IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 3 July 2023, accepted 28 July 2023, date of publication 3 August 2023, date of current version 25 August 2023.

Digital Object Identifier 10.1109/ACCESS.2023.3301811

SURVEY

A Detailed Relevance Analysis of Enabling Technologies for 6G Architectures

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This work was supported in part by the Rede Nacional de Ensino e Pesquisa (RNP), with resources from Ministério da Ciência, Tecnologia e Inovações e Comunicações (MCTIC), 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, under Grant 01245.010604/2020-14; and in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES)—Finance Code 001.

ABSTRACT As society evolves as a whole, new demands arise with increasingly demanding prerequisites, consequently requiring more significant effort to be met. Such demands cover emerging applications, such as remote surgeries in Smart Health use cases, whose latency and reliability network requirements cannot be met by current communication systems; or simply improving current applications with more challenging requirements to be achieved, such as increasing the transmission rate in a mobile network, offering Quality of Service (QoS), and consequently, better user experience. Therefore, enabling technologies must be chosen to design an appropriate 6G architecture to address such demands. However, the explosion of emerging applications focused on different scopes and requirements to be met makes choosing these enabling technologies extremely complex and unpredictable. Thus, this article aims to create a methodology for analyzing the relevance of enabling technologies and use it to design an optimal architecture capable of meeting the 6G demands. For this purpose, two methods named as Average (AVG) and Analytic Hierarchy Process (AHP) have been selected, whose objective is to determine the relevance of an enabler for the 6G architecture, taking into account different degrees of influencing variables for this analysis, such as adherence to a certain architectural model; popularity in the research area; degree of innovation; synergy with other enablers; and support for requirements. Each of these methods presents a particular result. In the case of the AVG method, the criteria and variables are evaluated independently, and the arithmetic mean is employed to combine the evaluations into a single measure of suitability. In contrast, the AHP method considers the relative importance of criteria and variables in order to classify an optimal set of enabling technologies capable of fulfilling the key roles to be performed by a 6G architecture, and consequently meeting the main 6G demands. Our evaluation provides a unique perspective on 6G enablers, identifying issues and fostering research for future mobile architectures. The results obtained also provide researchers with the necessary information to stay updated on emerging enabling technologies and their suitability for designing new optimized 6G architectures.

The associate editor coordinating the review of this manuscript and approving it for publication was Miguel López-Benítez.

INDEX TERMS 6G architectures, 6G enabling technologies, 6G requirements, 6G use cases, AHP, relevance analysis.

I. INTRODUCTION

Since the introduction of 5G, the mobile network architecture has undergone profound transformations that range from the separation of the control and data planes and the adoption of a service-based architecture in the Core Network (CN) [1] to the disaggregation of the Radio Access Network Radio Access Network (RAN) [2]. Many of these transformations were enabled by technologies such as Network Function Virtualization (NFV), Software Defined Networking (SDN), and Multi-access Edge Computing (MEC) aiming to bring the telecom infrastructure closer to those used in the cloud world, facilitating the support for virtualization and for customization of services through the instantiating of network slices.

As 5G networks are being commercially deployed, the scientific community is turning its attention to 6G architectures, although it is not clear yet what the next generation of mobile networks will be. On the one hand, it is expected that 6G will continue to advance the transmitted data rate to satisfy services that are increasingly demanding in terms of bandwidth. An example of such a service is holographic communications, which require peaks of up to 1 Tbps per user [3]. To achieve such a high data rate, it will be necessary to consolidate spectrum technologies introduced with 5G (e.g., millimeter Wave (mmWave)) as well as to exploit the spectrum in the THz and sub-THz bands [4]. Seeking to merge the digital and real worlds in all dimensions and ubiquitously, an increased number of instantiated slices, connected devices, and sensors is expected, requiring 6G to operate on a very high scale and in a hyper-connected and autonomous way [5], [6]. In this context, 6G networks are envisioned as ''networks of networks'', strongly integrating space and terrestrial networks, as well as making extensive usage of the location, sensing, and artificial intelligence technologies [7], [8], [9]. While services like Massive Machine Type Communications (mMTC), Ultra Reliable Low Latency Communications (uRLLC), and Enhanced Mobile Broadband (eMBB) will remain relevant in 6G, it is expected that a new set of demanding services such as telepresence [10] and immersive multi-modal, multi-user applications will be adequately supported in 6G [11]. In this context, flexibility will be a relevant requirement to accommodate the demands of different services. Therefore, 6G architectures are expected to advance the state-of-the-art in cloud-native solutions, emphasizing functional decomposition of services and reuse, specially in the access networks [12]. Due to the high degree of digitization of society in the 6G era, living or inanimate entities will be able to interact with a digital twin in real-time [13], [14]. Much of the traffic generated from these interactions will come from measuring or actuation of very tight control loops. Thus, communication latency to transmit such data must be extremely low so there is enough time to perform some kind of computation and make a decision [15]. Digital twins (representing industrial processes) and haptic applications (including holographic applications and multi-modal immersive applications) will require synchronization with strict requirements for jitter [16], [17], [18].

On the other hand, as wireless networks are a central element of a digitized society, it is expected that 6G networks can also contribute to sustainable, transparent, and reliable solutions, with a special focus on security and privacy [19], [20]. In summary, the 6G vision is being shaped in numerous academic and industrial papers. All these initiatives describe 6G as a ubiquitous, dynamic, autonomous, transparent, and reliable ecosystem. To realize this vision, several key technologies will be required, including new radio technologies, virtualization and architectural decomposition across the network, the pervasive use of AI/ML, and new security concepts to ensure resiliency, privacy, and trust. Indeed, in a survey comprising 119 articles from [22, 26-28, 30-144], we found 72 different technologies identified as 6G enablers.

Due to the explosive growth of different applications and use cases with increasingly challenging requirements, and consequently the emergence of new technologies capable of making it possible to meet these demands, the identification of possible 6G enabling technologies with the potential to overcome the challenges posed by the sixth generation of mobile networks is not sufficient to define an optimized network architecture.

In the face of this vast variety of possible enablers, there is also a problem related to the unpredictability and complexity of choosing the best technologies to compose a 6G architecture and fulfill the main roles in the network while meeting 6G demands. Thus, the following question arises: how to select the best set of enablers to design an optimized 6G architecture? To answer this question, an in-depth analysis is also necessary to direct the designers of future architectures to define which optimal technologies to use according to the 6G demands to be met.

Therefore, the answer to this question is by definition the motivation for this article, whose proposal is to map 6G enabling technologies and the variables that can influence their relevance, which includes, for example, the adherence of a certain enabler to an architectural scope, the levels of popularity and innovation in the research area, the synergy with other enablers, and the support for 6G network requirements to meet the use cases of the sixth generation of mobile networks. Thus, our work proposes a quantitative and qualitative analysis based on 6G enablers and conditioning variables as input parameters, to subsequently apply the chosen Average (AVG) and Analytic Hierarchy Process (AHP) methods for determining the importance degree of each enabler according to the its role in a 6G architecture.

To the best of our knowledge, this paper provides a unique perspective not explored in literature yet. In this context, our main contributions are:

i An in-depth review of current 6G architectures and a detailed comparison and discussion about how deep these proposals approach the 6G enabling technologies and their importance for the sixth generation of mobile networks;
ii A comprehensive literature review of 6G architectures, focusing on enabling technologies, use cases, architectural design scopes and requirements for 6G;
iii a quantitative and qualitative analysis of variables capable of conditioning the relevance of an enabling technology in a 6G architecture, which includes the adherence of an enabler in different architectural design scopes, its popularity and innovation levels in the research area, synergy with other enablers, and support to 6G requirements based on emerging applications and use cases;
iv An innovative and rich analysis to classify the enabling technologies based on conditioning variables previously mentioned (adherence to architectural design scopes, popularity, innovation, synergy, and support to 6G requirements) by using the AVG and AHP [21] methods for ranking their respective relevance levels for 6G. The main objective is to contribute to the research area in order to guide future 6G network architects to design optimized proposals while choosing a set of optimal enablers capable of better fulfilling the main 6G roles and meeting the 6G demands;
v A discussion about open issues, challenges and opportunities for future works.

For the reader's better understanding of our work, we present below the organizational structure of this article.

A. TEXT ORGANIZATION

Figure 1 summarizes our article's organization. For convenience, we compiled all the acronyms in Table 1. The remaining sections are organized as follows: Section II explores related 6G reviews and surveys. Section III describes the articles methodology: how we have searched the literature on relevant databases, 6G-related keywords, and research questions we would like to answer. In Section IV, we present the state-of-art on 6G, which includes: the key roles to be performed in a 6G architecture and a literature review of possible enabling technologies capable of performing these roles; 6G architectural Design Scope (DS)s; 6G use cases and 6G requirements. In Section V, we present a discussion on the conditioning factors that may impact the significance of an enabler based on the state-of-art on 6G previously detailed. These factors encompass conformity to various architectural design paradigms, the prevalence and degree of innovation and popularity associated with a specific technology, the complementary relationship with other enablers, and the extent to which the enabler satisfies the needs of diverse 6G applications and use cases. Then, Section VI presents a brief review of some possible methods that can be used in order to perform the relevance analysis of the 6G enabling technologies described in Section IV-A based on the conditioning variables previously described in Section V. Furthermore, it is presented the relevance ranking of the enablers by using the AVG and AHP chosen methods proposed for this analysis, employing a unique and innovative perspective, never explored in this research area. Finally, Section VII discusses the results obtained, in addition to future directions and recommendations, while Section VIII concludes the paper.

II. RELATED WORKS

6G architectures are expected to meet very demanding requirements. The use cases and applications alone are challenging and will require the integration of multiple technologies to be developed. Recently, these so-called enabling technologies have received a lot of attention from the scientific community, which led several works to discuss their importance in overcoming the challenges imposed by 6G. Hence, we analyze in this section the latest surveys focusing on 6G systems and enabling technologies and their contributions to meet the next generation's demands.

