), or similar methods of organization. ADL3 indicates that the proposal presents enabling technologies capable of deploying a 6G architecture. ADL4 refers to the application level. The word "S" means that the work focused on specific applications, while the word "W" represents an architecture considering many applications.

ADL5 considers the synergistic level among the previous ADLs. Some questions can be pointed out, such as: How can the proposed organizational structure (ADL2) and the enabling technologies (ADL3) be combined in a proposal to develop a 6G environment? How do ADLs meet the disruptive concepts mentioned in architecture (ADL1)? How can they be applied to meet application requirements (ADL4)? The level of discussion of possible answers to these questions is classified as low (L), medium (M), and high (H). The word "L" refers to architectures with a brief presentation of technologies, applications, and organizational structure without presenting synergistic details. The term "M" is assigned to works that discuss how to develop the proposed organizational structure while considering synergy among a few enabling technologies and applications. Finally, the word "H" is intended for proposals that illustrate the development of the 6G architecture in more detail, covering synergy among a large branch of enabling technolo-

Table 1: Comparison of related work.

| Ref. | ADLs | | | | | 6G Enablers | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | Energy | Sensing | Communication | Softwarization | Immutability | Intelligence | Security | Quantum |
| [31] | ✓ | LA | ✓ | W | M | ○ | ○ | ● | ● | ○ | ● | ○ | ○ |
| [4] | ✓ | OI | ✓ | W | L | ○ | ○ | ● | ● | ○ | ○ | ○ | ○ |
| [32] | ✓ | LA | ✓ | S | M | ● | ◐ | ● | ● | ○ | ● | ○ | ○ |
| [27] | ✓ | LA | ✓ | S | L | ○ | ○ | ● | ● | ○ | ◐ | ● | ○ |
| [33] | ✓ | OI | ✓ | W | H | ○ | ○ | ● | ● | ○ | ● | ○ | ○ |
| [34] | ✓ | LE | ✓ | W | H | ◐ | ◐ | ● | ● | ○ | ● | ● | ○ |
| [35] | ✓ | LA | ✓ | S | H | ● | ● | ● | ◐ | ○ | ● | ○ | ○ |
| [36] | ✓ | OI | ✓ | S | M | ○ | ◐ | ● | ● | ○ | ● | ● | ○ |
| [37] | ✓ | LE | ✓ | S | M | ○ | ◐ | ● | ● | ○ | ● | ◐ | ○ |
| [38] | ✓ | LE | ✓ | S | M | ◐ | ● | ● | ● | ◐ | ● | ◐ | ○ |
| [39] | ✓ | LA | ✓ | W | L | ◐ | ◐ | ● | ◐ | ◐ | ◐ | ◐ | ◐ |
| [40] | ✓ | OI | ✓ | W | L | ● | ○ | ● | ● | ○ | ● | ● | ○ |
| [41] | ✓ | LA | ✓ | W | H | ● | ● | ● | ● | ○ | ● | ◐ | ◐ |
| [42] | ✓ | LA | ✓ | W | H | ○ | ○ | ● | ● | ◐ | ○ | ○ | ○ |
| [43] | ✓ | LA | ✓ | W | H | ◐ | ○ | ● | ● | ○ | ● | ○ | ○ |
| [44] | ✓ | LA | ✓ | W | H | ○ | ● | ● | ● | ○ | ● | ◐ | ○ |
| [45] | ✓ | OI | ✓ | W | M | ◐ | ◐ | ◐ | ◐ | ◐ | ◐ | ◐ | ◐ |
| [46] | ✓ | OI | ✓ | W | M | ◐ | ◐ | ● | ● | ◐ | ● | ● | ◐ |
| [47] | ✓ | LA | ✓ | S | H | ● | ◐ | ● | ● | ○ | ● | ● | ○ |
| [48] | ✓ | OI | ✓ | W | H | ● | ● | ● | ● | ● | ◐ | ● | ◐ |
| [49] | ✓ | LA | ✓ | W | H | ◐ | ● | ● | ● | ○ | ● | ◐ | ○ |
| **D6G** | ✓ | LA | ✓ | W | H | ● | ● | ● | ● | ● | ● | ● | ◐ |

gies and applications and considering all the proposed architecture layers.

In previous work on the Brazil 6G project [50], we classified possible technological enablers capable of fulfilling these tasks into eight families: (1) energy to deal with devices that power up; (2) sensing and acting to cover Internet of things (IoT); (3) digital communications to provide connectivity; (4) softwarization to deal with the role of software in 6G; (5) immutability to add perennial, immutable, and decentralized information storage, as well as deterministic computing from smart contracts; (6) intelligence for autonomous decision-making to reduce human interference; (7) built-in security; and (8) emerging quantum technologies. Each family has a specific research area that we consider relevant for 6G. From previous research on [50], these enablers were selected to evaluate the related work and design our D6G proposal.

We analyzed the 6G literature to find articles that covered these same enabler families. We classify the related work as follows. Articles that do not discuss any enablers in a certain enabler family received the symbol ○ in Table 1. Articles that discuss any of the enablers of a specific enabler family but do not fully integrate them into the final proposed architecture received the symbol ◐. Articles that discuss and integrate enablers from a specific enabler family into the proposed final architecture received the symbol ●.

Yu et al. [31] contributed by proposing a new radio access network (RAN) architecture for 6G, a crucial aspect of digital connectivity. Additionally, the authors discussed a biological-inspired neuron-based approach to optimize the proposed RAN architecture. However, the article did not address the six remaining enabler families directly. Shah et al. [4] focused primarily on the role of IoT and digital communications for 6G connectivity. The authors discussed the evolution of connectivity from 4G to 5G and the proposed changes in 6G, highlighting the importance of IoT. However, the authors did not detail specific sensing and actuating details. Moreover, the article highlighted the role of AI in 6G but did not specifically address the concept of autonomous decision-making. Aspects such as energy for powering devices, softwarization, immutability, intrinsic security, and evolving quantum technologies are not directly discussed.

Feng et al. [32] presented a strongly related to digital communications for 6G connectivity and energy for powering devices. Moreover, the authors discussed aspects of softwarization, AI, and machine learning (ML). However, there is a limited focus on sensing and actuating. Intrinsic security, immutability, and quantum technologies are not covered at all. Li et al. [27] focused on digital communications and inherent security in the context of 6G technology. It presented a security reference architecture for 6G vehicle-to-everything (V2X) communication, highlighting the importance of this aspect in design. Cybertwins were also considered. However, the authors did not cover the immutability family, whose presence is strongly related to security.

Li et al. [33] presented a comprehensive study on the cognitive service architecture for 6G core networks. The authors explore the potential of cognitive computing and how to use it to improve the efficiency and performance of 6G. The role of cognitive services to facilitate human-like interactions is explored. The softwarization family was also touched upon, as cognitive services are software-based solutions. Lastly, the article discussed cognitive services for 6G. There is no support for the other enabler families, that is, energy, sensing, immutability, security, and quantum.

A comprehensive view of 6G was provided, focusing on digital communications, softwarization, intelligence, and intrinsic security by Liu et al. [34]. The authors discussed the evolution of digital communications from first generation cellular mobile networking (1G) to 6G, emphasizing the role of 6G in supporting global digitization. The concept of a "soft network" was introduced, highlighting the role of software in enabling a fully software-defined end-to-end (E2E) infrastructure. The article also investigated the concept of "native AI". Furthermore, it discussed "native security", which allows real-time optimization of security policies and proactive security defense. In summary, the proposed architecture integrates communication, softwarization, intelligence, and security enablers. Energy and sensing are discussed but not integrated. Immutability and quantum enablers are not even discussed.

Mahmood et al. [35] highlighted that the need for energy-efficient solutions should be considered as using renewable energy sources to power devices in 6G. This efficiency is especially relevant in industrial IoT networks where device energy consumption can be a significant concern. The article discussed the importance of reliable and efficient communication in industrial IoT networks. Moreover, the authors investigated how AI can be used for network management, resource allocation, and other tasks, minimizing the need for human intervention. In summary, this article covered integrating energy, sensing, communication, and intelligence enablers. Softwarization is discussed but is not clearly integrated. Immutability, security, and quantum technologies are not covered at all.

The work of Li et al. [36] provided a comprehensive exploration of 6G cloud-native design. The authors emphasized the importance of seamless connectivity in 6G networks, discussing how digital communication technologies can be used to achieve this. The article also delved into the significance of software's role in 6G, highlighting the potential of cloud-native systems to revolutionize network functionality and efficiency. Furthermore, the article explored the application of AI/ML in 6G, suggesting that these technologies are key enablers. The authors also underscored the need for security in 6G, advocating the development of secure and trustworthy networks. However, the authors do not cover energy, sensing, immutability, and quantum technologies in their integration.

An in-depth exploration of the challenges and requirements in designing a 6G testbed specifically for location use cases was provided by Khatib et al. [37]. The article discussed the role of IoT devices and sensors in these use cases, emphasizing the importance of digital communications. The authors also highlighted software's important role in designing and implementing these testbeds. The use of AI/ML for autonomous decision-making was also discussed, suggesting these technologies as key enablers in the 6G context. The article emphasized the importance of security in 6G, particularly in location-related issues, covering the integration of communication, softwarization, and artificial intelligence enablers. The manuscript also discusses the sensing aspects. However, there is no coverage for energy, immutability, and quantum technologies.

Letaief et al. [38] focused mainly on the role of AI in the context of 6G. The authors specifically addressed three of the eight technological enabler families more deeply. These studies included the role of AI in managing and interpreting data from IoT devices, improving communication and data transmission in 6G, and facilitating autonomous decision-making in 6G. The article discussed energy efficiency, energy harvesting, energy consumption, energy-aware AI models, and energy management. Moreover, the manuscript touched on immutability but did not delve deeply into it. Lastly, evolving quantum technologies were mentioned but not explored in depth.

Quy et al. [39] provided a comprehensive overview of the eight 6G technology enabler families to varying degrees. The authors discussed the role of intelligent energy management and energy harvesting technologies, IoT, the evolution of mobile networks integrating various networks for ubiquitous access, and blockchain and AI/ML in 6G. Moreover, the authors just mentioned quantum communication as part of research on 6G technology. Merluzzi et al. [40] presented the Hexa-X project's vision on AI and ML-driven communication and computation co-design for 6G. This project studies how AI/ML can be used for network management, optimization, and security and how they can be used to co-design information communications technology (ICT). A significant focus on energy efficiency and sustainable power sources for 6G was provided. The article also outlined the challenges and opportunities that come with data privacy, security, and algorithmic fairness. There was a significant effort to integrate energy, communication, softwarization, intelligence, and security enablers in a unique design. However, sensing, immutability, and quantum enablers are not covered.

Dogra et al. [41] thoroughly explored several crucial 6G technological enablers. The authors focused mainly on digital communications for 6G connectivity. The article analyzed significant energy aspects and softwarization, including several enablers. Although the authors addressed IoT, AI/ML for autonomous decision-making, intrinsic security, and quantum technologies to some extent, these topics appeared less central to the discussion. The concept of immutability received the least attention. This work integrates almost all enabler families. However, it does not include digital monetization (immutability) and security enablers in the proposed design, which are two fundamental aspects to be considered. Similarly, You et al. [42] emphasized extreme connectivity and multi-dimensional integration. The proposal designed an intelligent information infrastructure, enabling decentralized operation with the self-evolving network (SEN) as its pivotal component. Cutting-edge Physical technologies, such as cell-free massive multiple-input and multiple-output (MIMO), support this vision, aiming for comprehensive and uniform coverage across all application scenarios. The proposed architecture integrates communication and softwarization enablers but does not cover the remaining enabler families.

Chaoub et al. [43] emphasized that self-organizing networks (SONs) must be endowed with self-coordination capabilities to manage the complex relations between their internal components and avoid destructive interactions. The 6G networks open new opportunities to opt for a design-driven approach when developing self-coordination capabilities. The authors reviewed the history of SONs, including the inherent self-coordination feature, and argued that hybrid SON designs can be achieved by combining centralized and distributed management and control. Despite integrating communication, softwarization, and intelligence enablers, the work does not include the other enabler families in the proposed design. Tarik et al. [44] investigated the promising requirements of extended reality (XR) applications, emphasizing the heightened quality of experience (QoE) demands exceeding current technological capabilities. An innovative architecture based on the zero-touch service management (ZSM) framework was introduced using key enablers while addressing existing limitations. The architecture was structured in three distinct planes — deployment, domain-specific monitoring, and E2E conducting. The authors evaluated the architecture using showcased XR use-case scenarios and experiments. This work did not include energy, immutability, security, and quantum technologies in its proposed design. Other enabler families are present.

Jawad et al. [45] conducted a comprehensive survey of 6G enabling technologies, delineating the prospects for machine learning integration and elucidating the extant challenges. The document covers energy for devices, focusing on energy efficiency, harvesting, and green technologies, emphasizing sustainable power in 6G. It also highlights sensing and actuating for the IoT, discussing its integration in 6G. Digital communications for connectivity is a major focus, with extensive references to networks, communication protocols, and spectrum management, illustrating the foundational role of robust digital communications in 6G. The role of software in managing 6G infrastructure is highlighted under softwarization, including cloud computing, edge computing, and software defined networking (SDN). The article explores blockchain and decentralized technologies for secure, tamper-proof data storage. Intelligence for autonomous decision-making is highlighted with references to AI/ML, aiming to reduce human intervention in network operations. Intrinsic security is discussed, covering encryption, privacy, and trust mechanisms, underscoring the need for built-in security in 6G networks. The document also emphasizes quantum technologies, including quantum computing and communication, as key components of future 6G advancements. Notwithstanding its extensive discourse on 6G enabling technologies, the article refrains from proposing a complete 6G architectural framework.

Habibi et al. [46] analyzed pivotal enabling technologies for 6G network slicing, accentuating several critical components essential to the evolution of next-generation networks. The work introduced a novel architectural framework for network slicing in 6G, incorporating new enablers and disruptive concepts such as open, intelligent, and E2E slicing frameworks independent of previous cellular generations. It extensively discussed digital communications, network architecture, and connectivity, highlighting their critical role in 6G. The article emphasized software's role in 6G, particularly in network management and orchestration, citing softwarization, virtualization, slicing, and edge computing. The integration of autonomous decision-making mechanisms and intelligent systems is also prominently highlighted. Security is another critical area addressed. While the document acknowledges the relevance of energy efficiency, IoT sensing and actuating, and immutability through blockchain and decentralized technologies, these aspects are considered secondary. Quantum technologies are minimally mentioned, indicating they are not a primary focus.