For such, we reviewed eight articles from different databases dating from 2019 to 2023, and we classified them considering five fundamentals aspects: number of enablers (A1), number of clusters (A2), network requirements (A3), relevance analysis (A4), and methodology for merit analysis (A5). These aspects were set to provide the readers with a thorough comparison of the analyzed works regarding the enablers and their level of importance over multiple applications and perspectives. Thus, we defined A1-A5 as follows.

i **Number of Enablers (A1):** It consists of a quantitative examination of the number of enablers discussed in each paper. With this aspect, we intend to measure the completeness of the analyzed works regarding 6G. The enablers are responsible for meeting 6G demands and applications considering essential network requirements.
ii **Number of Clusters (A2):** It describes the number of enablers' clusters. The importance level of an enabler varies according to its role in the 6G architecture. Thus, we quantified the number of enablers' clusters considered in the related surveys. A cluster relates to a group of technical enabling technologies that support a specific key role to be performed in a 6G architecture.
iii **Network Requirements (A3):** This aspect quantifies the number of network requirements investigated in related surveys. In the literature, there is still no consensus on the number and which network requirements are necessary to deploy 6G. Many surveys agree on fundamental

FIGURE 1. **Organization of the remaining article.**

requirements related to data rate, coverage, mobility, and delay. Others have valued network requirements such as security, connection density, and battery life.

iv **Relevance Analysis (A4):** In this aspect, we check whether previous works performed a relevance analysis of 6G enablers. The relevance analysis assesses the importance of each enabler and ranks it according to its state-of-the-art level. For instance, not all surveys agree that quantum computing is essential for implementing 6G, while the network slicing enabler is well accepted. We used a blank circle (○) to refer to surveys that do not analyze the enablers' relevance. Half-filled circle (◐) denotes surveys wherein the authors partially analyzed the enablers' relevance. Finally, the filled circle (●) indicates whether the related survey brings a complete and detailed relevance analysis of the 6G enablers, including different scenarios, applications, and architectural design scopes.

v **Methodology for Merit Analysis (A5):** This aspect verifies whether the related survey uses a well-defined methodology to perform a merit analysis for each of the potential 6G enablers. Some surveys empirically selected enabling technologies for designing 6G systems without following a precise method. Again, we used a blank circle (○) to address surveys without any methodology for relevance evaluation of 6G enablers. On the other hand, a full

TABLE 1. Acronyms and definitions.

Acronym	Definition	Acronym	Definition
3GPP	3rd Generation Partnership Project	mMTC	Massive Machine Type Communications
5GNR	5G New Radio	mmWave	millimeter Wave
ACLR	Adjacent Channel Leakage Ratio	NFV	Network Function Virtualization
AHP	Analytic Hierarchy Process	NIC	Network Interface Card
AI	Artificial Intelligence	NOMA	Non-Orthogonal Multiple Access
AKA	Authentication and Key Agreement	NS	Network Slicing
AR	Augmented Reality	NTN	Non-Terrestrial Network
AVG	Average	OFDM	Orthogonal Frequency Division Multiplexing
CAV	Connected and Autonomous Vehicle	OFDMA	Orthogonal Frequency Division Multiple Access
CBA	Cost-Benefit Analysis	O-RAN	Open RAN
CBDC	Central Bank Digital Currency	OWC	Optical Wireless Communications
CFN	Compute First Networking	PHY	Physical Layer
CN	Core Network	PRA	Predictive Resource Allocation
CoCoCo	Communication, Computing, Control	QC	Quantum Computing
CoMP	Coordinated Multi-Point	QAC	Quantum-Assisted Communications
CR	Cognitive Radio	QI	Quantum Internet
D2D	Device-to-Device	QKD	Quantum key Distribution
DApps	Decentralized Applications	QML	Quantum Machine Learning
DLT	Distributed Ledger Technology	QoS	Quality of Service
DS	Design Scope	QR	Quick Response
DSA	Dynamic Spectrum Access	RAN	Radio Access Network
DT	Digital Twin	RF	Radio Frequency
E2E	End-to-End	RFID	Radio Frequency Identification
EAP-TLS	Extensible Authentication Protocol - Transport Layer Security	RIS	Reconfigurable Intelligent Surface
eMBB	Enhanced Mobile Broadband	SATSI	Space-Air-Terrestrial-Sea Integrated Networks
E-RAN	Elastic-Radio Access Network	SDN	Software Defined Networking
FAB	Fast Accurate Beamforming	SEN	Self-Evolving Network
HAP	High Altitude Plataform	SLAM	Simultaneous Localization and Mapping
HR	Holographic Radio	SOA	Service-Oriented Architecture
HTTPS-TLS	Hypertext Transfer Protocol Secure - Transport Layer Security	SON	Self-Organizing Network
IBN	Intent-Based Networking	SVN	Self-Verifying Names
ICN	Information Centric Networking	SWOT	Strengths, Weaknesses, Opportunities, and Threats
ICT	Information Communications Technology	THz	Terahertz
IIBS	Internet Information Broadcast Storage	TS-SDN	Temporospatial SDN
INC	In-Network Computing	UAV	Unmanned Aerial Vehicle
IoT	Internet of Things	UE	User Equipment
IRS	Intelligent Reflecting Surface	uHSLo	ultra-High Sensing and Localization
IT	Information Technology	uRLLC	Ultra Reliable Low Latency Communications
IWD	iNet Wireless Daemon	VLC	Visible Light Communications
KPI	Key Performance Indicator	VNF	Virtual Network Function
MAC	Media Access Control	VR	Virtual Reality
MCDA	Multiple-Criteria Decision Analysis	VRA	Variables for Relevance Analysis
MEC	Multi-access Edge Computing	XR	Extended Reality
MIMO	Multiple-Input and Multiple-Output	WBAN	Wireless Body Area Network
ML	Machine Learning	WPT	Wireless Power Transferring

circle (●) shows whether the survey applied a method to classify the enabling technologies through a relevance analysis for 6G networks.

With these definitions, we analyzed the following works [22], [23], [24], [25], [26], [27], [28], [29]. The results are described below and summarized chronologically in Table 2, where we highlight their contributions and gaps in terms of each aspect.

Zhang et al. [22] published one of the first articles on 6G. In this work, they identified eight network requirements, i.e., latency and spectrum efficiency, and 14 potential enabling technologies, such as Thz communications and AI, essential for building the foundation of the 6G architecture. Also, the authors established five clusters and discussed their influence on the network concerning application support. With this, they presented some potential challenges and visions for deploying 6G systems. Finally, the authors proposed design principles for an architecture capable of supporting typical connectivity scenarios. Despite its importance, this work did not introduce any relevance analysis or methodology to define the merit of each enabling technology.

Furthermore, Mohsan et al. [23] addressed 6G technologies into four different clusters: artificial intelligence-driven, special architectures, and evolutionary and revolutionary technologies. The authors also mentioned 15 enablers and network requirements for 6G. Among the enablers, five were outlined due to their potential relevance for guaranteeing a private and secure communication system. Here again, the authors did not follow any methodology to rank and analyze the enablers.

Lu and Zheng also presented in [24] a set of core technologies for 6G, sorted into five different topics: wireless communication technology and system, next-generation antenna and basic synthetic materials, next-generation channel coding and modulation technique, spectrum sharing, and other integrated new technologies. Then, the authors identified 12 enablers, such as ultra-massive MIMO and NOMA. In addition to these enablers, a network coverage framework was proposed considering the multiple scenarios and challenges envisioned for 6G. Still, the relevance and methodology aspects were not discussed in this work.

In [25], Yazar et al. presented an ultra-flexible 6G infrastructure by classifying the enablers that can meet this demand. The 31 enablers were divided into seven categories: flexible multi-band utilization, ultra-flexible PHY and MAC, ultra-flexible heterogeneous networks, integrated sensing and communications, intelligent communications, green communications, and secure communications. The authors also proposed a 6G framework with AI tools for designing a flexible cognitive engine, which was defined as a bridge between 6G applications and the possible enablers for meeting their requirements.

To understand the envisioned demands for 6G, Xiaohu et al. [26] sought to integrate the evolutionary and revolutionary premises of the next generation by presenting 15 enabling technologies essential to support 6G wireless systems. These enablers were divided into two groups: air interface and transmission technologies, and network architectures. In addition, authors considered new paradigm shifts, such as global coverage, all-spectra, AI enabled wireless networks and endogenous network security. A similar reasoning was employed in [27], in which the 6G enablers were categorized into five clusters: spectrum, networking, air interface, architecture, and paradigm. The authors comprehensively detailed 26 enablers and analyzed their impact on 6G KPIs by classifying them as generic/weak or specialized/critical. Here, the authors also meticulously described 15 network requirements and compared them to their 5G counterparts. Despite the analysis, both surveys [26], [27] did not provide any methodology for metric analysis.

In [28], Shahraki et al. discussed 6G requirements, trends, use cases, scenarios, and KPIs, and sorted 16 enablers in two clusters: evolutionary and revolutionary technologies. Here, a brief significance analysis was introduced to empirically score each requirement according to a specific application. The authors also highlighted future works and challenges to allow the integration of these promising technologies in the 6G architectural design.

More recently, Quy et al. [29] investigated 6G by proposing a visionary architecture to achieve global coverage. This architecture encompasses all four types of networks, i.e., space, aerial, terrestrial, and undersea networks.

This innovative approach leveraged 11 enablers and divided them into four clusters: endogenous AI, intelligent radio layer, network protocol, and real-time interactive system. Furthermore, this survey paid attention to spectrum enablers (THz and VLC), quantum communications, blockchain, and Metaverse-related technologies. As expected, the authors did not provide any relevance analysis or methodology to select and rank the enablers.

After carefully analyzing each survey, some observations can be drawn as recapped in Table 2. Regarding A1, the maximum number of enablers considered in a related work was 31. In A2, the enablers were grouped into up to seven clusters. For A3, we verified that the surveys covered practically the same network requirements, except when presenting a specific architecture. In A4, none of the related surveys presented an in-depth relevance analysis of the 6G enablers. As mentioned previously, relevance analysis is the ranking process used to determine the influence of an enabler to compose a 6G architecture. Finally, the A5 aspect checked which related surveys covered a relevance analysis of the enabling technologies using a well-defined methodology. And yet, none of the investigated surveys applied quantitative or qualitative analysis for ranking the relevance and merit of each enabler.