Ioannou et al. [47] explored several key enablers for 6G technologies. The manuscript delineates a distributed artificial intelligence architecture incorporating belief-desire-intention agents augmented with ML capabilities. The article discussed energy-related topics, particularly battery technology and energy efficiency. The article touched on IoT and related technologies. Digital communications is a major focus, highlighted by detailed discussions on device-to-device (D2D) communication, network structures, and connectivity solutions. Furthermore, the role of software in 6G is reflected in the coverage of edge computing and software controllers. Immutability is explored superficially. The article places significant emphasis on intelligence for autonomous decision-making. Security measures and protocols are explored. However, there is no substantial mention of evolving quantum technologies.

Another related study was conducted by Jahid et al. [48]. The article provided a DLT-based resource management framework integrating IoT, computing, services, and D2D communications. The article emphasized sustainable energy solutions, underscoring the importance of dynamic resource allocation and wireless power transfer. The critical role of IoT is highlighted through extensive discussions on massive machine-type communications and sensor integration. Digital communications are foundational, focusing on ultra-dense networks and resource allocation. The shift towards software-centric approaches is clear, with significant emphasis on cloud computing, edge computing, and network slicing. Immutability and decentralized architectures are prominently emphasized, particularly through the application of blockchain technology, which is anticipated to significantly enhance the security and transparency of operations. The article also underscores the transformative potential of AI and ML in network optimization and autonomous decision-making. Security is paramount, with robust discussions on secure communications and identity management. Lastly, the evolving role of quantum technologies, particularly quantum communication and quantum key distribution, is acknowledged as a pivotal component for future 6G networks. While the article delineates various key integration components, it lacks a cohesive, unified architecture that comprehensively synthesizes all the discussed elements. This precise aspect delineates the distinctiveness of our research in comparison to existing studies.

The final study under our examination was that of Corici et al. [49]. This work focused on advancing the research vision of software-centric 6G networks. The article emphasizes a system-level perspective, addressing the need for a coherent, E2E understanding of future core networks and their infrastructures. The proposed architecture significantly emphasizes digital communications for connectivity, with extensive discussions on RAN, spectrum management, and mobility. Softwarization is also a major theme, highlighted by the roles of virtualization, SDN, network functions virtualization (NFV), and cloud technologies in managing and optimizing networks. Intelligence for autonomous decision-making is heavily emphasized, with frequent references to AI and ML for automating network management and decision-making processes. While energy efficiency, IoT sensing and actuating, and security were moderately discussed, immutability and evolving quantum technologies received less attention. The document underscores the importance of software-centric and AI-driven advancements in the development of 6G.

We draw some conclusions based on Table 1 and the related work presented. Regarding the depth levels of the architecture, all related work met the requirements of ADL1 and ADL3, as the selection method for these articles was defined considering emerging and disruptive proposals based on 6G enabling technologies. Regarding ADL2, some architectures did not specify a detailed organizational structure, representing an overall illustration or a specific role of the proposal. However, a discussion about how to integrate its components is still needed. About ADL4, some proposals considered just a specific set of applications and guided the design to meet them, although some work provided an architecture focusing on 6G applications in general. In ADL5, we argue that the synergy between other ADLs is not often sufficiently detailed.

Concerning the main 6G enablers' families, we can observe in Table 1 that most of the architectures surveyed support technological enablers related to sensing and actuation, communication, softwarization, and intelligence roles in 6G. However, key roles of energy, immutability, security, and quantum must be more discussed and integrated into emerging 6G architectures. Moreover, we highlight that any new architectural designs must consider the need for technologies to fulfill the essential functions and requirements of 6G. Finally, Table 1 shows that although some of the most advanced proposals have been presented, the authors are ranked with high architectural depth levels. There are limitations related to the support of enabling technologies, coverage, and discussion of the overall 6G structure, as they usually focus on specific network components.

Telecommunications among unmanned aerial vehicles (UAVs) have gained significant attention due to advancements in wireless technology, cost-effective equipment, and networking communication techniques. Ali H. Wheeb et al. [51] presented a comprehensive review that covered various aspects of UAV networks, including communication links, mobility models, and research issues, focusing on topology-based routing protocols and future research challenges. In another, Ali H. Wheeb et al. [52] evaluated the Optimized Link State Routing (OLSR) protocol and its enhanced versions (D-OLSR, ML-OLSR, P-OLSR) for UAV ad hoc networks, particularly in search and rescue (SAR) missions, highlighting ML-OLSR's superior performance in terms of packet delivery ratio, latency, energy consumption, and throughput. Additionally, Naser, Marwa, and Ali H. Wheeb [53] presented a performance of the Gauss Markov (GM) and Random Waypoint mobility models in multi-UAV networks for SAR scenarios, indicating that the GM model offers the highest packet delivery ratio and lowest latency under high mobility conditions. The D6G architecture addresses similar challenges in UAV communications by integrating advanced enabling technologies. The D6G framework enhances UAV networks' flexibility, security, and efficiency by incorporating decentralized AI, digital twins, and smart contracts.

The proposed architecture in this work covers all ADLs at an adequate high-depth level, focusing on network components, 6G design principles, and their respective enablers responsible for the entire network operation. Therefore, our proposal outperforms the state-of-the-art regarding architectural depth levels and different assumptions detailed in Section 4. Our proposal is the only one that integrates AI-driven design with DTs and the digital market, incorporating functionalities for green tech, IoT, digital communications, softwarization, security, immutability, and quantum technologies.

## 3. Positioning 6G enablers

We positioned the 6G enablers in three strata as illustrated in Figure 1: (i) physical (hardware), (ii) abstraction (virtualization) and middleware, and (iii) services (software). Moreover, we highlight some use cases that 6G enablers can serve. This positioning is based on the related work performed, addressing the limitations of current and previous generations of mobile communications and introducing new capabilities that these generations are not designed to handle. The disruptive nature of this positioning is intentional in incorporating technological advancements that enhance the functionalities of the 6G architecture, creating an open, AI-driven digital market.

To make it easier to understand, we will introduce the eight 6G enabler families defined in Table 1 that are part of the proposed architecture. Each enabler is identified by the name X.Y, where X represents the family (X = 1, 2, 3...), and Y indicates the specific enabler (Y = A, B, C...) of a particular family X. Moreover, the 6G enabler families are distinguished by color, while the individual enablers are marked with letters. For example, 1.A is the first enabler A of family 1. This enabler is associated with energy harvesting technology.

In the physical stratum of Figure 1, various devices support all the physical and virtual functions of 6G. It is worth remembering that all the enablers that make up D6G were chosen in previous work of the Brazil 6G Project [50]. We have first energy harvesting (1.A) and green technologies (1.B), meaning that all possibilities for energy collection and optimization must be considered in the architecture. Two IoT enablers (2.A and 2.B) have been considered to sample physical world quantities, such as temperature, battery level, etc. THz communications (3.A) are a consensus in every 6G project. The same happens for ultra MIMO (3.B). Another very common enabler for 6G is intelligent reflecting surface (IRS)/reconfigurable intelligent surface (RIS) (3.C), which allows active signal improvement using AI. One possibility that is essential for the architecture to enable is cell-free operation (3.D).

The support for visible light communications (VLC) is also a choice we made [50] (3.E). In the same idea as allowing more topological flexibility, support for direct D2D communication is also a

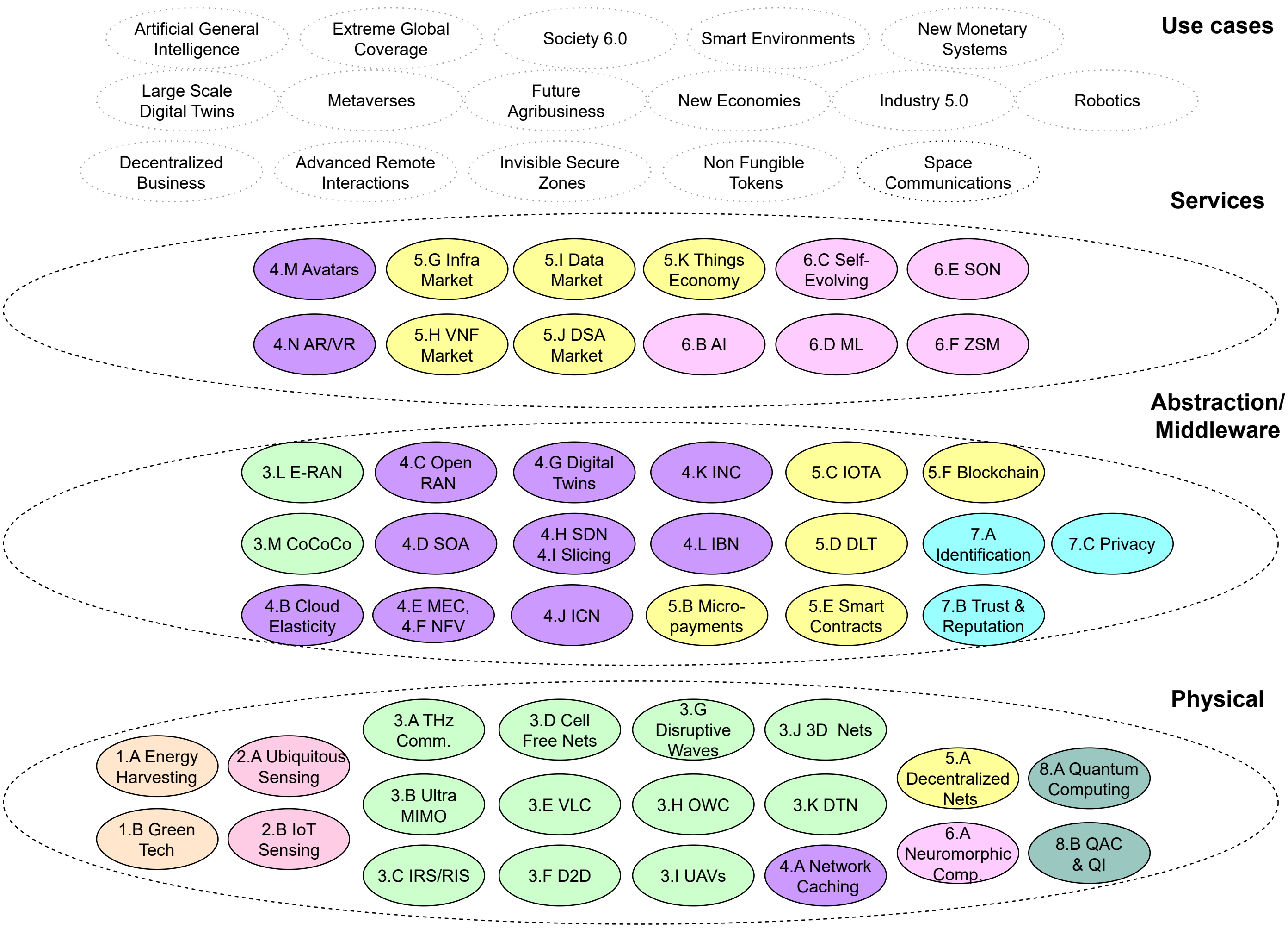



Figure 1: Positioning of 6G enablers and use cases in the architectural strata.

demand to be met (3.F). D6G must also accommodate disruptive waveforms (3.G), optical wireless communications (OWC) (3.H), and communication to unmanned aerial vehicle (UAV) (3.I) to form 3D networks (3.J). As the IoT strengthens, more and more devices will have intermittent connectivity. Therefore, D6G must accommodate delay tolerant network (DTN) (3.K). Network caching for temporary storage of content in the network is another technology selected for D6G (4.A). Moreover, D6G should be a decentralized network architecture (5.A), aligned with recent developments in DLT. Support for AI in hardware using neuromorphic computing (6.A) is another demand from D6G.

Figure 1 also introduces quantum computing (QC) (8.A) hardware that can be integrated with traditional and neuromorphic computing to optimize the solutions to problems through quantum-assisted communication (QAC). D6G is even considered to work with quantum applications running in quantum Internet (QI) (8.B). This integration already exists today, and we envision scenarios where quantum applications are added to traditional ones.

What is expected from a 6G architecture is that it includes most devices that exist today and accommodates new devices that will emerge by 2040. D6G offers conditions for having and connecting these devices in a flexible, programmable, and shared way. These hardware advances go beyond the capabilities of existing mobile communication generations, enabling improved energy efficiency, data processing, and exchange. In particular, incorporating neuromorphic and QC devices will allow the handling of advanced ML and AI algorithms, overcoming the limitations of conventional processing.

In the abstraction and middleware stratum of Figure 1, an enabler that extends open source RAN (OpenRAN) towards horizontal (physical) and vertical (virtual) elasticity is elastic RAN (E-RAN) (3.L). Applying this technique in the RAN scope is another case of communication, computing, control convergence (CoCoCo Convergence) (3.M), which D6G aims to generalize. In this context, cloud elasticity (4.B) algorithms must deal dynamically with computing demand variations. An example is the support for the data center portion of OpenRAN (4.C). The computational load of the OpenRAN components depends on the time of day, days of the week, occurrence of events, etc. The accommodation of computing resources to meet these demands is required for D6G. In general, D6G can be seen as service-oriented architecture (SOA) (4.D). Accommodating the life cycle of network functions on the edge (4.E) with multi-access edge computing (MEC) and in the core (4.F) with NFV is another demand to be met. D6G must handle the creation of DTs (4.G) for all physical components of the architecture.

Programming physical entities is also a highly desirable enablement for D6G. In this context, two enablers have been selected: SDN (4.H) and network slicing (NS) (4.I). Three other enablers related to disruptive networks were also included in the list. The information centric networking (ICN) (4.J) consists of distributing content by name, using temporary storage on the network (4.A), and deliveries that allow node mobility. The in-network computing (INC) (4.K) utilizes programmable network elements to perform route calculations before traffic reaches the edge or cloud servers. Finally, IBN (4.L) aims to improve expressiveness in networking. D6G intends to support these new approaches as virtual networks at first.

Another disruption that D6G aims to support is the digital monetization of the entire 6G architecture to support micropayments (5.B). In this context, IOTA (5.C) is a DLT (5.D) that supports digital payments in a decentralized way. Support for digital smart contracts (5.E) that offer deterministic computing associated with digital payments is another essential pillar of D6G. This feature is supported today in several blockchains (5.F). All of these features extend traditional security support, including identification (7.A), trust and reputation (7.B), and privacy (7.C).

In the abstraction and middleware stratum of Figure 1, there are several functions that: virtualize components (4.B, 4.C, 4.E, 4.F, 4.I, 5.E), slice physical and virtual resources (4.C, 4.H, 4.I), represent the physical (4.G), control the physical (4.E, 4.F, 4.G, 4.H, 4.I), offload traffic (3.L, 4.C, 4.J, 4.K), protect data (7.A-C, 5B-F), optimize (3.L, 4.C, 4.H, 4.I), converge controls (4.G, 4.H, 4.I) and digitally monetize assets (5.B-F). These functionalities offer unprecedented flexibility and control in resource allocation, sharing, monetization, data protection, and traffic management. This advanced level of virtualization, digital monetization, and control cannot be achieved with existing mobile communication systems.

The service stratum of Figure 1, supported by the abstraction and middleware stratum, encompasses human avatars (4.M) and augmented and virtual realities (AR/VR) (4.N) for interaction in the metaverse and augmented physical reality. Using DLT (5.D), several digital markets can be created for physical infrastructure (5.G), virtual network functions (VNFs) (5.H), data (5.I), dynamic spectrum access (DSA) (5.J), and things (5.K). AI (6.B) is integrated into these markets and metaverses to enable decision-making. Based on these resources, SEN can allow market-driven evolution (6.C). Moreover, ML is present (6.D) together with SON (6.E) and ZSM (6.F) to reduce human interference in operation.

This service stratum has support to create new realities (4.N), represent humans and reduce human interference (4.M, 6.B-F), and monetize assets creating new markets (5.G-K), self-organize and represent resources with context awareness (6.E), self-evolve (6.C), learn (6.B, 6.D), and optimize (6.A-F). Integration of advanced digitally monetized AI capabilities at the service level to empower the creation of new realities, the representation of humans, and self-learning signifies a major evolution beyond the capabilities of current mobile networks, fostering a new generation of advanced applications and services.

Finally, the upper portion of Figure 1 contains some cases of 6G use. Some are already well accepted in the community, such as agribusiness, advanced remote interactions (with drones or other far-end devices), large-scale DTs, intelligent environments, invisible secure zones, robotics, extreme global coverage, and space communications. Others are emerging, such as metaverses, decentralized business and ecosystems, society 6.0, industry 5.0, new economies, new monetary systems, non-fungible tokens (NFTs), artificial general intelligence (AGI) [54]. These use cases help us to illustrate the purposes of D6G. These emerging use cases signify the scope and potential impact of the proposed architecture in various sectors presented in the next section. Current communication technologies do not adequately serve these scenarios, underscoring the necessity of the innovations introduced in our proposal.

## 4. Disruptive 6G Architecture

This section presents the D6G architecture. The way enablers are integrated into the architecture is disruptive, without regard for maintaining compatibility with current and previous generations of mobile communications. The architecture has three strata, as shown in Figure 2, and 6G enablers are positioned following the previous Section 3. The Physical Stratum encompasses infrastructure enablers exposed to the software level through an intermediate Abstraction/Middleware Stratum. The physical infrastructure comprises devices, from antennas and fiber optics to data centers and satellites. Abstraction/Middleware Stratum supports software platforms and virtualization solutions such as hypervisors and container environments. The systems that enable the virtualization of physical resources and create cyber-infrastructure are in this stratum. A Service Stratum contains a decentralized services store comprising a digital market of VNFs implemented as smart contracts, including DTs. These services are dynamically coordinated to meet all use case requirements from all entities, including users, infrastructure, and service providers. Moreover, smart contracts run inside virtual machines (VMs) or containers.

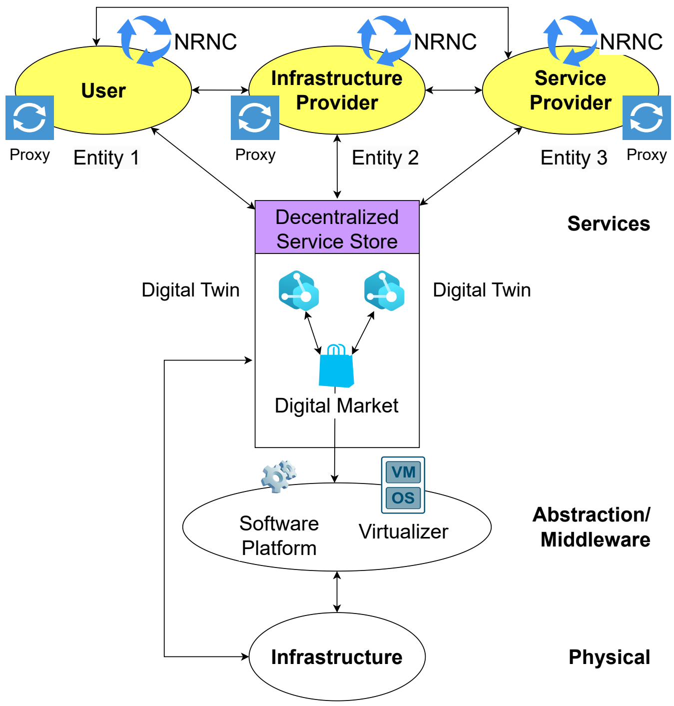



Figure 2: D6G architecture overview.

The digital market implements DTs as smart contracts, allowing dynamic contracting of physical/virtual resources. DTs reflect what each slice needs in their mirror features, and new services are allocated upon monetization. Based on decentralized service stores, services from several actors can be instantiated and integrated into DTs. For example, in Figure 2, three 6G entities are illustrated in the Service Stratum: (i) an end user of 6G, (ii) an infrastructure provider, and (iii) a Service Provider. End users will need services running as smart contracts in the decentralized service store, which the service provider hosts. In turn, the service provider demands many virtual cyber-infrastructure resources that the infrastructure provider offers as smart contracts. VNFs can be found and executed as smart contracts or codes called from them on the digital market. All 6G functions can be implemented this way, and the relationships between these three entities occur via purchase and sale on the digital market.

A name resolution and network caching (NRNC) service allows the presentation and discovery of resources, services, and interfaces using common communication languages between entities [12]. Both names and links between names and objects that describe entities (descriptors) can be employed. These descriptors include a definition of smart contracts as well. In Figure 2, the name resolution systems of different domains are connected according to the policies established by its representative, i.e., a *proxy* service. NRNC is essential throughout the 6G entity lifecycle since many lifecycle actions are related to their names and descriptors, a matter of language. Discovering well-known services by their names in a domain or across domains through authentication/authorization is necessary to automate several procedures, from *bootstrapping* to shutdown.

Representative proxy services can autonomously use NRNCs to discover existing physical or virtual entities by looking at the entity's point of view. AI can use these identifiers, locators, descriptors, and configuration files as *inputs* to neural networks or other AI/ML techniques. That is, the naming system provides inputs for decision-making, combined with requests made by the *proxy*, resulting in action plans/configurations to be executed on services and physical counterparts via DTs. Information from previous smart contract experiences can also be used when selecting new contracts. These contracts can even be considered in decision-making involving current and historical information from digital markets as input. This new model is centered on facilitating decentralized orchestration rather than centralized command and control solutions. Consensual agreements must be respected among participants in the 6G digital markets for stability.

In this context, the greatest asset in D6G will be knowledge of properly creating and serving the best slices for use cases, that is, AI and human accompaniment, while making optimal and custom slices. When the slice is no longer needed (timeout or service termination), the contracts are terminated, and the resources released. The proposed solution offers a new level of dynamism, autonomy, and resource optimization beyond the capabilities of existing architectures. We can create highly customized services that adapt to user needs in real-time using AI and DTs. This adaptation is not possible with current technologies, further justifying the disruptive approach of the D6G architecture.

Digital monetization of D6G is critical for several reasons. This monetization type allows the automation of transactions, making trading physical and virtual resources more efficient and autonomous. Furthermore, this automation can enhance the ability to meet user demand dynamically. Digital monetization could also enable the creation of new markets, such as infrastructure resource-sharing markets, opening up new revenue opportunities and helping to overcome return-on-investment challenges. Moreover, digital monetization may facilitate a broader range of participants in the ecosystem, from individuals to small businesses, improving accessibility and inclusivity. Open markets promote innovation and competition, improve consumer choice, and drive technological advancements instead of monolithic solutions from a single manufacturer that may limit diversity, hinder innovation, and create vendor lock-in scenarios.

Immutability and the ability to enable smart contracts are also pivotal aspects of the digital monetization approach adopted in D6G. Immutability is essential to ensure the reliability and transparency of transactions. Once a transaction is recorded, it cannot be altered, creating trust among participants and preventing disputes. Smart contracts are protocols that facilitate, verify, and enforce the negotiation of a digital contract. These contracts allow the automatic execution of transactions and agreements without intermediaries, increasing efficiency and securely reducing human intervention. Furthermore, smart contracts can be programmed to respond dynamically to different conditions and contexts, which is key for dynamic negotiating physical/virtual resources within the D6G architecture context. We discuss each stratum of D6G architecture in the following sections.

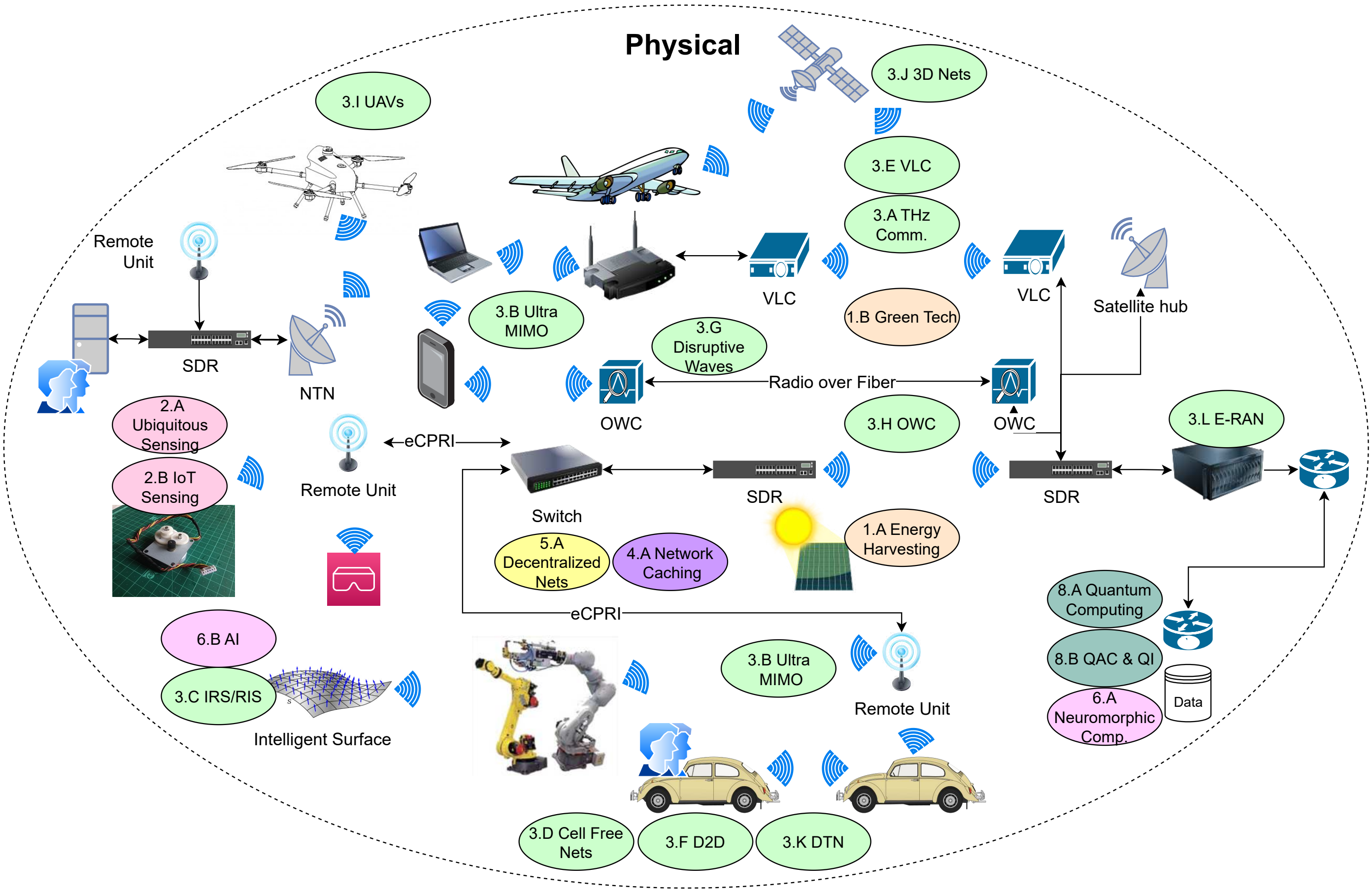



Figure 3: D6G physical stratum.

### *4.1. Physical Stratum*

Figure 2 presents a physical stratum illustration for D6G. This vision contrasts with the one initially presented in this section, demonstrating how the components are incorporated into the architecture and operate together. From Figure 3 and the results in the previous sections, we have the following components in the physical layer: (i) energy collectors; (ii) sensors and actuators; (iii) protocol *gateways* (IoT and others); (iv) computers of all kinds; (v) data storage devices; (vi) network devices - switches, routers, access points; (vii) photonic devices; (viii) OWC and VLC devices; (ix) smartphones; (x) vehicles of all types (boats, planes, cars, buses); (xi) remote radio units; (xii) *data centers* (edge, regional, metropolitan, national, international); (xiii) UAVs (*drones*, balloons); (xiv) satellites (geostationary orbit (GEO), medium earth orbit (MEO), low earth orbit (LEO); (xv) smart surfaces; (xvi) augmented reality devices (glasses, holography); (xvii) robots; and (xviii) software defined radio (SDR). A wireless network interconnects these components in different frequency bands. Satellite terminals are connected using a high-end computer and an SDR, able to service remote or poorly served areas easily. Sensors, actuators, robots, intelligent surfaces, and other IoT devices are connected through *gateways*, *access points*, OWC, and even VLC.

Ground vehicles can connect in ad hoc networks (with D2D *communication*) or via satellite. At the edge of the access network, servers are used to process, store, and exchange information. The switches provide programmable multi-protocol connectivity via P4. Remote units are connected wirelessly or over fiber optics, supporting VLC and OWC (including *Radio over Fiber*). Remote units implement the entire radio frequency (RF) part and the lower part of physical layer (PHY). In the aggregation portion of the network, modulated optical signals are converted back to RF for processing in SDR or server. Servers can perform high PHY processing, including multi-cell cooperative techniques.