After analyzing all five aspects, we found that most studies lack a detailed analysis of relevance or the usage of innovative and efficient methodologies to classify the importance of enabling technologies in 6G network development. To fulfill this gap, we present a comprehensive discussion on the next generation of mobile communications, encompassing 72 enabling technologies and 8 enablers' clusters. We also consider 4 design scopes of 6G architectures, different use cases, and their respective requirements. For this, a complete and deep relevance analysis is developed using an innovative methodology to define the relative importance of the enablers addressed in 6G scenarios through two different techniques. These methodologies will be detailed in the next section.

TABLE 2. Comparison among the related works from the point of view of the 6G enabling technologies.

			A1-A5 Aspects					
Ref.	**Year**	**Title**	**A1:** Number of Enablers	**A2:** Number of Clusters	**A3:** Network Requirements	**A4:** Relevance Analysis	**A5:** Methodology for Merit Analysis	**Comments**
[22]	2019	6G Wireless Networks: Vision, Requirements, Architecture, and Key Technologies	14	5	8	○	○	The paper dives into use cases, key network requirements, and technologies to support intelligent 6G wireless networks. Unlike ours, this survey focuses on a building base architecture for 6G networks considering technical objectives and design principles present in the state-of-the-art.
[23]	2020	6G: Envisioning the Key Technologies, Applications and Challenges	15	4	15	◑	○	Some technologies were considered as new 6G paradigms. In addition, a few 6G enablers were addressed, considering only the privacy and security concerns.
[24]	2020	6G: A Survey on Technologies, Scenarios, Challenges, and the Related Issues	12	5	10	○	○	Since the article performs a general overview of 6G, which is not only directed to core technologies, a relevance analysis of approached enablers was not performed.
[25]	2021	6G Vision: An Ultra-Flexible Perspective	31	7	12	◑	○	The paper presents a 6G framework with a proposal of a flexible cognitive engine which analyze applications and define the possible enablers for meeting respective requirements. Enablers are introduced only within a radio access technology perspective.
[26]	2021	Towards 6G Wireless Communication Networks: Vision, Enabling Technologies, and New Paradigm Shifts	15	2	7	○	○	New paradigm shifts were not classified as enabling technologies (i.e.: AI enabled wireless networks). In addition, as the focus of the paper is not only about the technologies, a deep analysis of enablers were not addressed.
[27]	2021	The Road Towards 6G: A Comprehensive Survey	26	5	15	◑	○	The analysis of enablers is based on the technical requirements of 6G, specifically in terms of a set of KPIs.
[28]	2021	A Comprehensive Survey on 6G Networks: Applications, Core Services, Enabling Technologies, and Future Challenges	16	2	13	○	○	The article introduces a survey on 6G, presenting general aspects of the future networks, not focusing on its enablers, specifically. Therefore, it was not accomplished a detailed analysis about the 6G technologies in this paper.
[29]	2023	Innovative Trends in the 6G Era: A Comprehensive Survey of Architecture, Applications, Technologies, and Challenges	11	4	5	○	○	This survey introduces a new vision for 6G architecture focused on extreme global coverage. The authors mainly discuss the technological enablers essential for achieving this new integrated architecture.

III. METHODOLOGY

This survey has adopted the methodology presented in Figure 2. First, we began with a literature review on relevant databases, namely IEEE, Springer, Elsevier, IRTF, and Google Academics databases. A set of *keywords* related to 6G architectures have been adopted: 6G, 6G architectures, 6G networks, beyond 5G, THz communication, 6G blockchain, 6G digital twins, 6G NFV, network slicing, service function chaining, 6G SDN, VNF performance evaluation, marketplace, distributed ledger technology, smart contracts, blockchain-enabled, blockchain-enhanced, IOTA, decentralized network, neuromorphic computing, in-network computing, computing in the network, in-network processing, cloud elasticity, radio access network, quantum networking, quantum computing, quantum Internet, and open access radio networks. In this set, we also considered keywords such as enablers, requirements, survey, and use cases.

The second step implied on formulating the questions which we would like to answer in our research, while the third step is intended to map how to actually answer them. For this, we started by defining the main research question (*Main Question* - MQ) and several specific correlated questions (*Sub-Questions* - SQs) that should be answered to address the proposed objectives. These questions are also presented in Table 3. They were formulated with the following reasoning:

- MQ: We want to rank the most relevant enabling technologies for 6G.
- SQ1: It aims to define the key roles to be performed by a 6G architecture. In addition, we defined a set of clusters in which the 6G enabling technologies addressed in our literature review can be classified. Therefore, each cluster refers to a key role previously defined that is expected to be performed in a 6G architecture, being composed by a set of enablers capable of fulfilling these specific

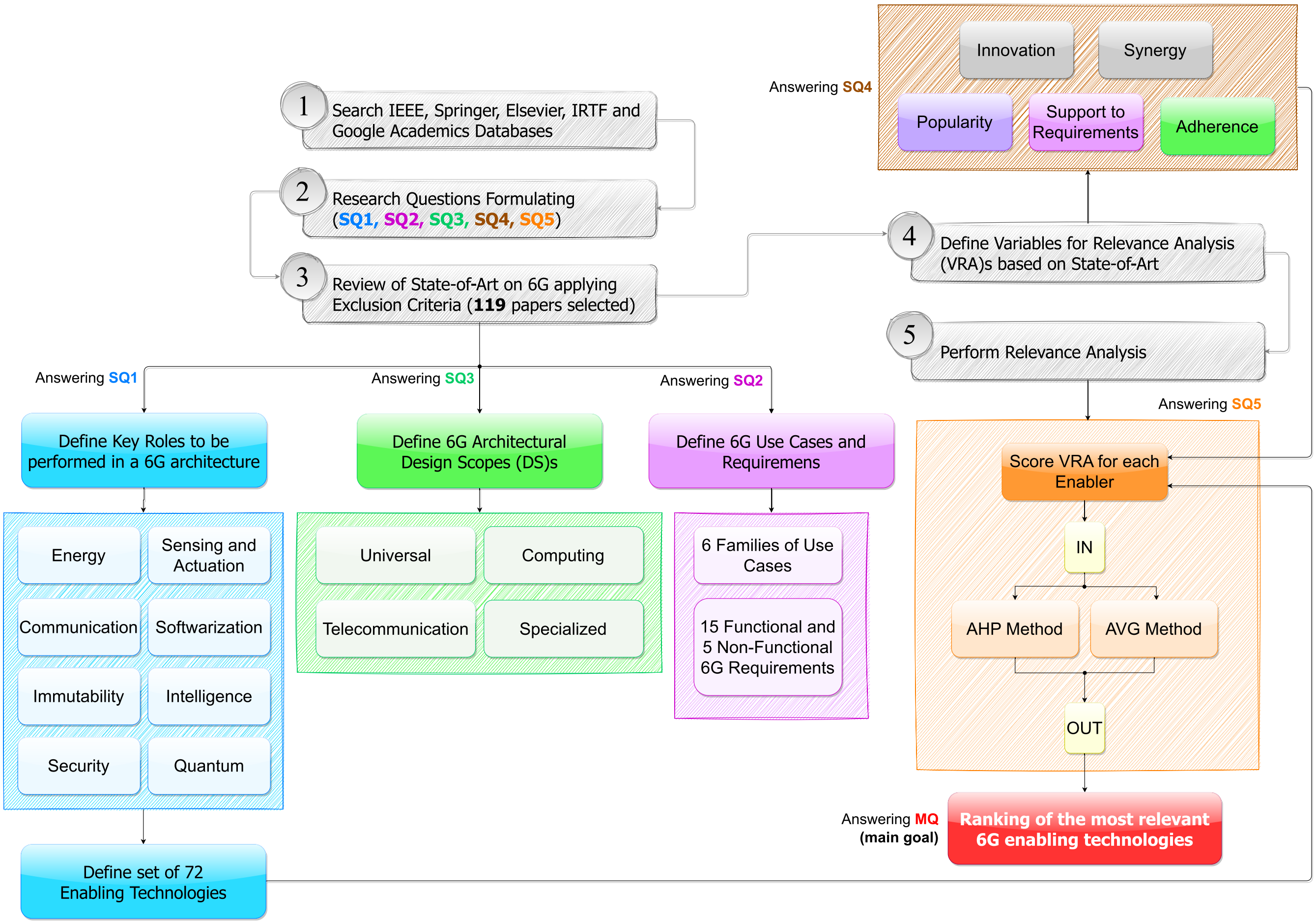

FIGURE 2. Methodology applied in this article.

responsibilities. The literature review of key roles for 6G architectures and enabling technologies will be detailed in Subsection IV-A.

- SQ2: It aims to discover the correlation between 6G enablers and use cases, in addition to determine user and network requirements for 6G architectures. In other words, we want to investigate the relevant 6G use cases, their requirements, and how enabling technologies help achieve them. he enablers are expected to support in one or more 6G challenges. The 6G use cases and requirements will be described in Subsection IV-B.
- SQ3: We want to determine the main architectural design scopes used to design a 6G architecture and how the enabling technologies can be classified into these DSs in order to later analyze the importance level of an enabler for each scope. Subsection IV-C will present in more details the DSs defined for our relevance analysis.
- SQ4: Through the in-depth literature review performed in our paper to answer SQ1, SQ2 and SQ3, we would like to use these results to map the influencing variables capable of conditioning the relevance of an enabling technology for a 6G architecture (VRAs). The VRAs will be detailed in Section V.
- SQ5: It intends to provide a rank of priority for enabling technologies. Based on the set of main 6G enabling technologies pointed out by the results from SQ1, combined with the influencing VRAs discovered through SQ2, SQ3 and SQ4, we can score the impact of these variables for each enabler. These results will be used as input parameters in the methods selected to perform our relevance analysis. In order to answer this sub-question, we must also choose the optimal methods that will be used for applying this relevance analysis and ultimately rank the most relevant 6G enabling technologies, answering the MQ. The VRAs scoring, the analysis methods and the ranking of the most relevant 6G enablers will be deeply discussed in Subsections VI-A, VI-B and VI-C, respectively.

In the third step, we introduced a review on the state-of-the-art of 6G in order to answer the SQ1, SQ3 and SQ3 sub-questions. This review was performed by analyzing and partially reading papers selected in step 1. The selection gave preference to references that deal with the integration of enablers for 6G and *beyond* 5G. Also, it covers 6G technologies, architectures, use cases and requirements that have the potential to be implemented in 6G. Then, we applied the exclusion criteria presented in Table 4, which was performed manually. Based on this review, we selected 72 enabling technologies grouped into 8 different clusters considering similar principles and functions for fulfilling the key roles to design a 6G architecture in order to answer SQ1. Furthermore, we mapped 6 families of 6G use cases, 15 functional and 5 non-functional 6G requirements, in addition to 4 6G architectural DSs, for answering SQ2 and SQ3, respectively. The clusters of enablers, DSs, 6G use cases and requirements will be used to further define and scores the VRAs, answering SQ4.

As previously mentioned, the initial results were refined for answering SQ5, ranking 6G enablers according to the VRAs scoring and selected metrics for the analysis methods. The scoring activity was performed quantitatively (when possible) and qualitatively. As our main contribution in this article, two significant metrics have been defined based on the scores obtained: (i) AVG; and (ii) AHP. In AVG, we calculate the average of the VRAs scoring for each enabling technology considering a value from 0 to 10 for its relevance, whose value of five (5) was adopted as the passing score. In contrast, the AHP method proposes the value of one (1) addressed to the sum of the enablers' scores on each cluster responsible for designing a specific key role in a 6G architecture. Based on this premise, it makes possible to analyze the most relevant enabling technologies for each specific key role of the 6G architectures by adopting as passing score the median of the score values of the enablers in each cluster. Consequently, these results make it possible to design an optimized 6G architecture that relies on the most critical enablers to fulfill the 6G key roles. The selection criteria for the used methods will be discussed in more details in Subsection VI-B.

In the next Section, we introduce the state-of-art performed in our paper, comprising the surveyed 6G enabling technologies and their respective clusters as a result to answer SQ1; 6G use cases and requirements to answer SQ2; and architectural DSs to solve SQ3.

IV. STATE-OF-ART ON 6G

In this Section, we performed an in-depth state-of-art on 6G architectures based on the methodology and the exclusion criteria described in the previous Section. The main goal of this literature review is to define the key roles of a 6G architecture and consequently the possible 6G enabling technologies capable of performing theses key roles. In addition, the state-of-art also provides a detailed review related to architectural DSs, 6G use cases and requirements, which will be needed to further define the conditioning variables for the relevance of an enabler. Table 5 illustrates an overview of the state-of-art on 6G architectures.

According to Table 5, 119 papers related to 6G architectures were used for performing the state-of-art, in which all of them discuss about 6G key roles and enabling technologies. As result, we mapped 8 key roles to be carried out by a 6G architecture and 72 possible enabling technologies capable of performing these tasks. In addition, based on this literature review, we also mapped 4 architectural DSs, 6 families of use cases, 15 Functional and 5 Non-Functional 6G Requirements, whose results will be used to further define the variables capable of conditioning in the relevance of an enabling technology. As a result, this state-of-art also intends to answer SQ1, SQ2 and SQ3 sub-questions previously defined in Table 3, in addition to also support SQ4 and SQ5.

For better understanding of the reader, the results achieved by this state-of-art are organized in the following Subsections. Subsection IV-A presents the key roles to be accomplished by a 6G architecture and the enabling technologies capable of performing these roles. Subsection IV-B introduces the 6G use cases and network requirements presented in our state-of-art. Finally, Subsection IV-C describes the DSs also mapped in our literature review.

A. KEY ROLES OF A 6G ARCHITECTURE AND ENABLERS PRESENTATION

6G enablers are relevant technologies for developing the next generation of mobile devices support. Enablers can be found in different stages of development and might evolve even further for a successful deployment in 6G. The role of each enabler inside the 6G architecture depends virtually on its principles and characteristics. For a better organization of the paper, this section is divided into Subsections IV-A1 and IV-A2. In Subsection IV-A1 we provide a taxonomy that groups essential 6G enablers into clusters of key roles to be accomplished by 6G architectures, while in Subsection IV-A2 we describe each one of the enabling technologies sorted into these groups.

1) KEY ROLES OF A 6G ARCHITECTURE

The set of key roles to be performed by a 6G architecture was defined by a taxonomy based on the state-of-art introduced in our paper and previously summarized in Table 5. These key roles are described in Table 6.

We grouped the enabling technologies capable of performing key roles to be fulfilled by a 6G architecture into different clusters, in which each cluster is related to a specific key role described in Table 6, With this rationale, we grouped all energy-related enablers in an Energy Enablers Cluster. The Sensing and Actuation Enablers Cluster corresponds to themes related to IoT and physical world monitoring. The Communication Enablers Cluster are typically linked to mobile telecommunication networks. The Softwarization Enablers Cluster includes all the enablers associated with the increasing role of software in a 6G architecture. Another Cluster has emerged from enablers related to immutable distributed record of information and deterministic computing (Immutability Enablers Cluster). The Intelligence Enablers Cluster shelters the increasing use of network intelligence, self-knowledge, and the capacity of reducing human interference in management and operations. The last two groups cover security (Security Enablers Cluster) and the quantum world (Quantum Enablers Cluster). It is important to note

TABLE 3. Research questions.

Type	Description
MQ	What are the most relevant enabling technologies for 6G?
SQ1	What are the key roles to be performed by 6G architectures and the possible enabling technologies to fulfill these roles
SQ2	What are the main 6G use cases and their network requirements to be met?
SQ3	In which architectural design scopes new enabling technologies can be applied?
SQ4	What are the main variables that can influence in the relevance of an enabling technology for 6G architectures?
SQ5	Based on chosen method(s), what is the relative importance of each enabler for fulfilling the key roles of the 6G architectures?

TABLE 4. Quality check criteria.

Type	Description
C1	Elimination of references that are unrelated or that cannot provide enablers for 6G.
C2	Elimination of articles older than 2018, with few exceptions of historical relevance.
C3	Elimination of dissertations and theses.
C4	Deletion of conference papers and other types, including non-peer-reviewed papers. Some IEEE conference papers and IRTF *drafts* were kept as they were considered relevant to the work.
C5	Elimination of articles that do not address architecture or are not directly related subjects, for example, enablers.

that this taxonomy emerged from the articles analyzed when applying our novel methodology. It is not the will of the authors, but rather the result of the process explained above.

2) ENABLERS PRESENTATION

In this Subsection, we sorted 72 enabling technologies into 8 distinct clusters of key roles for designing a 6G architecture. Table 7 indicates the enablers of the Energy Enablers Cluster, i.e., Energy Harvesting, WPT, and Green Technology. These enablers refer to energy supply, expenditure, and transfer. Energy Harvesting is an important alternative to batteries, as power harvesting devices can balance conflicting design goals of lifespan and performance [145]. To increase battery longevity, several energy harvesting methods can be applied in 6G, including radio-frequency, micro-vibrations, and sunlight [36] harvesting. In WPT, energy transmission is performed using wireless communication as a connection channel between a power source and a device [146]. This technology is necessary in several use cases related to 6G, especially those involving IoT. With IoT, multiple business verticals will benefit from its versatility to support different types of sensors [146], being an important enabler for an always-connected society. Green technologies aim to reduce the impact of information and communication systems on the environment. It aims at sustainable development of industries and reduction of the human impact on the environment, collaborating to protect and conserve nature and biodiversity [38].

Table 8 presents the enablers related to the Sensing and Actuation Enablers Cluster. These enablers consist of Ubiquitous Sensing and IoT-Based Sensing technologies. Providing the network with real-world data in real time will be a challenging task for 6G. Ubiquitous and IoT-based Sensing will allow the development of several new use cases on Farming of the Future, Large-Scale DT, and Advanced Remote Interactions [149]. For example, Large-Scale DT use cases require high-precision sensing for positioning digital representations of real-world objects and collecting meaningful data from them (e.g., speed, altitude, etc.). Sensing technology is also crucial for implementing IWD [24], WBANs [150], SLAM algorithms [151], CAVs [152], among others.

The Communication Enablers Cluster, presented in Table 9, is the largest group of enablers. It represents the efforts to evolve data communication ranging from the traditional PHY layer, e.g., THz Communication and VLC, to high-level abstractions, e.g., IIBS and CoCoCo Convergence. In this cluster, THz Communication and SATSI are some of the most recognized technologies as part of the 6G networks, with ongoing preliminary experiments. SATSI are part of the initiative named NTN, introduced by the 3GPP as an evolution of the traditional terrestrial RAN, which may also include UAV, HAP, and 3D Networks. Similar to THz Communication, VLC and OWC also seek to explore other spectrum bands. IRS/RIS devices have also been praised for the next generation due to their innovative characteristics and recent advances in engineering new materials. Furthermore, other evolved traditional approaches have been considered for this cluster, such as Ultra-Massive MIMO, FAB, Ultra-Dense Networks, Intelligent OFDMA, Disruptive Waveforms, and Cell-Free Networking. Cell-Free Networking changes the

TABLE 5. Review of state-of-art on 6G.