A satellite *hub* receives signals from the satellite and forwards them for processing in SDR and server. The same applies to the VLC and OWC connections. Direct communication between SDRs (at the edge and aggregation) is also possible and desirable. At the core of the network, high-capacity servers support several enablers. Communication between aggregation and core servers occurs under TCP/IP routers. However, other protocol architectures could be used, such as NovaGenesis [12, 29, 30]. The hosting of virtual functions can occur in access, aggregation, and core. Balloons, airplanes, *drones* and other UAVs add the 3D characteristic to 6G.

### *4.2. Abstraction/Middleware Stratum*

Figure 4 shows the abstraction/*middleware* stratum. We have the following components that use the previously selected enablers: (i) **Legacy Controllers** - implement controllers of all types, i.e., SDN, open RAN (O-RAN), 5G core (5GC), any 5G technology controller or earlier; (ii) **Legacy Managers** - they operate according to imperative resource management without autonomic computing. Traditional management protocols, for example, simple network management protocol (SNMP) or network configuration protocol/yet another next generation (NETCONF/YANG) are used. Legacy managers interact with service layer components; (iii) **Virtualizers** - hypervisors and container environments control the infrastructure resources for virtualization. Physical network resources are virtualized through programmable cutting equipment. Virtual switches can be implemented as VNFs in the services stratum, supported by physical network slices. Virtualizers also include the management of physical resources in which virtualization is carried out. For example, the scope of virtualized infrastructure manager (VIM)[1], life-cycle will be used to instantiate virtual functions from NFV, such as *OpenStack*; (iv) **Software platforms** - the service-based architecture demands the support of platforms to perform various abstraction and *middleware* functions.

[1]VIM is a component of the NFV architecture responsible for managing physical and virtualized resources.

The main component of this stratum is the virtualizer, as illustrated in Figure 2. It supports the virtualization of physical resources, as well as *middleware* needed for VMs, containers, and *unikernels*. Representatives can describe traditional software platforms in the 6G service ecosystem. SDN drivers (*OpenFlow*, P4, *Stratum* and other current technologies) may still be needed in the context of 6G. However, with the decentralization of DTs in conjunction with DLTs, a market for control services is also decentralized. Legacy controllers can participate in this market, executing commands through network control protocols. Similarly, the traditional management plane (e.g., SNMP) can also be inserted as legacy network management services. Finally, we have several software platforms needed to support DLTs, digital markets, security, micropayments, slicing, temporary storage, new realities (augmented reality (AR)/virtual reality (VR)), and service orientation.

### *4.3. Service Stratum*

Finally, the service stratum encompasses several innovative and legacy services, which co-exist through open digital markets, relying on *middleware* platforms and virtualizers from the stratum below. Each actor plays a vital role in creating a dynamic, functional environment that supports innovative and legacy services within open digital markets. The virtual functions are crucial for executing necessary information processing, storage, and exchange, providing resource, capability, and availability exposure functions. Other components that will be described below, such as name resolution and network caching, DTs, Autopilots, Assistants, Representatives (Proxies), Facilitators, Digital Markets, Wallets, and Avatars, collaborate to implement a distributed service architecture. Each actor fulfills distinct roles, from name resolution and temporary storage of popular content to representing individuals and col-

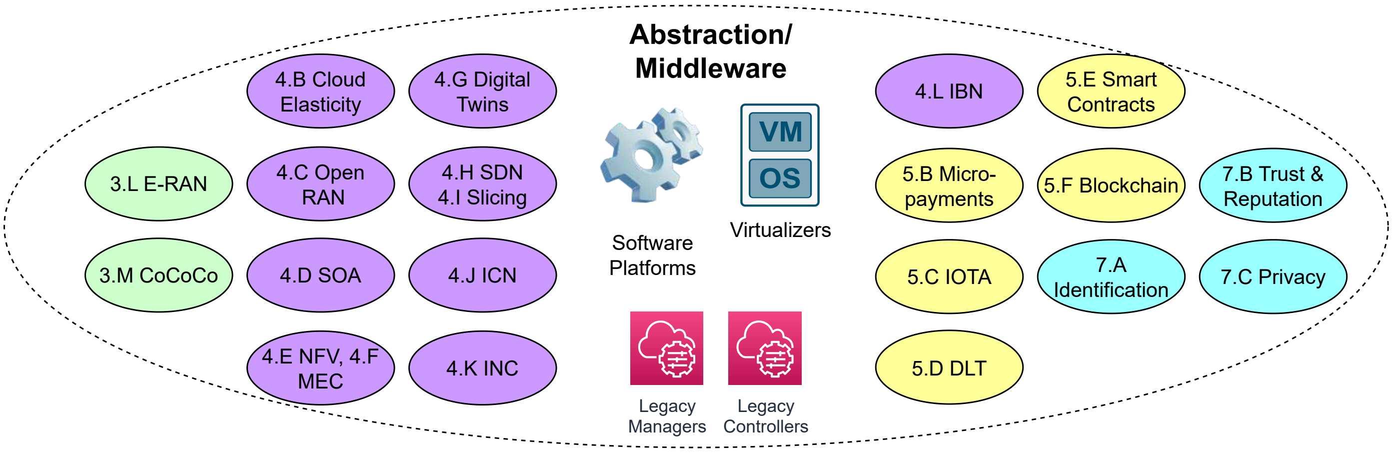



Figure 4: Overview of the abstraction and middleware stratum.

lectives (called entities), facilitating service graph construction, managing digital markets, processing payments, and enabling interaction in alternate realities.

The importance of these actors stems from their combined ability to enable interoperability, efficiency, loose coupling, and functionality, thus facilitating the support necessary for the complexity of the service environment. Without these components, the operations and transactions essential for functioning within the open digital markets would be inefficient or impossible. Therefore, these actors represent key pillars within the Service Stratum, contributing to a comprehensive and modular architecture design. Below is a discussion of these services and their value to the D6G architecture. Figure 5 illustrates the service structure of a certain entity in D6G. The concept is that entities from infrastructure, service, and content providers use the same structure to enable service life cycling. Even users can adhere to the same pattern, as they will have the same services at home.

VNFs implement all information processing, storage, and exchange functions as web services (decentralized in DLT as smart contracts). Moreover, VNFs perform resource/capabilities/availability exposure (for directory services). These functions expose names to the name resolver and discover possible partners for dynamic service graph composition. Virtual functions can search for potential service-

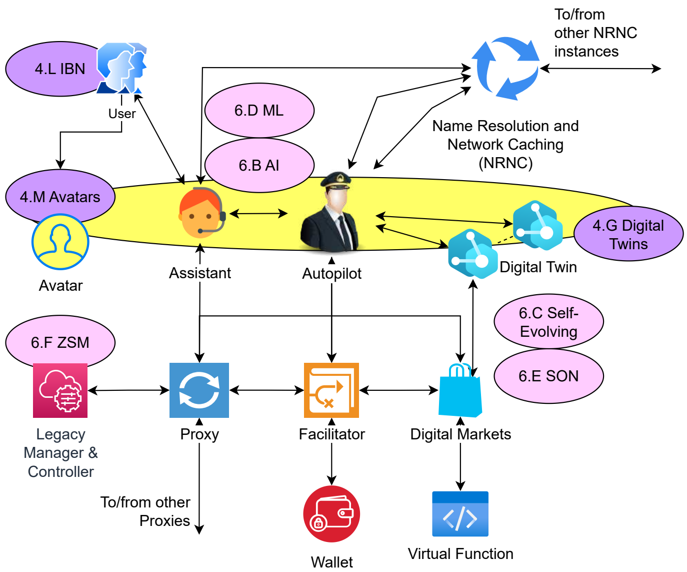



Figure 5: General view of entity structure with a user, an operator, or a service provider.

level agreements (legacy) or selection/adjustment in smart contracts (novel approach). These functions use facilitators to find possible service graphs to which they can connect. Hiring can be done directly between VNFs or representative services (proxies). VNFs can be implemented and activated by smart contracts and may have other programs that only process through DLT.

**Name Resolution and Network Caching** is a VNF that stores relationships between names. It also integrates a network cache for the temporary storage of popular content. Caches can store information (names, identifiers, descriptors, possible smart contracts) of physical resources, services, interfaces, and firmware. Such an approach follows the NovaGenesis design [12].

**DTs** represent everything that is physical and cannot be virtualized. DTs must control all types of resources, imperatively from contracts formed with other services. Moreover, DTs implement controllers of all kinds, SDN, O-RAN, 5GC, etc. That is, representatives are also controllers of the represented.

**Autopilots** are trained AI algorithms that run in high-level programming languages (high energy fingerprints) or are embedded in neuromorphic computers (low energy fingerprints). Autopilots can be integrated into autonomic computing, allowing for both ML and trial and error algorithms. Autopilots also act in decision-making in a domain or organization. Moreover, autopilots optimize and configure contracted resources and services, interacting with name resolutions and facilitators to determine the best opportunities in digital markets. When established contracts are in effect, autopilots interact with DTs to reflect in the physical world decisions about contracts in the digital markets.

**Assistants** are representatives of individuals, differing from representatives of organizations or collectives. These individuals are called *proxies* and are implemented as VNFs. Assistants are enhanced versions of current systems such as *Apple Siri*, *Alexa*, and *ChatGPT*.

**Representatives (Proxies)** represent collectives, such as people living in residences, buildings, condominiums, companies, operators, among others. Representatives store policies, preferences, contract models, and intentions, among other important information for contracting 6G services. According to organizational policy, representatives receive demands from assistants in a certain domain and proceed with the hiring or releasing resources and services. Representative proxies are also implemented as VNFs. Legacy domain *middleware* platforms can also be represented by auxiliary instances of this component, e.g., for NFV, DLT.

**Facilitators** receive demands for 6G slices and facilitate the construction of service graphs for them. Facilitators assemble and return suggestions of possible service graphs from what exists in decentralized markets or legacy service directories. Moreover, facilitators hire VNFs in the markets to implement slices, facilitating the discovery of existing *smart contracts*, their characteristics and clauses, among other aspects. Facilitators can be employed not only in digital markets but also in other applications.

**Digital Markets** offer various implementations of VNFs, including previous generation components (4G, 5G). In practice, markets can be supported through environments with DLTs and *smart contracts*, or even traditional *cloud* environments (no immutability and, therefore, less secure). Markets form real stores, where facilitators, representatives, autopilots, among other components, can fetch, contract, and sell resources (such as physical things, electromagnetic spectrum, physical networks, antennas, towers, edge *sites*,) and services. The dynamic composition is not limited to a single market (closed or open); stores from traditional suppliers can also be integrated.

**Wallets** for digital money are required to pay for resources and services. Facilitators need digital wallets when hiring material or VNFs when forming service graphs. 6G will encompass an open market formed by all existing players, and payments are a requirement in any market.

**Avatars** are virtual objects that allow a person to interact in other realities. Avatars differ from assistants since they do not represent people in their absence. Avatars are the presence of biological persons themselves in different realities. A requirement to achieve the desired metaverse application.

## 5. Multiple drone connectivity: advanced 6G remote interactions use case

We employ advanced remote interactions through a drone connectivity use case, shown in Figure 6, to illustrate the high-level functionality of the D6G architecture. This particular use case, as elaborated in Section 3, exemplifies one of the primary application scenarios to maintain sophisticated remote interactions with devices sit-

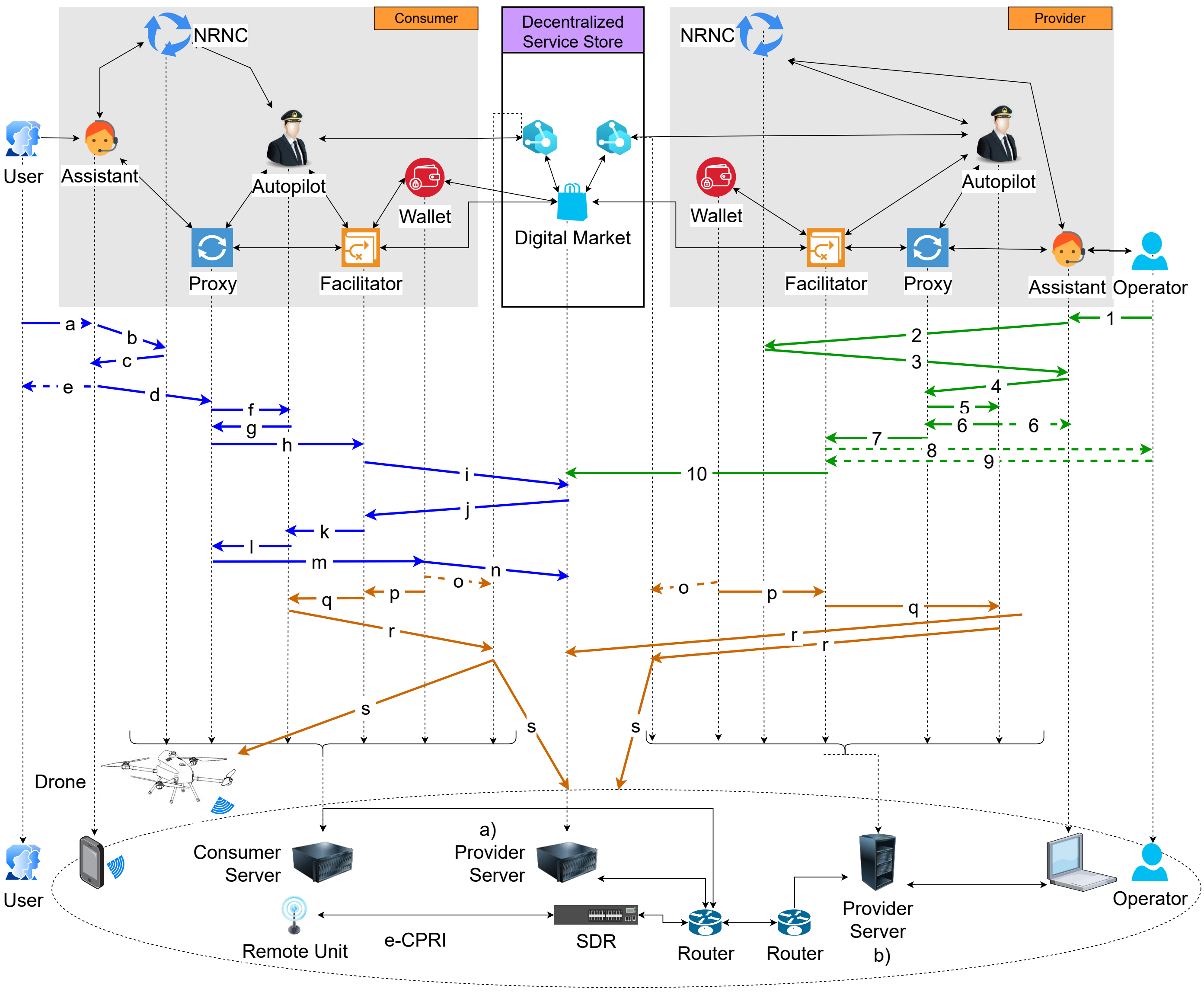



Figure 6: Sequence diagram for the 6G use case for three drone connectivity in a small city. Entity N has a drone that D6G will provide with connectivity and services. In this use case, N = 3, i.e., three users have each drone to be served.

uated at considerable distances from users. This use case is representative of the possibilities of 6G since it involves DTs, AI, and digital asset monetization. The bottom of the figure illustrates the physical devices that host the above software. Users (consumers) use smartphones to connect to a remote radio unit. The same happens with the drone. Through the RAN implemented by an evolved common public radio interface (eCPRI), access is provided to the consumer's server. The provider has two servers: a) one in the middle of the figure allocated to run DLT nodes, therefore supporting digital market components; b) a server to run the other components of D6G at the middleware and service stratum. A human operator uses a laptop to interact with a digital assistant. Facilitating efficient and effective communication between drones and/or users represents one of the most compelling and innovative use cases of 6G technology, as examined by Jiang et al. [55], Bajracharya et al. [56], and Wang et al. [57].