Reference	6G Key Roles and Enablers	Families of Use Cases						Approach of Architectural Design Scope(s)	Approach of 6G Requirements
		F1	F2	F3	F4	F5	F6		
[22]	✓	✓		✓	✓		✓		✓
[26]	✓	✓						✓	✓
[27, 30–47]	✓							✓	
[28, 48–50]	✓			✓	✓				
[51], [52]	✓							✓	✓
[53–55]	✓				✓				
[56–58]	✓					✓			
[59–61]	✓				✓			✓	
[62–64]	✓				✓			✓	✓
[65], [66]	✓				✓	✓			
[67–70]	✓	✓	✓	✓	✓	✓	✓	✓	
[71–86]	✓								
[87], [88]	✓	✓		✓	✓	✓		✓	
[89], [90]	✓	✓		✓	✓	✓			
[91–96]	✓			✓					
[97], [98]	✓	✓	✓	✓	✓	✓		✓	
[99], [100]	✓			✓	✓			✓	
[101], [102]	✓			✓	✓	✓			
[103], [104]	✓	✓							
[105–107]	✓	✓			✓				
[108], [109]	✓	✓		✓	✓				✓
[110], [111]	✓				✓				✓
[112], [113]	✓								✓
[114]	✓	✓	✓		✓	✓	✓	✓	✓
[115]	✓	✓	✓			✓		✓	
[116]	✓		✓					✓	✓
[117]	✓		✓	✓				✓	✓
[118]	✓	✓	✓		✓	✓		✓	✓
[119]	✓	✓	✓	✓	✓	✓		✓	✓
[120]	✓					✓		✓	✓
[121]	✓					✓			
[122]	✓	✓	✓	✓	✓	✓	✓		✓
[123]	✓	✓		✓	✓				
[124]	✓			✓				✓	
[125]	✓	✓		✓	✓			✓	
[126]	✓	✓	✓	✓	✓				
[127]	✓			✓					✓
[128]	✓		✓	✓	✓				
[129]	✓	✓						✓	
[130]	✓	✓		✓	✓	✓			✓
[131]	✓	✓	✓					✓	
[132]	✓				✓				✓
[133]	✓	✓			✓			✓	
[134]	✓					✓		✓	
[135]	✓						✓	✓	
[136]	✓			✓		✓			
[137]	✓		✓	✓	✓	✓		✓	
[138]	✓			✓				✓	✓
[139]	✓			✓		✓		✓	
[140]	✓	✓		✓				✓	✓
[141]	✓	✓				✓		✓	
[142]	✓	✓	✓	✓	✓	✓	✓		
[143]	✓		✓					✓	
[144]	✓	✓						✓	

cellular network concept by adopting massively distributed MIMO systems and providing more service antennas than user devices. Moving on, HR goes a step further by combining some traditional concepts with advanced ones in

TABLE 6. Key roles to be performed by a 6G architecture.

Key Roles	Description
Energy	Energy supply, expenditure, and transfer are responsible for the system power supply.
Sensing and Actuation	Sensing of the physical world. The programmability of connected things.
Communication	Connectivity among architectural components, including aspects from physical, link, and network layers. Digital systems and networks. It includes new communication technologies.
Softwarization	Role of the software in 6G. It includes aspects related to virtualization, servitization, representation (digital twins), slicing and functional fragmentation, and enablers related to new virtual or augmented realities.
Immutability	Covers principles associated with the immutable register of information and decentralized deterministic computing. Also includes the so-called DLT and related topics, such as micro-payments, tokenization, smart contracts, and crypto-assets.
Intelligence	Support to decision making through AI, ML, SON and automatic pilots techniques. It includes the AI hardware, such as neuromorphic computing.
Security	Covers the essential security pillars: secrecy, integrity, authentication, availability, authorization, trust, transparency, identity, identification, traceability, and reputation.
Quantum	Includes quantum-related technologies applied to computing, communications, security, and machine learning.

TABLE 7. Enablers for energy cluster.

Enabler	Description
Energy Harvesting	Capacity of harvesting energy from the environment using, for instance, vibration/motion energy, thermal energy, light or RF radiation [145].
Wireless Power Transferring	Consists of transmitting energy using wireless communication as channel between the energy source and the device [146] [147].
Green Technology	Helps to reduce the environmental impact of information and communications technologies, aiming at a sustainable development of the technological sector [38] [148].

TABLE 8. Enablers for sensing and actuation cluster.

Enabler	Description
Ubiquitous Sensing	Ability to sense the physical world ubiquitously, providing remote control, discovery, data aggregation, and management of large-scale networks of sensors and actuators [153].
IoT-based Sensing	It is based on the IoT paradigm and primarily focuses on providing thousands of small interconnected devices that can work collaboratively with a common purpose [154].

order to build a highly innovative enabling technology. Other enablers are focused on high-level communication issues, mainly IIBS, CoCoCo Convergence, and PRA. Moreover, E-RAN represents the intense softwarization process started in 5G, which introduced elasticity and other cloud computing concepts to the communication infrastructure. Due to the extensive demands of 6G networks, other past generations' enablers have also arisen as a possible solution. This is the case of D2D, Delay-awareness and Intermittent Connectivity, DSA, and CR. Finally, Molecular Communication offers the opportunity to support specific scenarios, such as body networks, employing molecule-based nanotechnology to transport information. While this enabler has been investigated for over a decade, it is still considered a novelty.

The Softwarization Enablers Cluster, presented in Table 10, comprises the enablers related to programmability, virtualization, servitization, representation, slicing, functional fragmentation, and new realities (whether virtual or augmented). Such enablers include: SDN, TS-SDN, NFV, MEC, Network Slicing, O-RAN, DT, Avatars, Data Orientation, Service Orientation, Compute First Networking, INC, Network Caching, IBN, AR/VR and Cloud Elasticity. With the proliferation of mobile and IoT devices, 6G is expected to be highly distributed, having more network functions executed at the edge. In this context, the Softwarization of the network will evolve even further to support new paradigms and applications. For instance, paradigms that increase the programmability of the network, such as SDN and NFV, will still be relevant in 6G since these technologies simplify the infrastructure configuration. In particular, TS-SDN will perform an essential role in the inter-operation and coordination of NTN. Another key enabler that simplifies network configuration and operation is IBN. With 6G, network optimization is envisioned to be orchestrated by AI and ML algorithms. Such a feature will allow a natural integration of IBN into the network architecture.

Alternatively, micro-services and other trends in Service Orientation will promote the utilization of smaller software functions deployed and executed independently. Smaller software functions enable better software management in cloud-native environments due to the replication of individual components through cloud elasticity. Cloud elasticity also mitigates resource over-provisioning and promotes lower energy consumption, which is a crucial issue in 6G. With more functions and services being pushed to the edge, more computing and caching capabilities will be introduced in the immediate proximity of the users. Therefore, paradigms that incorporate computing into the network, such as MEC, Compute First Networking and INC will be widely adopted. To fulfill the requirements of such dense network edges, O-RAN opens up the RAN from a single vendor environment to a standardized, multi-vendor, and intelligent controller structure, which will be consolidated in 6G. Finally, as virtualization evolves, new applications and vertical markets will arise exploring DT, Avatars, and AR/VR. This diverse and dense environment will impose a significant challenge to Network Slicing, especially in terms of E2E slice management.

The Immutability Enablers Cluster, presented in Table 11, addresses persistent and unchangeable registry and decentralized deterministic computing often operated by DLT in the form of Smart Contracts. Blockchain is the most common DLT employed in both public and permissive networks. Bitcoin, Ethereum, Solana, and Cardano are examples of public Blockchain-based cryptocurrencies, while Linux Hyperledger, R3 Corda, Quorum, and MultiChain are examples of permissive Blockchains [195]. Alternatively, the IOTA environment is a permissive solution focused on IoT devices where it employs a unique structure known as Tangle. Unfortunately, some of these technologies do not support Smart

TABLE 9. Enablers for communication.

Enabler	Description
UAV	Flying platforms are used as a key enabler for various 6G applications such as aerial base stations to improve coverage, capacity, reliability, and energy efficiency in wireless networks and floating mobile terminals within a cellular network [118], [155].
THz Communication	THz spectrum ranges from 0.1 THz to 10 THz, turning into a viable solution for new applications such as holographic communications, wireless cognition, sensing, positioning, and imaging [156], [157].
VLC	VLC provides data transmission through modulation of light waves in the visible spectrum, with wavelengths ranging from 380 nm to 750 nm [158].
Ultra-Massive MIMO	It is an ultra-dense scenario of antennas proposed to solve distance-related problems, by supporting wireless data rates of up to several Tbps [159].
IRS/RIS	This technology is capable of significantly improving the performance of wireless communication networks by intelligently reconfiguring the wireless propagation medium using a large number of low-cost passive reflective elements integrated into a flat surface [160], [161].
OWC	It is a strategy to employ optical signals in visible (> 380 nm and < 750 nm), ultraviolet (< 380 nm) and infrared (> 750 nm) spectrum [162]. Normally used in short-distance communications due to the inherent limitations of propagating optical signals in environments with physical obstacles.
SATSI Networks	It is composed of systems that integrate terrestrial, air, space, and maritime networks [31], [118].
D2D	This technique allows direct communication between devices, such as cellphones or vehicles, without contacting the network infrastructure [163].
NOMA	NOMA is an effective radio access technique whose advantages include better spectral efficiency, reduced latency, high reliability, and massive connectivity, allowing higher data rates as expected of 6G wireless systems [164].
FAB	FAB is a technique that focuses a beam at a specific receiver rather than scattering the signal in all directions from a transmitter, resulting in a faster and more reliable connection. It is based on complete analog, digital, or a combination of both (hybrid) beamforming [165].
Haptic Protocols	These protocols are related to applications that involve touch, perception and manipulation of real objects. It is focused on 6G applications and services aimed at the Tactile Internet, being more sensitive to jitter and latency [126], [166].
Ultra-Dense Networks	Based on the distribution of a large number of small cells known as micro, pico, and femtocells. These networks are characterized by lower energy consumption and cost and higher user density and capacity [167].
IIBS	Strategy in which information is collected, selected, and sent to a satellite periodically. This data is later transmitted to distributed servers provided by the satellite and, finally, sent to end-users by the servers [168].
CoMP	It refers to different techniques that coordinate the transmission and reception of systems served by geographically separated antennas. These algorithms allow interference management and performance improvement on the UEs side [169].
Intelligent OFDMA	It is a standard related to OFDM for supporting multiple users and enabling access points to communicate with multiple clients with varying bandwidths. This technique allows allocating an entire channel to a single customer or partitioning it to serve multiple clients simultaneously.
HAP	HAP are fixed radio stations located at an altitude of 20-50 km with the potential to provide broadband connectivity to on-terrestrial users [135].
Disruptive Waveforms	New waveforms need to consider network performance, frame structure design, parameter selection flexibility, and signal processing algorithm complexity in addition to supporting flexible splitting of the network.
Delay-awareness and Intermittent Connectivity	The ability of a system to handle latency variations, which is particularly common in mobile networks, and temporary loss of connectivity of a node without affecting the communication [170], [171].
CoCoCo Convergence	Convergence among communication, computing and control systems defined for 6G as a standard enabler to solve timeliness and resilience problems due to coupling between them [172].
PRA	PRA employs the user's behavioral history to optimize the system's QoS. The average rate on networks can be predicted directly from the history of average rates, or indirectly from the traffic load and the user's trajectory [173].
DSA	DSA aims to mitigate the scarcity of RF spectrum by allowing secondary networks to access idle licensed frequency bands [174].
CR	RF systems capable of detecting which frequency bands are available to allocate users without causing out-of-band interference [175].
3D Networks	3D Networks are the integration of heterogeneous technologies such as satellite, submarine, UAV, and maritime connectivity to terrestrial communication systems as a solution to improve data rate and coverage imposed by future networks [118], [176].
E-RAN	E-RAN consists of increasing or reducing the computing capacity on-demand by adjusting the number of physical and virtual machines. With E-RAN, the degree of elasticity is improved allowing the fine-tuning of its actions [116].
HR	HR is an essential enabler for 6G networks due to its ability to manipulate the atributes of different electromagnetic propagation regimes. It requires an optimized control of radiation beams obtained by adopting large intelligent antennas on mobile devices or access point [177].
Cell-Free Networking	Cell-Free Networking is a type massively distributed MIMO system. It uses time division duplex communication and a large number of service antennas geographically distributed operating together to serve a smaller number of user devices [178].
Molecular Communication	In this communication system, molecules transport information between two points, being supported by nanotechnology [179].