Three drone enthusiasts (consumers) want to create a temporary 2-day event in a small city served by an infrastructure and services provider. A consumer is illustrated in the left portion of Figure 6. Like this consumer, service providers also have human operators (professionals in this case) and their assistants, as illustrated on the right side of the figure. The provider must first register smart contracts in the digital market (in the middle of the figure) to make such a scenario possible.

The process is started by a human operator (1) who talks or sends text messages to his assistant. The operator wants a 6G connectivity service for drones by employing an SDR-based eCPRI fronthaul. The assistant queries (2) the operator's NRNC about existing devices, networks, software platforms, and virtualized infrastructures to support such a scenario. The NRNC delivers information about such resources (3). The assistant sends a query to the provider proxy (4) to deploy the service according to the provider's policies. The proxy consults the domain autopilot to check if some smart contracts have already been deployed (5). If some already registered smart contract can fit the demand, the autopilot indicates its name to the proxy (6). Otherwise, autopilot informs that a new smart contract should be developed (also in 6). The results return not only to the proxy but also to the assistant, which reports the status for the human operator.

The proxy requests that the facilitator proceed (7) when a new smart contract needs to be developed and registered on the digital market. The facilitator creates new smart contracts based on the query, policies, and wallet information, using AI, e.g., ChatGPT or similar tools can synthesize a smart contract to perform such a task. The result is sent back (8) to the user for improvements, testing, and final development. The final version proceeds through the facilitator for registration in the digital market (9 and 10). The dotted lines in Figure 6 indicate that some step can be repeated a few times until it is completed. All the smart contracts required to implement the 6G connectivity service for drones are registered and ready to run. It is essential to observe that the registered smart contracts will run when monetized by a client. The virtual functions required to form the service graph of such slices will run after contract monetization.

All weekend event participants want to control their drones through a 6G operator that provides infrastructure and services. These participants want to take pictures, record drone videos, share media, and post them on social networks. Each drone has a DT that runs separately in each user's domain. On the eve of the event, all owners ask their assistants using natural language for a slice of the 6G network to use their drones (a). The assistant communicates through chat or voice recognition with users, sending a request to the local NRNC to fetch the name of the domain proxy (b). After receiving this data (c), the assistant sends a request to its domain representative (proxy) to meet the demand (d). The representative is, in fact, responsible for solving the problem, while the assistant's primary role is to understand and report what is happening (e). Similarly, the dotted lines indicate that some step can be repeated several times and is not shown in the figure so as not to impair understanding.

The proxy checks the autopilot to see if something similar has been done before (f). If so, it uses information from a previous solution to hire entities again through a facilitator (not shown in Figure 6). If this slice has never been assembled before (g), with similar or identical characteristics, the proxy triggers the facilitator (h) to find possibilities for contracts that can meet the demand. The facilitator queries (i) smart contracts from the digital market and provides contracting options to the facilitator (j). The facilitator informs the autopilot about option (k), which decides and informs the proxy (l). The facilitator hires the resources necessary for the slice in the digital markets, including physical resources (compute, storage, and network), critical VNFs, demanded RF spectrum, and so on, using the user wallet function (m and n). In short, a proxy buys portions of shared (or dedicated) resources with a digital wallet in one or more markets.

Note that in this scenario, each user proxy may make different decisions, which result in other contracted slices and which may be better suited to the temporary event problem. Smart contracts, when monetized, reserve resources for the duration of the event. Alternatively, for a time shorter than the duration of the event, according to each participant's decision. Proxy adheres to user preference labels and policies, such as preferred currency for payments, operators, etc.

Once payments are made, smart contracts trigger slice creation at the infra/service provider. The first step is instantiating several DTs in the transaction (o), assuming they are not running before, not only in the client domain but also in the provider. Moreover, the payment drives the updates on the facilitators (p), which inform the autopilots about the new slice (q). Autopilots start to configure DTs in user and provider domains (r). The provider autopilot configures the VNFs started in the digital market by smart contracts (r). DTs forward configurations to respective physical counterparts (s). All necessary configurations are performed to prepare drone traffic in user and provider domains. Observe that DTs on the user side configure drones for this slice. Simultaneously, DTs on the operator side prepare all infrastructure to meet smart contracts' expected experience and quality.

## 6. Modeling and Performance Evaluation

This section discusses the modeling of the DG6 components considering the lifecycle of phyallows usresources and VNFs in Subsection 6.1. Moreover, we analyze the performance evaluation for each DG6 component, investigating the utilization these components have and the communication delays in Subsection 6.2.

### *6.1. Modeling the DG6 components*

We employed Jackson's Theorem with an M/M/1 queuing system for each D6G component [58] to model the 6G drone connectivity use case of Figure 6. Our model focuses on evaluating utilization (how much each component is used) and total delay for two moments in the lifecycle of physical resources and VNFs: (i) deployment via smart contracts and (ii) hiring. In other words, our model concentrates on assessing the extent to which each component is employed and the overall delay during physical resources and VNFs deployment and their further use.

We developed a queuing theory Jackson network (QTJN) tool in Python to compute usage probabilities and performance parameters. Moreover, we defined the mean transaction service rates ($\mu$s) for each component of the D6G architecture. These $\mu$s rates indicate the average service rate that each component processes transactions. All average service rates are expressed as transactions per minute and cover information processing and communication delays. Therefore, the model specifies how many transactions per minute each component can handle and forward to another component following the information flow presented in Figure 7. Each component $i$ can receive traffic external to the network ($\gamma_i$) or internal feedback traffic ($\lambda_i$).

Table 2 summarizes the parameters adopted in the evaluations. Each component has a number (No.) from 1 up to 20. A reference (Ref.) is also adopted for each component, as well as a Name. For example, component No. 3 has reference UNRNC and name user name resolution and network cache (UNRNC). The column External Input details the external traffic that arrives in a certain component. For instance, the external traffic entering the UNRNC component is zero, i.e., $\gamma_{UNRNC}$=0. This means that there is no external traffic to the network that reaches the UNRNC. In fact, only three components receive user external traffic: drone user (U), provider operator (O), and payment execution from provider wallet (PW). They are all used to characterize the demands generated by manual interference in our evaluation scenario. These rates model both requests made by the provider's human operator when deploying smart contracts and final user requests for contracting virtual resources and functions registered in DLT. Only one user has been modeled since the other users in the use case experience the same performance in the 6G model.

The user side in Figure 7 encompasses a user name resolution and network cache (UNRNC), a user proxy (UP), a user autopilot (UAP), a user facilitator (UF), a user wallet (UW), a drone twin (DrT) and a physical drone (D). Table 2 contains all the smart contract usage model values. For each component, the table shows which Output Transaction(s) are leaving the component and the names of the Next Node(s) con-

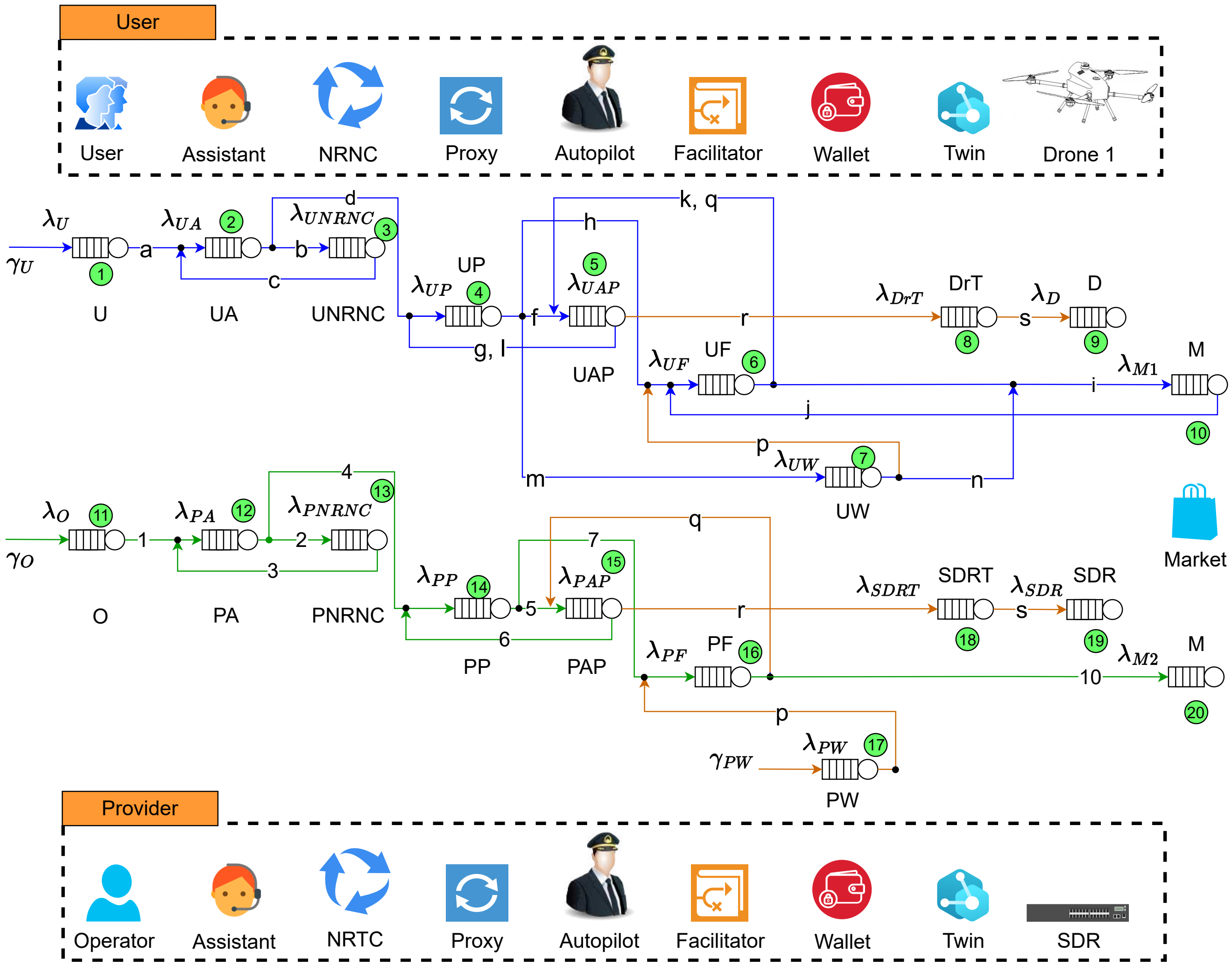



Figure 7: Queuing theory model for 6G drone connectivity use case. Each 6G component is numbered $i = 1$ to 20.

nected. For each component output, an Output Probability ($r_{j,i}$) is associated accordingly to Jackson's Theorem. The provider side comprises a provider name resolution and network cache (PNRNC), a provider proxy (PP), a provider autopilot (PAP), a provider facilitator (PF), a provider wallet (PW), a software-defined radio twin (SDRT), and a physical software-defined radio (SDR).

The model allows calculating the probability that a transaction leaves a certain system and goes to another one. For example, the probability that a transaction leaves the provider wallet (PW) and goes to the provider facilitator (PF) is 100%. Table 2 shows this scenario configuration on line No. 17. All these probabilities were considered in Jackson's network topologies [58]. Equation 1 calculates the effective traffic at each component of the 6G model, i.e., $\lambda_i$, which is the internal arrival rate of each queuing system (node $i$ in Figure 7).

$$\lambda_i = \gamma_i + \sum_{j=1}^{M} r_{j,i}.\lambda_j \qquad (1)$$

where, $\gamma_i$ is the external network traffic at system $i = 1$ to 20, while $r_{j,i}$ is the probability that a certain transaction leaves system $j$ and moves to system $i$. $M$ is the total number of systems in the network, that is, 20 in our scenario.

Applying this equation to all components generates a linear system of equations. Solving this system allows one to determine its internal input rates ($\lambda$s) and all other performance metrics, including system utilization and delays. We can use

Table 2: Queuing theory model for 6G slice building with variables, meanings, and assumed values.

| No. | Ref. | Name | External Input | Internal Input | Output Transaction(s) | Next Node(s) | Outputs Probabilities | Service Rate (Trans/Minute) |
|---|---|---|---|---|---|---|---|---|
| 1 | U | User | $\gamma_U$=0.2 | $\lambda_U$ | $a$ | UA | $r_{1,2}$=1 | $\mu_U$=19 |
| 2 | UA | User Assistant | $\gamma_{UA}$=0 | $\lambda_{UA}$ | $b, d$ | UNRNC, UP | $r_{2,3}$=0.5, $r_{2,4}$=0.5 | $\mu_{UA}$=39 |
| 3 | UNRNC | User NRNC | $\gamma_{UNRNC}$=0 | $\lambda_{UNRNC}$ | $c$ | UA | $r_{3,2}$=1 | $\mu_{UNRNC}$=20 |
| 4 | UP | User Proxy | $\gamma_{UP}$=0 | $\lambda_{UP}$ | $f$, $h$, $m$ | UAP, UF, UW | $r_{4,5}$=0.33, $r_{4,6}$=0.33, $r_{4,7}$=0.33 | $\mu_{UP}$=50 |
| 5 | UAP | User Autopilot | $\gamma_{UAP}$=0 | $\lambda_{UAP}$ | $g$, $l$, $r$ | UP, DrT | $r_{5,8}$=0.5, $r_{5,4}$=0.5 | $\mu_{UAP}$=52 |
| 6 | UF | User Facilitator | $\gamma_{UF}$=0 | $\lambda_{UF}$ | $k$, $q$, $i$ | UAP, M | $r_{6,5}$=0.5, $r_{6,10}$=0.5 | $\mu_{UF}$=49 |
| 7 | UW | User Wallet | $\gamma_{UW}$=0 | $\lambda_{UW}$ | $p$, $n$ | UF, M | $r_{7,6}$=0.5, $r_{7,10}$=0.5 | $\mu_{UW}$=23 |
| 8 | DrT | Drone Twin | $\gamma_{DrT}$=0 | $\lambda_{DrT}$ | $s$ | D | $r_{8,9}$=1 | $\mu_{DrT}$=21 |
| 9 | D | Drone | $\gamma_D$=0 | $\lambda_D$ | - | - | - | $\mu_D$=22 |
| 10/ 20 | M | Market | $\gamma_M$=0 | $\lambda_{M1}$, $\lambda_{M2}$ | $j$ | UF | $r_{10,6}$=1 | $\mu_{M1}$=53, $\mu_{M2}$=50 |
| 11 | O | Operator | $\gamma_O$=1 | $\lambda_O$ | *1* | PA | $r_{11,12}$=1 | $\mu_O$=20 |
| 12 | PA | Provider Assistant | $\gamma_{PA}$=0 | $\lambda_{PA}$ | *2*, *4* | PNRNC, PP | $r_{12,13}$=0.5, $r_{12,14}$=0.5 | $\mu_{PA}$=40 |
| 13 | PNRNC | Provider NRN | $\gamma_{PNRNC}$=0 | $\lambda_{PNRNC}$ | *3* | PA | $r_{13,12}$=1 | $\mu_{PNRNC}$=1000 |
| 14 | PP | Provider Proxy | $\gamma_{PP}$=0 | $\lambda_{PP}$ | *5*, *7* | PAP, PF | $r_{14,15}$=0.5, $r_{14,16}$=0.5 | $\mu_{PP}$=1000 |
| 15 | PAP | Provider Autopilot | $\gamma_{PAP}$=0 | $\lambda_{PAP}$ | *6*, $r$ | SDRT PP, UF | $r_{15,18}$=0.5, $r_{15,14}$=0.5 | $\mu_{PAP}$=1000 |
| 16 | PF | Provider Facilitator | $\gamma_{PF}$=0 | $\lambda_{PF}$ | *6*, *10*, $q$ | PAP, M | $r_{16,15}$=0.5, $r_{16,20}$=0.5 | $\mu_{PF}$=500 |
| 17 | PW | Provider Wallet | $\gamma_{PW}$=2 | $\lambda_{PW}$=0 | $p$ | PF | $r_{17,16}$=1 | $\mu_{PW}$=200 |
| 18 | SDRT | SDR Twin | $\gamma_{SDRT}$=0 | $\lambda_{SDRT}$ | $s$ | SDR | $r_{18,19}$=1 | $\mu_{SDR}$=20 |
| 19 | SDR | SDR | $\gamma_{SDR}$=0 | $\lambda_{SDR}$ | - | - | - | $\mu_{SDR}$=30 |

the number of feedbacks provided in Figure 6 to model the required transactions and to estimate the total delay for an operator to deploy a smart contract in the digital market. This procedure involves nodes 11 through 20 in this figure. In this case, Equation 2 provides total delay for a smart contract deployment.

$$E\{T_{TotalD}\} = E\{tq_O\} + 2.E\{tq_{PA}\} + E\{tq_{PNRNC}\} + 2.E\{tq_{PP}\} + 2.E\{tq_{PAP}\} + 3.E\{tq_{PF}\} + E\{tq_{PW}\} + E\{tq_M\} + E\{tq_{SDRT}\} + E\{tq_{SDR}\} \quad (2)$$

This equation calculates the expected total delay for deploying a smart contract in a 6G network. This delay includes the time transactions pass through various network components. Each term in the equation represents the expected queuing time at a specific component in the network, and the coefficients indicate the number of times a transaction is expected to pass through that component. Here's a breakdown of each term in the equation:

- $E\{tq_O\}$: The expected mean delay at the operator node (O). This node is responsible for initiating the deployment process.

- $2.E\{tq_{PA}\}$: Mean delay at the provider assistant node (PA), which is multiplied by 2 because the transaction passes through this node twice during the deployment process. See Figure 6 for reference.

- $E\{tq_{PNRNC}\}$: Mean delay at the provider name resolution and network cache node (PNRNC).

- $2.E\{tq_{PP}\}$: Mean delay at the provider proxy node (PP), which is also traversed twice during the process.

- $2.E\{tq_{PAP}\}$: Mean delay at the provider autopilot node (PAP), traversed twice as well.

- $3.E\{tq_{PF}\}$: Mean delay at the provider facilitator node (PF), which is traversed three times.

- $E\{tq_{PW}\}$: Mean delay at the provider wallet node (PW).

- $E\{tq_M\}$: Mean delay at the market node (M).

- $E\{tq_{SDRT}\}$: Mean delay at the software-defined radio twin node (SDRT).

- $E\{tq_{SDR}\}$: Mean delay at the software-defined radio node (SDR).

The time it takes to establish a 6G connectivity slice for drone connectivity once the operator has deployed the required smart contracts can be estimated if the transactions in Figure 6 are carried out according to the feedback given in the same figure. In this case, Equation 3 offers the total delay.

$$E\{T_{TotalC}\} = E\{tq_U\} + 2.E\{tq_{UA}\} + E\{tq_{UNRNC}\} + 3.E\{tq_{UP}\} + 3.E\{tq_{UAP}\} + 3.E\{tq_{UF}\} + E\{tq_{UW}\} + E\{tq_M\} + E\{tq_{DT}\} + E\{tq_D\} \quad (3)$$

This equation calculates the expected total delay for a user to contract a 6G connectivity slice. This delay includes the time taken for transactions to pass through various components of the 6G network from the user's perspective. Each term in the equation represents the expected queuing time at a specific component in the network, and the coefficients indicate the number of times a transaction is expected to pass through that component. The meaning of each equation term is as follows:

- $E\{tq_U\}$: Mean delay at the user node (U).

- $2.E\{tq_{UA}\}$: Mean delay at the user assistant node (UA), which is multiplied by 2 because the transaction passes through this node twice.

- $E\{tq_{UNRNC}\}$: Mean delay at the user name resolution and network cache node (UNRNC).

- $3.E\{tq_{UP}\}$: Mean delay at the user proxy node (UP), which is traversed three times.

- $3.E\{tq_{UAP}\}$: Mean delay at the user autopilot node (UAP), also traversed three times.

- $3.E\{tq_{UF}\}$: Mean delay at the user facilitator node (UF), traversed three times.

- $E\{tq_{UW}\}$: Mean delay at the user wallet node (UW).

- $E\{tq_M\}$: Mean delay at the market node (M).

- $E\{tq_{DT}\}$: Mean delay at the drone twin node (DT).

- $E\{tq_D\}$: Mean delay at the drone node (D).

This expression estimates the total delay for contracting a 6G slice from the sum of the delays experienced by each component from 1 to 10. $E\{tq_U\}$ is the total delay in QS 1, $E\{tq_{UA}\}$ is the total delay in QS 2, and so on. All these expected individual queuing times are calculated using the M/M/1 formula at Equation 4, which calculates the average delay in each component.

$$E\{tq_i\} = \frac{1}{\mu_i - \lambda_i} \quad (4)$$

Regarding the occupancy of the systems that make up the 6G model, Equation 5 gives an occupancy in terms of the number of transactions for each system. Therefore, this expression allows us to determine the mean number of transactions performed in each component.

$$E\{q_i\} = \frac{\rho_i}{1 - \rho_i} \quad (5)$$

Therefore, this equation estimates the mean queueing system occupation ($E\{q_i\}$) in terms of the mean amount of transactions stored and served. It is essential to highlight that $\rho_i$ is the utilization of a certain component $i$. The direct sum of the mean occupation for all systems gives us the occupancy of the entire 6G model. Furthermore, the queueing system (QS) utilization metric in M/M/1 systems, which indicates the extent of system usage, is determined by the following:

$$\rho_i = 1 - p_0 \quad (6)$$

where $p_0$ is the probability that a certain component $i$ is empty.

These equations provide deep analytical insights into system behavior, helping to identify bottlenecks and optimize resource allocation. Utilizing queuing theory and Jackson's theorem, these models provide essential predictive capabilities for designing 6G architectures. They allow for evaluating utilization and delays in each component, showing the bottlenecks. Understanding the delays in deploying smart contracts or contracting slices is fundamental for 6G design. These equations quantify these delays, offering valuable insights into the system's responsiveness and adequacy. Additionally, they assist in resource allocation, ensuring that the system can handle expected loads without excessive delays or resource wastage. Through scenario analysis, these models abstract real-world applications such as drone deployment or smart contract implementation. Furthermore, they establish performance benchmarks, allowing continuous improvement and validation of the 6G architecture design.

### *6.2. Performance Evaluation*

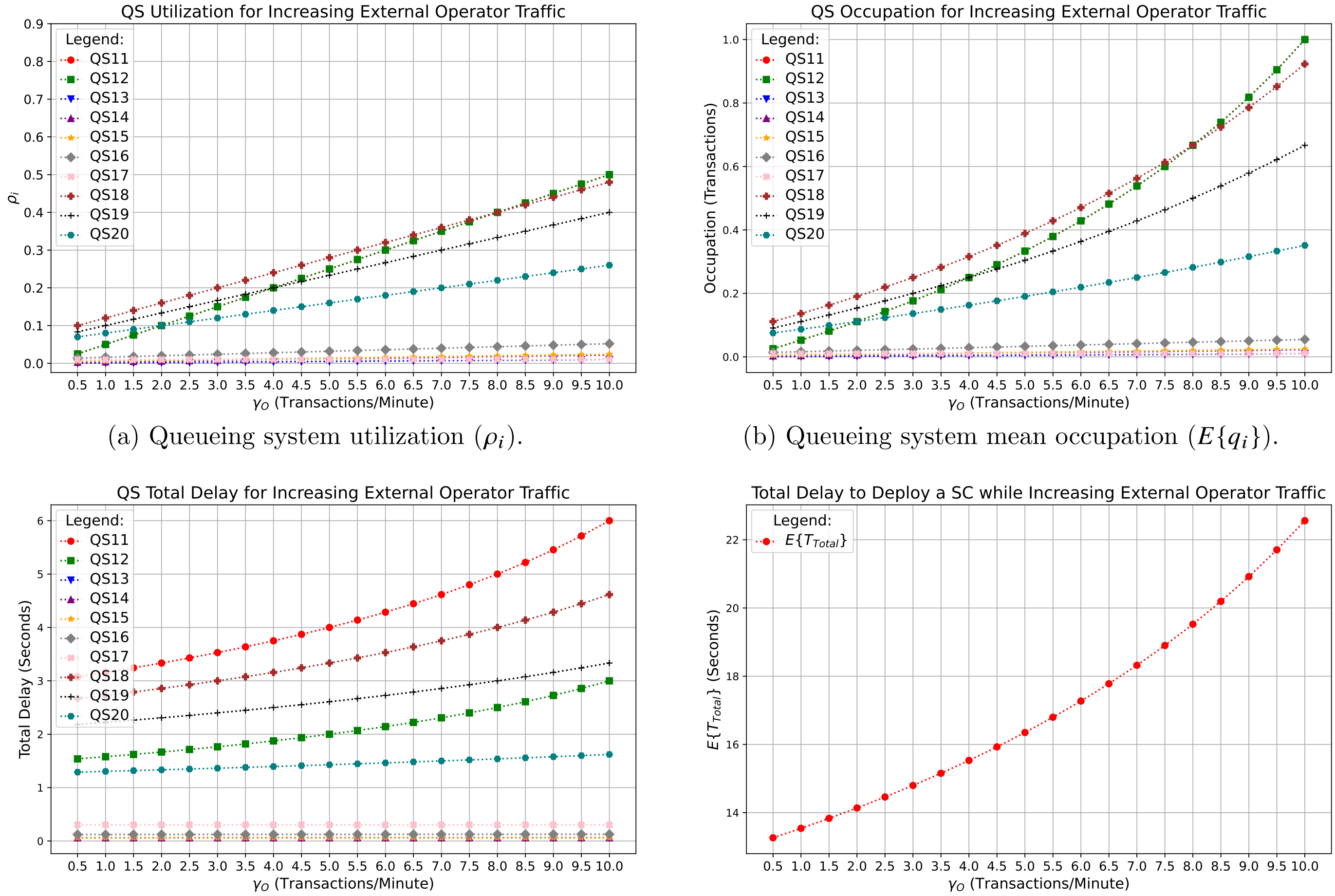
This subsection analyzes an operator deploying a smart contract in the digital market. Afterward, we investigate the user contracting a 6G connectivity slice. We primarily focus on increasing the transaction arrival rate generated from humans and assess the system's performance in response.

#### *Operator Deploying a Smart Contract in the Digital Market*

The provider operator must interact with an assistant application to implement a smart contract, as shown in Figure 6. It is fundamental to note that the model calculates performance metrics for a single, smart contract deployment. If several smart contracts are required, the delay must be multiplied accordingly. The delay must be multiplied if several smart contracts are required. Figure 8a shows the QS utilization metric, i.e., $\rho_i$ calculate by using Equation 6.

The lower the probability that a QS is empty, the higher its utilization. In the worst case, utilization (U) is approximately 50% in QS18 and QS12, followed by $\rho_{19}$=40% (SDR), $\rho_{20}$=25% (M), and $\rho_{16}$=7% (PF). In this case, all QSs have an acceptable utilization for the scenario under study. That is, the system components are effectively utilized without overburdening. The high utilization rates in QS18 and QS12, up to 50%, indicate that these components handle a substantial portion of the workload efficiently. Meanwhile, lower utilization rates in other components, such as $\rho_{16}$ in 7%, suggest ample capacity is available to handle additional load if necessary. This balance in utilization ensures that no single component becomes a bottleneck, leading to a more robust and reliable system. We can conclude that the service rates specified in Table 2 are well chosen, providing a good trade-off between efficiency and capacity. This insight is crucial to optimizing the performance of our 6G solution, as it confirms that the architecture can support smart contract deployments effectively, maintaining acceptable levels of performance even under varying load conditions.

Figure 8b shows the occupation of QSs in terms of mean transactions calculated by using Equa-




(a) Queueing system utilization ($\rho_i$).

(b) Queueing system mean occupation ($E\{q_i\}$).