Contracts, which are an essential 6G enabler. With Smart Contracts, the Blockchain's information architectures can explore digital monetizing transactions through Tokenization. In this context, cheap transaction fees provided by IOTA and other DLTs are crucial to enable service and resource monetization via Micropayments. In other words, these features will revolutionize digital markets by allowing the commercialization of Data, Connected Things, Electromagnetic Spectrum, Virtual Network Functions, and Infrastructure and Network Slices. These emerging digital payment markets will deeply impact the design and implementation of 6G systems.

Table 12 presents the Intelligence Enablers Cluster, whose enabler are related to decision-making and AI hardware, including AI, ML, SON, SEN, Zero-Touch management, and Neuromorphic Computing. To support 6G's demanding requirements, the network needs to evolve towards a

TABLE 10. Enablers for softwarization cluster.

Enabler	Description
SDN	SDN brings programmability to networks by finely orchestrating and controlling applications and services [180].
TS-SDN	TS-SDN enables SDN applications to make network decisions based on the location, movement, and orientation of devices or assets in space, providing greater flexibility in network operation and infrastructure programmabilit [181].
NFV	NFV is a paradigm that transforms the way networks are built and operated, consolidating network functions, originally based on proprietary hardware, into commercial servers, using virtualization technologies found in cloud computing environments [182].
MEC	MEC is an extension of RAN with processing and storage capabilities similar to the ones used in cloud computing. It takes advantage of the proximity between end-users and service providers to create an IT environment with ultra-low latency and high bandwidth [183].
Network Slicing	It represents the end-to-end logical networks running on a common underlying physical or virtual infrastructure (isolated from each other) with independent management, which creation is available on demand [184].
O-RAN	O-RAN is an open standard for programmability and virtualization of the RAN, in which functions are fragmented, distributed, virtualized, and executed in a local data center following an NFV model [115].
DT	DT s a digital representation or virtual copy of machines, systems, and other physical entities. It is considered a critical technology for industrial plants to improve productivity and quality and reduce costs [185], [186].
Avatars	Avatars are fictitious representations of persons or objects in a virtual plane. For instance, in 3D holography, the Avatar characterizes the object to be teleported, build, and projected in real time. [187].
Data Orientation	It is a concept wherein the network is centered on data, content, or information. Unlike the *host*-oriented Internet architecture, devices communicate based on named data rather than IP addresses [188].
Service Orientation	It is a software design paradigm that emphasizes modular development, flexible systems, reusable components, and a common communication language. With Service Orientation, computing resources are provided ubiquitously on demand [189], [190]
Compute First Networking	It is a distributed computing environment that provides a programming platform through a decentralized resource allocation approach for use cases related to information exchange, processing, and storage architecture [47].
INC	It is a network-embedded computing concept to deploy processing functionality in network devices such as switches and NIC [140].
Networking Caching	The Network Caching is a mechanism that provides temporary storage to reduce bandwidth, server load, and response time [191].
IBN	IBN is a network management framework in which the administrator's intent is expressed abstractly and prescriptively, transferring their intent to every network device automatically. With IBN, operators can adjust network parameters regardless of the infrastructure diversity [192].
AR/VR	AR is a technology that combines both the virtual and real world to enhance the user's perception of their surrounding environment. On the other hand, VR simulates a computer-generated environment and allows a virtual interaction between users and the virtual world [193].
Cloud Elasticity	It refers to the cloud's ability to manage and adapt its resources on demand [194].

TABLE 11. Enablers for immutability cluster.

Enabler	Description
DLT	DLT is a data structure for registering transactions immutably and uniquely. Each DLT uses different data models and technologies based on public-key cryptography, peer-to-peer distributed networks, and consensus mechanisms [196].
Blockchain	Blockchain consists of a list of connected data blocks where each block contains the transaction's information. Its integrity and immutability are guaranteed through a hash function, calculated by the miners. This procedure, also known as registration, is responsible for establishing the connection between blocks and creating the Blockchain network [197].
Tangle (IOTA)	Tangle is an alternative DLT structure wherein every new transaction validates two previous ones. A weighting mechanism determines which pending transactions will be validated by the new one. With this feature, energy expenditure is reduced and validators are not rewarded in digital currency. The IOTA environment focuses on IoT devices and employs Tangle to perform decentralized, perennial, and immutable registration of cost-free transactions. Also, IOTA supports Smart Contracts [198].
Smart Contracts and Tokenization	They are immutable and executable programs that act on the terms and conditions of a given contract using a computing infrastructure. These contracts operate like distributed programs on a blockchain network and can be used in a decentralized manner without dependence on a centralized third party [199].
Micropayments	Micropayments refer to a DLT technology capable of performing value transfers (in terms of crypto assets) of less than one cent of a dollar, allowing the digital monetization of 6G and IoT.
Data Market	It employs DLT and Smart Contracts to buy and sell randomized (or authorized) data by its owner [200].
Connected Things Market	The Connected Things Market or Economy of Things is defined as the sharing of IoT resources via DLT, also being supported by Smart Contracts [198], [201].
Electromagnetic Spectrum Market	This market arises by joining DSA and DLT technologies. Due to spectrum scarcity, wireless devices are evolving to support opportunistic and shared frequency allocation. Thus, with DLT, the underused spectrum can be digitally monetized and commercialized [187], [174].
Virtual Network Functions Market	The Virtual Network Functions Market arises from the convergence between NFV and DLT, in which a VNF is executed as DApps in a DLT [202].
Infrastructure and Slices Market	A business model based on connectivity offered by operators, leading to an ecosystem in which multiple parties offer different resources on demand. The basis for this market are enablers related to network softwarization and new technologies, such as Blockchain [203] and AI [204].

fully-AI driven ecosystem, where intelligence will natively integrate the network instrumentation, management, physical-layer signal processing, resource management, and service orchestration. Indeed, such a movement has become possible thanks to today's greater computing power. ML is the branch of AI that has stood out the most. ML is dedicated to learning input data and continuously improving the accuracy of the outputs using automatic optimization methods. In a fully-AI driven ecosystem, network management tasks such as planning, delivery, deployment, provisioning, monitoring, and optimization are executed automatically without human intervention. The term Zero-Touch Management is usually employed to designate such a management process. On the other hand, the complexity of zero-touch management justifies the revisiting of some enablers that had been previously investigated such as SON and SEN. The former can be used to apply QoS policies to reduce latency and increase reliability, to improve efficiency (both energy and spectral), or even to enforce security and privacy assurance policies. The latter can significantly impact various 6G requirements given the ability to meet restricted indicators, such as high availability and energy efficiency. Finally, Neuromorphic Computing can accommodate AI and ML algorithms in hardware with a much lower energy expenditure than the current ones.

Table 13 presents the description of the Security Enablers Cluster, composed of Homomorphic Encryption, Privacy, Trust/Reputation, and Identification Technologies. From a

TABLE 12. Enablers for intelligence cluster.

Enabler	Description
AI	As known, AI is a set of complex techniques that support the decision-making and optimization of mobile networks. One of 6G's main goals is to completely integrate AI into its architecture, approaching intelligence as a platform and a means of optimizing the entire system. ML techniques are applicable in multiple scenarios, such as radio control, core or access functions (physical or virtual), and communication between RANs [40], [107].
Neuromorphic Computing	Neuromorphic computing aims to understand and abstract the essence of natural neural architectures to design new artificial digital computers. It uses neuromorphic devices to mimic the operation of biological neural subsystems, such as some cognitive functions of the brain [205]. It has a much smaller energy fingerprint and can scale to larger deep learning networks.
Zero-Touch Management	It is used to designate a management process whose tasks (e.g., planning, deploying, provisioning, monitoring, optimizing, and decommissioning) are performed automatically, preferably without any human intervention [206].
ML	ML is an AI technique applicable to different 6G logic levels. ML is divided into offline learning, where the initial data set is used to train the predictor, and online learning, where the new data set is employed to perfect the predictor through progressive learning [130], [207], [208].
SON	It is a term that proposes concepts of autonomous computing and AI to manage radio in mobile networks, more specifically aimed at automating aspects of planning, configuration, optimization and self-healing [209].
SEN	It is a concept proposed by [210] as a SON evolution, by using more sophisticated AI techniques in order to create networks not only capable of decision making without human intervention, but also capable of learning and adapting.

TABLE 13. Enablers for security cluster.