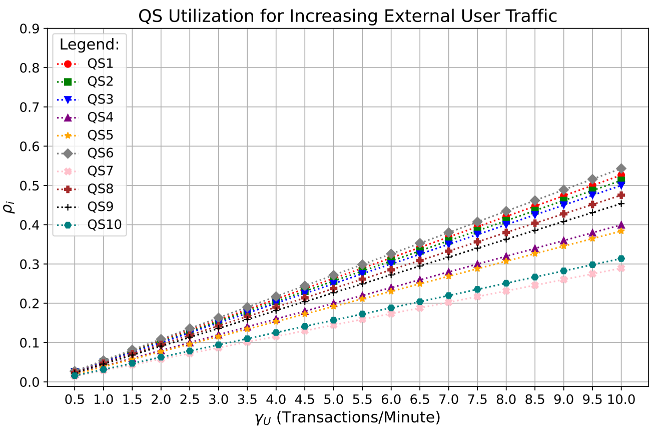
(c) Queueing system mean total delay ($E\{tq_i\}$).

(d) Estimate of the total delay in deploying an SC.

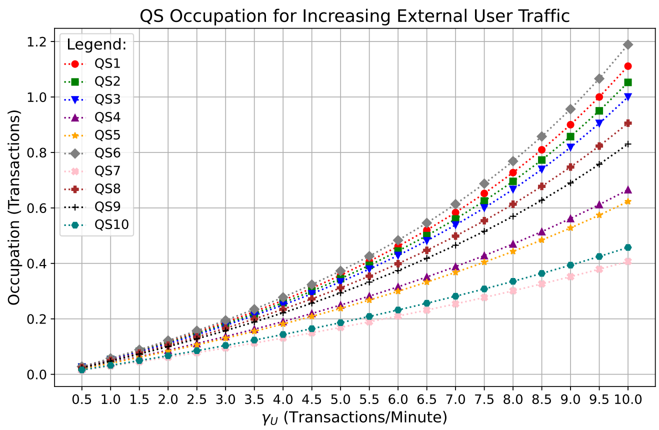
Figure 8: Results for operator deploying for a smart contract in D6G components.

tion 5. As expected, systems with higher utilization have higher occupations, i.e., PA has $E\{q_{12}\} = 1$ mean transaction, and SDRT has $E\{q_{18}\}$=0.92 mean transactions. PNRNC, PAP, and PW have very small occupations due to their high service rates ($\mu_i$). These occupancy values are low, indicating a lightly loaded network. The total QS mean transaction delay as calculated by Equation 4 is depicted in Figure 8c. The worst total QS delays have been identified as $E\{tq_{11}\}$=6 seconds in the system that models the operator (O), $E\{tq_{18}\}$=4.5 seconds at SDRT, and $E\{tq_{19}\}$=3.3 seconds at SDR. All these results are for $\gamma_O$=10 transactions per minute. These delay values are acceptable in a smart contract deployment process. The analysis of mean transaction occupation and delay across the different systems provides important insights for the 6G architecture. The low occupation values for components such as PNRNC, PAP, and PW suggest that the network is not overly congested and can handle additional transactions without significant performance degradation. The system's efficiency is further validated by the acceptable delay values, showing that even with a load of 10 transactions per minute, essential operations can be executed within an acceptable time span. This ensures effective scalability and performance maintenance, confirming the configuration and service rates are optimized for the intended drone application.

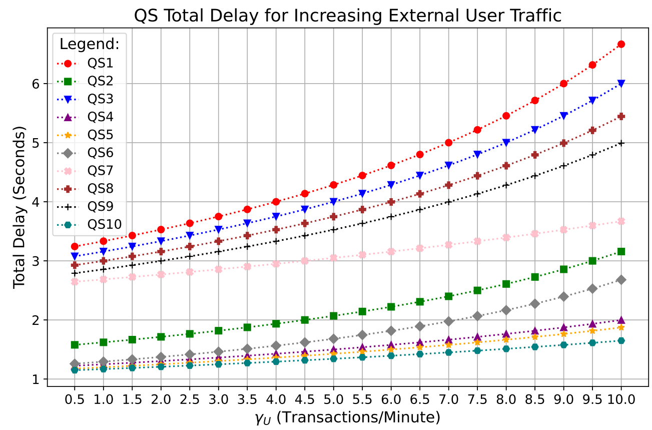
The last result for this sequence is shown in Figure 8d. It presents the estimate of the total delay for an operator to deploy a smart contract in a digital market according to Equation 2. $E\{T_{TotalD}\}$ ranges from 13.5 seconds when $\gamma_O$=0.5 transactions per minute, up to $E\{T_{TotalD}\}$=22.2



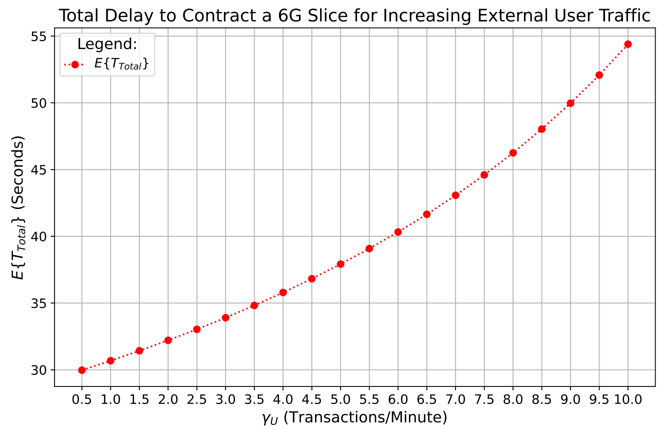

(a) Queueing system utilization ($\rho_i$).




(b) Queueing system mean occupation ($E\{q_i\}$).




(c) Queueing system mean total delay ($E\{tq_i\}$).




(d) Estimate of the total delay in contracting a 6G slice.

Figure 9: Results for user contracting a D6G slice.

seconds when $\gamma_O$=10 transactions per minute. This result is crucial for understanding the performance limits of our 6G architecture when deploying smart contracts. The range of delay values from 13.5 to 22.2 seconds indicates that the system can handle varying loads efficiently, maintaining acceptable performance even as the transaction rate increases. This demonstrates the robustness of service rates and the overall design of the network in managing smart contract deployments. However, it also underscores the potential for increased delays with consecutive contract implementations, emphasizing the need for optimization in high-volume scenarios. In summary, these delay values are acceptable for a single-smart contract deployment. However, a more significant delay may occur if many contracts are implemented in series.

*User Contracting a 6G Connectivity Slice*

Once the smart contracts have been established, the next step is to contract to them. This step is the purpose of the performance analysis discussed in this subsection. Figure 9a shows the QS utilization metric accordingly to Equation 6. The lower the probability that a QS is empty, the higher its utilization. Observe that QS utilization is close to each other, meaning that service rates ($\mu_i$) are within the acceptable range for the scenario under study. When contracting the smart contract, the workload on all 6G components is similar and low. Figure 9b shows the mean QS occupation for transactions. As expected, QS with larger utilization (UF) also has more transactions queued or being processed. The highest occupations for the chosen service rates are UF, user terminal, UA, and UNRNC. However, it is worth noting that this occupancy level is adequate for the tasks performed by these components of D6G. However, UW, M, UAP, and UP have smaller occupations. UF has a mean of 1.2 mean transactions in the system, while UW has 0.4 mean transactions. These results confirm the efficiency and balance of D6G in handling smart contract transactions. The uniform and minimal workload observed across all 6G components indicates that the architecture is efficiently optimized for the task, with service rates that prevent any single component from becoming a bottleneck. The higher utilization and corresponding occupancy in key components like UF, user terminal, UA, and UNRNC indicate that these network parts effectively manage their roles. The lower occupancy in components like UW, M, UAP, and UP shows sufficient capacity to handle more transactions without overloading the system.

The mean total QS delay (queue plus service) is reproduced in Figure 9c. UF has a mean of 6.7 seconds per transaction in the system, while UW has 3.7 seconds per transaction. A small total delay was obtained for the digital market (M) with 1.65 seconds, followed by UAP (1.8 sec) and DT (2 sec). It is fundamental to highlight that delays in 6G components are acceptable. Figure 9d shows the estimated delay in contracting a 6G slice from the digital market according to Equation 3. It should be noted that this delay contains the number of turns that a transaction takes in QS according to Figure 6. The increase in the transaction rate on the user system ($\gamma_U$) leads to a slightly exponential increase in $E\{T_{Total}\}$. This behavior happens because feedback in Jackson's network model increases the queuing time as more transitions arrive per minute. In the worst case, where the $\gamma_U = 10$ transactions per minute, $E\{T_{TotalC}\} = 53.7$ seconds, it means that even with a high transaction rate (contracting ten services per minute), the D6G architecture can handle contracting a new slice in a reasonable time. In the best case, the $\gamma_U = 1$ transaction every two minutes, $E\{T_{TotalC}\} = 30$ seconds according to the assumed service rates in Table 2. Changing these rates $\mu_i$ will affect all service networks. Therefore, smaller delays to contract a 6G slice can be obtained by optimizing service capacities. The D6G model keeps transaction delays relatively low, even at significant transaction rates (10 transactions per minute).

The acceptable delay times across various components, such as UF, UW, and the digital market, indicate that the system is designed to handle transactions efficiently without causing significant latency. The gradual exponential rise in overall delay as transaction rates increase emphasizes the effect of network feedback on queuing durations, highlighting the necessity of optimizing service capacities. Even in the worst-case scenario of 10 transactions per minute, D6G maintains a reasonable total delay, demonstrating its robustness. These results confirm that current service rates and network configurations effectively support offered transaction volumes, ensuring our proposed architecture meets the requirements of the 6G drone connectivity application. These results show a slice of contracting time that we consider adequate for 6G. In addition, optimizing service capacities further makes achieving even lower delays possible, enhancing the overall efficiency and user experience in 6G networks. Thus, this model enables the scaling of the complete D6G solution based on anticipated increases in average demand.

## 7. Conclusion and future work

We designed a disruptive 6G architecture (D6G) considering the selected enablers and the design principles. DG6 architecture has been divided into three strata: (i) physical, (ii) *middleware* and platforms, and (iii) services. The physical layer encompasses all visible and tangible infrastructure enablers, including all types of devices, equipment, networks, *cloud*, among others. We divided the physical stratum into three segments: (a) access, (b) aggregation, and (c) core. The *middleware*/platforms layer included virtualization, monetization, *servitization*, security, storage, slicing, and programmability features. In the services stratum, we had numerous VNFs for naming, storage, computing, orchestration, control, management, life cycling, resources exposure, entity discovery, facilitation, contracting, digital market using DTs, autopilot, and representation of physical and human operators/users. Moreover, we proposed a decentralized, open, and digitally monetized service store with various network functions from current generations (4G, 5G), beyond 5G, and 6G. The interfaces between the NFVs can be published in a distributed name resolution system, allowing the discovery and contracting at run time of infrastructure, virtualized resources, and services.

D6G aims to create a hyper-converged environment in which 6G components can evolve and be delivered through smart contracts in DLT technology. VNFs deployed in containers or VMs are supported for compatibility and scalability. However, the best innovation is executing VNFs by monetizing smart contracts in public and permissioned DLT or central bank digital currency (CBDC). The role of DLTs in the D6G architecture is the main difference between the 6G architectures proposed in the literature and possible 5G evolutionary architectures.

We developed a queuing theory model based on Jackson's theorem to evaluate the D6G architecture. The estimated delay to deploy a smart contract in a 6G domain was evaluated when an operator's external traffic increased from 0.5 up to 10 transactions/minute. In the worst case, this delay was equal to 23 seconds, an adequate value for a practical 6G application. Moreover, our model allowed us to estimate the total delay in contracting a 6G slice from a digital market where previous smart contracts have been deployed. Moreover, in the worst case, when the external traffic of the user was ten transactions per minute, this delay was evaluated as 53.7 seconds. This result means that even with a very high transaction rate, the proposed architecture can deal with contracting a new slice in a reasonable time.

The next steps on D6G are: (i) to detail architectural requirements more deeply, (ii) to evaluate existing smart contract DLT technologies that can support D6G requirements, (iii) to provide a fine-grained specification of the architecture encompassing key enablers for a proof-of-concept (PoC) proposal. Such a specification is challenging since it must map the VNFs planned to run through smart contracts or reimplement them in this format. Additionally, the specification of AI-based components (autopilots, assistants, proxies, and facilitators) and their interactions is another challenging point of attention. DTs will demand a significant investment in time due to the scales of representing every asset on the physical stratum, including the novel ones, such as neuromorphic computing, OWC, disruptive waves, and IRS/RIS, among others, (iv) to implement the PoC and train all components for initial testing. The availability of data for training is a fundamental issue to consider. Furthermore, creating, configuring, and testing the decentralized service store and digitized resource markets is another problematic point, (v) to establish an evaluation methodology and its associated experimental design, (vi) to evaluate performance experimentally. The modular design adopted favors parallel development, training, and testing. The principles of openness, collaboration, and sharing adopted in the project favor the formation of a consortium for a decentralized roadmap. New business models can also be explored.

As it is practically impossible to standardize every detail of such a significant architecture, the essential action is to standardize its main/fundamental pillars/enablers and their interactions (interfaces) so that the remaining ingredients will fit naturally in a self-organized way. We would propose the following if it were necessary to choose a minimal subset of enablers for an initial PoC. Sensing and Acting - IoT sensing; Communications - THz communications, Ultra MIMO, IRS/RIS, D2D, disruptive waves, OWC, UAVs, and 3D nets; Softwarization - Cloud elasticity, Open RAN, SOA, network caching and slicing, NFV/MEC, DTs, SDN, IBN; Immutability - DLT, smart contracts, all markets; Intelligence and Security - all enablers.

## Acknowledgment

This work was partially supported by RNP, with resources from MCTIC, Grant No. 01245.020548/2021 − 07, under the Brazil 6G project of the Radiocommunication Reference Center (Centro de Referência em Radiocomunicações - CRR) of the National Institute of Telecommunications (Instituto Nacional de Telecomunicações, Inatel), Brazil, and by Huawei, under the project Advanced Academic Education in Telecommunications Networks and Systems, contract No PPA6001BRA23032110257684. Furthermore, it is supported by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) - Finance Code 001. The authors also thank CNPq, FAPEMIG, and Vivavox Telecom. We also thank the people of the Brazil 6G project.

## References

[1] Gartner, Gartner Hype Cycle, https://www.gartner.com/en/research/methodologies/gartner-hype-cycle, accessed: 2022-06-30 (2022).

[2] H. Kim, Artificial Intelligence for 6G, Springer Science & Business Media, 2022.

[3] A. Ghosh, *et al.*, 5G Evolution: A View on 5G Cellular Technology Beyond 3GPP Release 15, in: IEEE Access, Vol. 7, 2019, pp. 127639–127651. doi:10.1109/ACCESS.2019.2939938.

[4] B. M. Shah, M. Murtaza, M. Raza, Comparison of 4G and 5G Cellular Network Architecture and Proposing of 6G, a new era of AI, in: 5th CITISIA, 2020, pp. 1–10. doi:10.1109/CITISIA50690.2020.9371846.

[5] H. Ganame, *et al.*, Evolutionary Algorithms for 5G Multi-Tier Radio Access Network Planning, in: IEEE Access, Vol. 9, 2021, pp. 30386–30403. doi:10.1109/ACCESS.2021.3058619.

[6] W. Miao, *et al.*, Unlocking the Potential of 5G and Beyond Networks to Support Massive Access of Ground and Air Devices, in: IEEE Transaction on Net. Sci. and Engineering, Vol. 8, 2021, pp. 2825–2836. doi:10.1109/TNSE.2021.3051294.

[7] A. Ibrahim, *et al.*, Heuristic Resource Allocation Algorithm for Controller Placement in Multi-Control 5G Based on SDN/NFV Architecture, in: IEEE Access, Vol. 9, IEEE, 2021, pp. 2602–2617. doi:10.1109/ACCESS.2020.3047210.

[8] M. Vaezi, *et al.*, Cellular, Wide-Area, and Non-Terrestrial IoT: A Survey on 5G Advances and the Road Toward 6G, in: IEEE Communications Surveys & Tutorials, Vol. 24, 2022, pp. 1117–1174. doi:10.1109/COMST.2022.3151028.

[9] N. Zohar, Beyond 5G: Reducing the handover rate for high mobility communications, in: Journal of Commun. and Networks, Vol. 24, 2022, pp. 154–165. doi:10.23919/JCN.2022.000001.

[10] M. Manalastas, *et al.*, Design Considerations and Deployment Challenges for TurboRAN 5G and Beyond Testbed, in: IEEE Access, Vol. 10, 2022, pp. 39810–39824. doi:10.1109/ACCESS.2022.3166947.

[11] A. Zappone, M. Renzo, M. Debbah, Wireless Networks Design in the Era of Deep Learning: Model-Based, AI-Based, or Both?, in: IEEE Transaction on Communication, Vol. 67, 2019, pp. 7331–7376. doi:10.48550/arXiv.1902.02647.

[12] A. M. Alberti, *et al.*, Naming and name resolution in the future internet: Introducing the NovaGenesis approach, in: Future Gener. Computer Systems, Vol. 67, 2017, pp. 163–179. doi:10.1016/j.future.2016.07.015.

[13] B. Cao, *et al.*, Many-Objective Deployment Optimization of Edge Devices for 5G Networks, in: IEEE Transaction on Net. Scien. and Engineering, Vol. 7, 2020, pp. 2117–2125. doi:10.1109/TNSE.2020.3008381.

[14] W. Saad, M. Bennis, M. Chen, A Vision of 6G Wireless Systems: Applications, Trends, Technologies, and Open Research Problems, in: IEEE Network, Vol. 34, 2020, pp. 134–142. doi:10.48550/arXiv.1902.10265.

[15] K. Yue, *et al.*, A Survey of Decentralizing Applications via Blockchain: The 5G and Beyond Perspective, in: IEEE Communications Surveys & Tutorials, Vol. 23, 2021, pp. 2191–2217. doi:10.1109/COMST.2021.3115797.

[16] A. Mamane, *et al.*, Scheduling Algorithms for 5G Networks and Beyond: Classification and Survey, in: IEEE Access, Vol. 10, 2022, pp. 51643–51661. doi:10.1109/ACCESS.2022.3174579.

[17] L. Kao, W. Liao, 5G Intelligent A+: A Pioneer Multi-Access Edge Computing Solution for 5G Private Networks, in: IEEE Communication Standard Magazine, Vol. 5, 2021, pp. 78–84. doi:10.1109/MCOMSTD.001.2000036.

[18] S. Sargam, et al., Adoption of 5G in Developing Economies: A Supply Side Perspective from India, Telematics and Informatics (2023) 102034doi:https://doi.org/10.1016/j.tele.2023.102034.

[19] A. Jalalian, S. Yousefi, T. Kunz, Network slicing in virtualized 5G Core with VNF sharing, Journal of Network and Computer Applications 215 (2023) 103631. doi:https://doi.org/10.1016/j.jnca.2023.103631.
URL https://www.sciencedirect.com/science/article/pii/S1084804523000504

[20] A. Jain, N. Gupta, M. Sreenu, Blockchain based

smart contract for cooperative spectrum sensing in cognitive radio networks for sustainable beyond 5G wireless communication, Green Technologies and Sustainability 1 (2) (2023) 100019. doi:https://doi.org/10.1016/j.grets.2023.100019.

[21] B. Sonkoly, et al., 5G Applications From Vision to Reality: Multi-Operator Orchestration, IEEE Journal on Selected Areas in Communications 38 (7) (2020) 1401–1416. doi:10.1109/JSAC.2020.2999684.

[22] T. B. da Silva, *et al.*, Toward Future Internet of Things Experimentation and Evaluation, in: Internet of Things Journal, Vol. 9, IEEE, 2022, pp. 8469–8484. doi:10.1109/JIOT.2021.3114540.

[23] D. G. Pivoto, *et al.*, Cyber-physical systems architectures for industrial internet of things applications in Industry 4.0: A literature review, in: Journal of Manufacturing Systems, Vol. 58, ScienceDirect, 2021, pp. 176–192. doi:10.1016/j.jmsy.2020.11.017.

[24] A. M. Alberti, *et al.*, NovaGenesis Applied to Information-Centric, Service-Defined, Trustable IoT/WSAN Control Plane and Spectrum Management, in: Sensors, Vol. 18, MDPI, 2018. doi:10.3390/s18093160.

[25] Z. Allam, D. S. Jones, Future (post-COVID) digital, smart and sustainable cities in the wake of 6G: Digital twins, immersive realities and new urban economies, in: Land Use Policy, Vol. 101, ScienceDirect, 2021, p. 105201. doi:10.1016/j.landusepol.2020.105201.

[26] K. Ramezanpour, J. Jagannath, A. Jagannath, Security and privacy vulnerabilities of 5G/6G and WiFi 6: Survey and research directions from a coexistence perspective, Computer Networks 221 (2023) 109515. doi:https://doi.org/10.1016/j.comnet.2022.109515.

[27] G. Li, *et al.*, SecCDV: A Security Reference Architecture for Cybertwin-Driven 6G V2X, in: IEEE Transaction on Vehicular Technology, 2021, pp. 1–1. doi:10.1109/TVT.2021.3133308.

[28] C. Yang, et al., SMART Intent-Driven Network Management, IEEE Communications Magazine 61 (1) (2023) 106–112. doi:10.1109/MCOM.002.2200119.

[29] A. M. Alberti, , *et al.*, Advancing NovaGenesis Architecture Towards Future Internet of Things, in: IEEE Internet of Things Journal, Vol. 6, 2019, pp. 215–229. doi:10.1109/JIOT.2017.2723953.

[30] T. B. da Silva, , *et al.*, Toward Next-Generation and Service-Defined Networks: A NovaGenesis Control Agent for Future Internet Exchange Point, in: IEEE Network, Vol. 36, 2022, pp. 74–81. doi:10.1109/MNET.008.2100555.

[31] Q. Yu, , *et al.*, A Fully-Decoupled RAN Architecture for 6G Inspired by Neurotransmission, in: Journal of Commun. and Infor. Networks, Vol. 4, Report, 2019, pp. 15–23. doi:10.23919/JCIN.2019.9005430.

[32] H. Feng, *et al.*, Bidirectional Green Promotion of 6G and AI: Architecture, Solutions, and Platform, in: 5th CITISIA, Vol. 35, 2021, pp. 57–63. doi:10.1109/MNET.101.2100285.

[33] Y. Li, *et al.*, Cognitive Service Architecture for 6G Core Network, in: IEEETransaction. on Ind. Informatics, Vol. 17, 2021, pp. 7193–7203. doi:10.1109/TII.2021.3063697.

[34] G. Liu, *et al.*, Vision, requirements and network architecture of 6G mobile network beyond 2030, in: China Communications, Vol. 17, 2020, pp. 92–104. doi:10.23919/JCC.2020.09.008.

[35] N. H. Mahmood, *et al.*, A Functional Architecture for 6G Special-Purpose Industrial IoT Networks, in: IEEE Transaction on Ind. Informatics, Vol. 19, 2023, pp. 2530–2540. doi:10.1109/TII.2022.3182988.

[36] Q. Li, *et al.*, 6G Cloud-Native System: Vision, Challenges, Architecture Framework and Enabling Technologies, in: IEEE Access, Vol. 10, 2022, pp. 96602–96625. doi:10.1109/ACCESS.2022.3205341.

[37] E. J. Khatib, *et al.*, Designing a 6G Testbed for Location: Use Cases, Challenges, Enablers and Requirements, in: IEEE Access, Vol. 11, 2023, pp. 10053–10091. doi:10.1109/ACCESS.2023.3240775.

[38] K. B. Letaief, *et al.*, Edge Artificial Intelligence for 6G: Vision, Enabling Technologies, and Applications, in: IEEE Journal on Selection Areas in Communication, Vol. 40, 2022, pp. 5–36. doi:10.1109/JSAC.2021.3126076.

[39] V. K. Quy, *et al.*, Innovative Trends in the 6G Era: A Comprehensive Survey of Architecture, Applications, Technologies, and Challenges, IEEE Access 11 (2023) 39824–39844. doi:10.1109/ACCESS.2023.3269297.

[40] M. Merluzzi, *et al.*, The Hexa-X Project Vision on Artificial Intelligence and Machine Learning-Driven Communication and Computation Co-Design for 6G, IEEE Access 11 (2023) 65620–65648. doi:10.1109/ACCESS.2023.3287939.

[41] A. Dogra, R. K. Jha, S. Jain, A Survey on Beyond 5G Network With the Advent of 6G: Architecture and Emerging Technologies, IEEE Access 9 (2021) 67512–67547. doi:10.1109/ACCESS.2020.3031234.

[42] X. You, et al., Toward 6G TK$\mu$ Extreme Connectivity: Architecture, Key Technologies and Experiments, IEEE Wireless Communications 30 (3) (2023) 86–95.

[43] A. Chaoub, et al., Hybrid Self-Organizing Networks: Evolution, Standardization Trends, and a 6G Architecture Vision, IEEE Communications Standards Magazine 7 (1) (2023) 14–22. doi:10.1109/MCOMSTD.0002.2200049.

[44] T. Taleb, et al., Toward Supporting XR Services: Architecture and Enablers, IEEE Internet of Things Journal 10 (4) (2023) 3567–3586. doi:10.1109/JIOT.2022.3222103.

[45] A. T. Jawad, R. Maaloul, L. Chaari, A comprehensive survey on 6g and beyond: Enabling technologies, opportunities of machine learning and challenges, Com-

puter Networks 237 (2023) 110085. doi:https://doi.org/10.1016/j.comnet.2023.110085.
URL https://www.sciencedirect.com/science/article/pii/S1389128623005303

[46] Habibi, Mohammad Asif and others, Toward an Open, Intelligent, and End-to-End Architectural Framework for Network Slicing in 6G Communication Systems, IEEE Open Journal of the Communications Society 4 (2023) 1615–1658. doi:\blue{10.1109/OJCOMS.2023.3294445}.

[47] Iacovos Ioannou and others, A novel Distributed AI framework with ML for D2D communication in 5G/6G networks, Computer Networks 211 (2022) 108987. doi:\blue{https://doi.org/10.1016/j.comnet.2022.108987}.

[48] Abu Jahid and Mohammed H. Alsharif and Trevor J. Hall, The convergence of blockchain, IoT and 6G: Potential, opportunities, challenges and research roadmap, Journal of Network and Computer Applications 217 (2023) 103677. doi:\blue{https://doi.org/10.1016/j.jnca.2023.103677}.

[49] Corici, Marius-Iulian and others, Organic 6G Networks: Vision, Requirements, and Research Approaches, IEEE Access 11 (2023) 70698–70715. doi:\blue{10.1109/ACCESS.2023.3293055}.

[50] Pivoto, Diego G. S. and others, A Detailed Relevance Analysis of Enabling Technologies for 6G Architectures, IEEE Access (2023) 1–1doi:\blue{10.1109/ACCESS.2023.3301811}.

[51] Wheeb, Ali H. and others, Topology-Based Routing Protocols and Mobility Models for Flying Ad Hoc Networks: A Contemporary Review and Future Research Directions, Drones 6 (1) (2022). doi:10.3390/drones6010009.

[52] Wheeb, Ali H. and others, Performance Evaluation of Standard and Modified OLSR Protocols for Uncoordinated UAV Ad-Hoc Networks in Search and Rescue Environments, Electronics 12 (6) (2023). doi:10.3390/electronics12061334.

[53] Naser, Marwa T. and Wheeb, Ali H., Implementation of RWP and Gauss Markov Mobility Model for Multi-UAV Networks in Search and Rescue Environment, International Journal of Interactive Mobile Technologies (iJIM) 16 (23) (2022) pp. 125–137. doi:10.3991/ijim.v16i23.35559.

[54] B. Goertzel, S. Giacomelli, D. Hanson, C. Pennachin, M. Argentieri, SingularityNET: A decentralized, open market and inter-network for AIs (2021).
URL http://singularitynetagi.com/whitepaper.pdf

[55] X. JIANG, M. SHENG, N. ZHAO, C. XING, W. LU, X. WANG, Green uav communications for 6g: A survey, Chinese Journal of Aeronautics 35 (9) (2022) 19–34. doi:https://doi.org/10.1016/j.cja.2021.04.025.
URL https://www.sciencedirect.com/science/article/pii/S1000936121001801

[56] R. Bajracharya, R. Shrestha, S. Kim, H. Jung, 6g nr-u based wireless infrastructure uav: Standardization, opportunities, challenges and future scopes, IEEE Access 10 (2022) 30536–30555. doi:10.1109/ACCESS.2022.3159698.

[57] X. Wang, Y. Guo, Y. Gao, Unmanned autonomous intelligent system in 6g non-terrestrial network, Information 15 (1) (2024). doi:10.3390/info15010038.
URL https://www.mdpi.com/2078-2489/15/1/38

[58] J. Walrand, P. Varaiya, Sojourn times and the overtaking condition in jacksonian networks, Advances in Applied Probability 12 (4) (1980) 1000–1018. doi:10.2307/1426753.