Enabler	Description
Homomorphic Encryption	It is a cryptographic method that allows mathematical operations on data to be performed on ciphertext rather than on the data itself. The ciphertext is an encrypted version of the input data, which is processed and then decrypted to obtain the desired output.
Privacy Technology	The concept of privacy is related to the right to control the types of sharing and use of personal information [222]. Digital privacy can be guaranteed with randomness, either by adding noise or randomizing the raw data itself or by a function or statistic calculated directly on the data [223].
Trust/Reputation Technology	In service-oriented architectures, there is the notion of trust networks, which are networks formed by reputable services at the time of dynamic composition. On the other hand, DLTs are trustless solutions in which trust resides in the immutability of transactions and the deterministic computation provided by Smart Contracts. Therefore, both trust and DLT networks are needed to cover the entire 6G project space [224].
Identification Technology	To identify means to point to an entity uniquely in a context, scope, or set. New naming techniques have been discussed in the Future Internet landscape, such as SVN, which can be used as identifiers for content, services, devices, operating systems, and virtual network functions to make 6G networks more secure [225]. However, the adoption of SVN could require disruptive architectures.

security and privacy perspective, the 6G enablers need reconsideration of prior security traditional methods [211]. Novel authentication, encryption, access control, communication, and malicious activity detection must satisfy the higher standards of future networks [212]. In addition, new security approaches are necessary to ensure trustworthiness and privacy [211], [213]. In this context, some technologies are relevant to guarantee safe network access, such as 6G AKA, quantum-safe cryptographic schemes, and physical layer security [214], [215]. Homomorphic Encryption is an encryption method that allows working with encrypted data without decrypting it, minimizing the possibility of exposing the information. To achieve this goal, the computing processes can be performed directly on encrypted data [216]. Using homomorphic encryption, services can take advantage of cloud computing and storage with guaranteed security. It ensures usability by exchanging information securely since encrypted data can only be decrypted by the data owner using a secret key. Most homomorphic cryptography uses public-key encryption schemes, although public-key functionality is not always required [216], [217]. In the context of 6G networks, the systems can establish a higher data security standard without breaking business processes or application functionalities. These systems can ensure information privacy while deriving intelligence from their sensitive data [211]. Other use cases of Homomorphic Encryption include analytics aggregation with privacy-preserving encryption, information supply chain consolidation, and automation and orchestration with operating and triggering off of encrypted data for machine-to-machine communication [211]. Digital Privacy Technology is associated with the usage of information, sharing, and control of personal data. The digital privacy for 5G networks is performed by randomness in data sharing. Such randomness can be achieved by adding noise or randomizing the raw data itself, and through a static mathematical function calculated directly on the shared data. This system can be considered a principle for 6G networks to improve digital security. Regarding the concept of trust, the 6G architecture should be built by considering embedded trust into its design principle, increasing the information security level [213]. Based on this premise, Trust/reputation Technology considers trust modeling, policies, and mechanisms that need to be defined in the entire 6G network [213]. A trustworthy network can be achieved considering trust/reputation in all layers or end-to-end trust and policy-based architecture domain security [218]. In 6G, it is expected that network-based information technologies can be trusted to provide promising outcomes even in the face of malicious actors trying to interfere in it [213], [218], providing services significantly better than networks commonly used today [213]. Regarding identification technologies, some enablers can be cited, such as biometrics authentication, new open authentication protocols for non-3GPP access networks, and enhanced EAP-TLS [219], [220]. In addition, it can be pointed to mutual authentication for core network components with blockchain, end-to-end encryption, as well as cryptography and signaling integrity [221]. In application domain security, service-based architecture security, new HTTPS-TLS 3.0, quantum homomorphic and differential privacy are emerging terms considered in the literature [211], [215], [219].

Finally, aiming at emerging technologies in the context of 6G networks, the Quantum Enablers Cluster can be highlighted, including enablers such as QC, QAC and QI, QML, and Post-Quantum Security. Table 14 describes these enablers.

TABLE 14. Enablers for quantum technologies.

Enabler	Description
QC	It is a new computing theory in which the computer is considered a physical system governed by physical laws at very small scales, i.e., quantum mechanics, which is the most known accurate model of reality [226], [227].
QAC and QI	QAC uses quantum state exchange to improve traditional telecommunications systems by increasing the capacity of these systems and adding new functionalities [114], [228]. QI, on the other hand, aims to take advantage of quantum key distribution, secure byzantine agreements, distributed quantum computing, and physical sensors enhanced by quantum systems, integrating the quantum with non-quantum networks [229].
QML	It explores the interaction of QC and ML ideas, covering different areas, such as space exploration, nanoparticles, creation of new materials through molecular and atomic maps, medical research, and connection security through the fusion of IoT and Blockchain [230], [231].
Post-Quantum Security	It involves security techniques that can support attacks from quantum computers and its use on 6G networks since quantum computers will be available soon [134]. Postquantum cryptography, for example, deals with encryption algorithms that are secure even under attack from a quantum computer [232].

QC uses the principles of quantum mechanics and exploits these principles to perform operations on data. Quantum computers will be able to perform computational tasks in much smaller steps than conventional computers, in addition to genuinely unprecedented tasks, such as teleporting information, breaking currently used secret codes very quickly, and generating real random numbers [227]. QAC uses quantum state exchange to enhance traditional telecommunication systems [114], [228]. This technology promises to increase the capacity of these systems and include new functionalities. Using quantum algorithms improves channel estimation, multi-user detection, precoding, and data routing. The QI [229] aims to take advantage of quantum key distribution, secure Byzantine agreements, distributed quantum computing, and physical sensors enhanced by quantum systems. QML is an area of research that explores the interaction of ideas from quantum computing and ML. QML will cover different areas, such as space exploration, nanoparticles, creation of new materials through molecular and atomic maps, medical research, and connection security through the fusion of IoT and Blockchain.

The advent of quantum computers brought a problem to current security systems, which would be susceptible to several vulnerabilities under an attack of quantum computers. Postquantum security is an area that involves security techniques that can withstand attacks from quantum computers. Post-quantum cryptography, for example, deals with encryption algorithms that are secure even under attack from a quantum computer [232]. For the 6G design, quantum technologies can contribute to several approaches. For instance, QC can solve computationally complex problems in 6G related to optimization, such as finding optimal solutions for wireless resource allocation. QAC and QI can improve 6G security, by deploying QKD over the backhaul to connect radio access networks and the core network. QML, as previously mentioned, can contribute to 6G promoting ubiquitous wireless artificial in the network. Finally, it is expected that Post-Quantum Security will bring many advantages for quantum-enabled 6G, such as quantum-safe security, improved privacy protection, and communication efficiency from quantum-based real-time optimizations [233].

With the set of the key roles to be performed by a 6G architecture and the main enabling technologies defined, we consequently answered the SQ1 previously described in Table 3. In the next Subsection, we aim to answer the SQ2, related to main use cases and requirements for 6G systems.

B. 6G USE CASES AND REQUIREMENTS

Based on the state-of-art performed in our work, we mapped the 6G use cases into 6 different families. In addition, we also defined 15 Functional and 5 Non-Functional 6G Requirements to be met in order to make possible the development of these 6G use cases. Next, we described in the Subsections IV-B1 and IV-B2 the the literature review of 6G use cases and requirements, respectively.

1) 6G USE CASES

In the literature, some 6G use cases are already based on services available in 5G, accompanied by a vast enhancement in performance. This is the case of scenarios involving XR, which are an evolution of VR/AR, and connected robots building on the improvements enabled by 5G in industrial processes [110]. There are also use cases involving new disruptive applications, such as holography communications, which enables distant objects (or people) to be represented in 3D [67]. Similar to the approach proposed in [234], we grouped a set of representative use cases foreseen for 6G into use cases' families according to the type of usage and capabilities needed. These use cases' families are briefly described below.

a: EXTREME WORLDWIDE COVERAGE

This family encompasses use cases that demand for communication anywhere on the planet, including remote and hard-to-reach areas. This demand arises from several applications, such as the need to obtain valuable or even critical information for survival, scientific activities conducted in remote regions, economic activities performed in unassisted areas, and monitoring of biomes and animals, among others. Given its scope, this family also includes use cases that deal with sustainability, such as energy and water efficiency and reduced carbon emissions. Some examples of use cases in this context are global connectivity, global monitoring, and reduction of carbon emissions.

b: FARMING OF THE FUTURE

Smart farming is the usage of intelligent information and communication systems, such as sensors, IoT, cloud-based processes, machine learning, and farm networking, in everyday farm routines. These technologies can support crop cultivation, livestock farming, and logistics applications to boost the agriculture vertical with increased production, reduced cost and waste [235]. Examples of use cases in this family include high-precision livestock, agriculture, and logistics.

c: LARGE-SCALE DT

This family emphasizes the need for a closer integration between the virtual and physical worlds, enhancing the latter with the assistance of the former (i.e., the virtual world). With large-scale interactive virtual models, it is possible to assist decision-making with unprecedented information, accuracy, and speed. Large-scale DT also allow operations in the physical world to be instantaneous and straightforward. Naturally, given its size and complexity, simulation models and AI are critical to the success of this family of use cases. Dynamically Smart Cities and Industry 5.0 are valuable examples.

d: ADVANCED REMOTE INTERACTIONS

This family comprises use cases dedicated to providing new ways of interaction experiences, such as immersive tactile communication, telemedicine, and events. Immersive tactile communication involves the ability to interact with people and objects in virtual environments with perceptions of temperature, weight, and touch pressure, among other sensations. Applications of immersive telemedicine and manipulation of hazardous elements (radioactive, chemical, and biological), among others, are part of the spectrum of immersive tactile communications. On the other hand, immersive events will employ XR to expand communication, interaction, and content consumption (e.g., media, sports, games, among others), making them more natural.

e: INVISIBLE SAFE ZONES

While surveillance solutions have evolved significantly, there are still invasive and stressful approaches, for example, in banks, airports, and stadiums. Problems associated with crime, violence, theft, access to unauthorized areas, and terrorism are still relevant across the planet. The Invisible Safe Zones family focuses on use cases that address these scenarios, offering more suitable solutions using anticipated technologies for 6G, such as advanced sensing and high communication and computing infrastructure flexibility. Some examples of use cases in this scenario are security in public spaces, transparent control of crowds, and networks without infrastructure.

f: SPATIAL COMMUNICATION

This family focuses on the challenges of earth-moon communication and the transmission on the moon's surface. The importance of this family lies in the recent resumption of interest in investments in space projects, including sub-orbital, orbital, lunar, and other flights. In this context, long-distance communication and interference in the absence of an atmosphere are some of the significant challenges, primarily to support advanced applications. Earth-moon communication and communication on the moon's surface are some use cases of this family.

After identifying the use case families, we utilized these families to derive both functional and non-functional requirements for a 6G system, as detailed below.

2) 6G REQUIREMENTS

In network design, some characteristics are essential for selecting the appropriate enabling technology capable of supporting a specific use case. Here, we categorized these attributes into functional and non-functional requirements.

Traditionally, the functional requirements concern communication aspects such as throughput, latency, and coverage. However, for 6G networks, researchers have also include other aspects related to sensing, security, and mobility [236], [237]. Unlike the functional requirements, the non-functional ones are not associated with network functions but focus on aspects such as management and security.

Guided by our literature review and the use cases described in Section IV-B1, we provide in Table 15 a list of functional requirements identified for 6G [236]. This table indicates all the necessary requirements to fulfill a specific use case family.

In Table 15, the cell coverage concept is extended to shelter not only base stations but satellite stations as well, expanding coverage to up to 3,000 km.

Furthermore, Reliability is a key requirement for 5G networks. In 6G, the network is expected to achieve a new level of reliability with 99.9999999% (or 1-10^{-9}, as shown in Table 15). Energy efficiency have also become an essential requirement in 6G. The aim is to surpass in ten times the actual 5G network and to reach an efficiency one hundred times greater for the spatial communication use case. This last demand arises for communication on the lunar surface, given the energy production and storage restrictions in this environment.

The requirements associated with Sensing and Positioning are Spatial Accuracy of mobile devices and RF and Image Resolution. These requirements are often employed for applications that demand image capture through RF signals or multi-spectral cameras. Here, the term "Nominal" refers to an RF/Image resolution equivalent to 1920 × 1080 pixels, while "Critical" refers to 4K or 8K resolutions. In this context, it is worth highlighting the requirement for spatial precision of some families, such as Large-Scale DT and Advanced Remote Interactions, with a value of 1 cm, in addition to the Spatial Communication that may require less than 0.1 cm. The reason for such a low value in the Space Communication family is related to some critical tasks performed remotely, such as docking space vessels or lunar modules.

Regarding Security and Privacy requirements, we used the 5G network as a reference. Therefore, the term "Nominal" means that the requirement must be at the same level as these networks, while "Critical" indicates a higher level. Some families, such as Large-Scale DT, Advanced Remote Interactions, and Invisible Safe Zones, handle a high volume of sensitive data and demand a secure and private architecture.

TABLE 15. List of key requirements for the use case families of 6G networks.

Requirements	Use Cases Families					
	Extreme Worldwide Coverage	**Farming of the Future**	**Large-Scale DT**	**Advanced Remote Interactions**	**Invisible Safe Zones**	**Spatial Communication**
Throughput/User (Mbps)	10^{-1} up to 10	10^{-1} up to 10^2	10^{-1} up to 10^3	10 up to 10^6	10 up to 10^2	10^2 up to 10^3
Peak Throughput (Gbps)	> 1	> 1	> 100	> 10^4	> 100	> 10
Latency (ms)	< 20	< 1	< 1	< 1	< 20	< 10 / < 3.000 *
Coverage per Cell (km)	50 up to 3000**	> 50	< 1	< 1	< 1	> 50
Reliability	1-10^{-5}	1-10^{-5}	1-10^{-9}	1-10^{-9}	1-10^{-7}	1-10^{-5} / 1-10^{-9} *
Energy Efficiency	10x mMTC	10x mMTC	10x eMBB	10x eMBB	10x eMBB	100x eMBB
Spectral Efficiency (Related to 5GNR)	1x	1x	10x	10x	10x	1x
Spatial Accuracy (cm)	< 100	< 10	< 1	< 1	< 10	< 0,1
RF/Image Resolution	Nominal	Critical	Nominal	Nominal	Critical	Critical
ACLR without filter	Nominal	Critical	Critical	Nominal	Critical	Nominal
Access to Spectrum	With and without license	With and without License	With and without license	With license	With and without license	With and without license
Security	Nominal	Nominal	Critical	Critical	Critical	Critical
Privacy	Nominal	Nominal	Critical	Critical	Critical	Nominal
Density of Terminals (1/km^2)	100	100	10^4	10^4	10	10
Speed (km/h)	< 250	< 250	< 80	< 80	< 80	< 30

* Communication in lunar surface / Earth-lunar communication
** Considering satellite coverage

With these, some new concepts have emerged such as Cyber-security 360 and Privacy-by-Engineering Design mentioned in [237]. Cyber-security 360 refers to not only focusing on end-to-end security but also considering a top-down approach (from architecture and protocols to embedded software). The primary motivation is that most security vulnerabilities arise from poorly written code. The Privacy-by-Engineering Project aims to ensure that privacy mechanisms are natively integrated into the protocols and architecture. The intent is to provide the highest level of privacy by default unless explicitly stated otherwise.

As mentioned earlier, the non-functional requirements are related to network management and security aspects. Here, we identified 5 distinct non-functional requirements, as described below.

(i) **Flexibility:** The identified use cases for 6G networks have different functional requirements. For example, throughput per user can range from 100 Kbps to 1 Tbps, while spatial accuracy ranges from 0.1 to 100 cm, depending on the use case family. In this context, the 6G networks must be highly flexible by efficiently adapting its characteristics to every scenario.

(ii) **Modularity:** With 5G networks, telecommunications systems have evolved to be highly complex. Naturally, it is expected that the next generation will progress even further by expanding its support to new resources and applications. Thus, a modular approach is an essential feature for 6G networks, which will allow a required functionality to be activated on demand.

(iii) **Robustness:** Telecommunications systems are traditionally robust by adding extra layers of redundancy to their infrastructure. Since 5G, robustness has been receiving a lot of concern due to the intense adoption of softwarization, virtualization, and cloudification. Furthermore, in 6G networks, robustness will be an essential characteristic for more sensitive applications, such as telemedicine.

(iv) **Programmability:** In 5G networks, programmability was already considered an important requirement. With 6G, the network will push this demand to a new level by allowing standardized programming for different types of equipment at an unprecedented scale and speed. Heterogeneous systems will be a common trait of Large-Scale DT, and programmability is essential to support such a use case.

(v) **AI/ML as Service:** In 6G networks, AI/ML has been envisioned to permeate all network layers. With this feature, AI/ML will be extensively explored enabling a myriad of new services and applications, as mentioned in Advanced Remote Interactions and Invisible Safe Zones use cases. Thus, AI/ML as a service will become an essential 6G requirement for allowing the use of standardized interfaces, model sharing, and shared and controlled access to data, among other advantages.

Based on the state-of-art of 6G use cases and requirements previously presented, we answered the SQ2 defined in Section III. In the next Subsection, we discuss about the architectural DSs.

C. DESIGN SCOPES

Since the importance of an enabling technology can vary according to its role in 6G, we here provide a set of architectural DSs to group related works whose 6G architectures have similar concepts. By adopting this rationale, we can later analyze all important enablers for each DS.

TABLE 16. DS1-DS4 design scopes for 6G architectures.

Name	Design Scope	Description
DS1	Universal	DS1 focuses on all physical and virtual infrastructures for global and interplanetary coverage. It represents a wider range of architectures without focusing on a specific aspect. DS1 usually covers multiple uses cases.
DS2	Telecommunications	DS2 deals with 6G telecommunications networks and systems. In other words, it focuses on aspects related to the exchange of information between terminals and nodes. It might even address computing topics, but only to support communications systems. In general, DS2 is related with existing architectures of mobile networks, components, and concepts, and envisions an evolution of the current architecture.
DS3	Computing	DS3 addresses topics related to computing in data centers and edges and distributed and decentralized networks. It focuses on aspects related to information processing for the development of 6G networks. Although some network-related discussions may arise, they are not the main priority of DS3.
DS4	Specialized	DS4 represents aspects that demand a specific scenario or architecture for their deployment. Here, we included, among others, network security and management.

The 4 DSs considered for the Adherence VRA are described in Table 16. DS1 encompasses universal scopes, focusing on global coverage. Usually, this scope integrates enablers from the other DSs documented here. DS2 cover traditional mobile telecommunications networks, including 4G, 5G and beyond. DS3 consists of studies associated to computing. Finally, DS4 encompasses specialized architectures with fewer enablers in specific or limited scenarios.

Through this Subsection, the SQ3 detailed in Section III is finally answered.

Based on database provided by our state-of-art, encompassing key roles to be performed by 6G architectures, enabling technologies capable of making it possible, use cases, network requirements, and architectural DSs, we can now determine the VRAs to answer SQ4 as previously described in Table 3. The VRAs are the variables capable of influencing in the relevance of an enabler for a 6G architecture and will be presented in the next Section.

V. VARIABLES FOR RELEVANCE ANALYSIS

In this section, we present the VRAs previously mentioned on Section III. The VRAs are variables with potential to influence in the relevance of an enabling technology for a 6G architecture. For this proposal, we considered 5 VRAs, named as Adherence, Popularity, Innovation, Synergy, and Support to Requirements. The main goal is to later calculate the impact of each variable in the relevance of an enabler. The next subsections describe the 5 VRAs, how and why these variables were selected supported by the state-of-the-art previously performed, as well as their respective roles for the relevance analysis of the 6G enabling technologies. In addition, Subsection V-F defines the metric proposed to score the VRAs for each enabler.

A. VRA 1: ADHERENCE

One of the variables capable of influencing the relevance of an enabler is the Design Scope (DS) of the 6G architectural project in which it will be used, which may vary according to a specific application or demand. To facilitate this understanding, let's take the UAV as an example, which is an enabling technology already widespread in 5G networks and previously described in Subsection IV-A2. To meet the 6G demand for global coverage, the scope of the architectural project must be designed with technologies capable of enabling communication in terrestrial, space, maritime, and aerial domains.

In this case, UAV networks can be extremely important, and consequently, this enabler is highly relevant. On the other hand, this enabler does not have the same relevance in an architectural project scope designed for a demand for remote surgeries in a Smart Health use case, since the main technologies to make this application possible must be directed to meet maximum reliability requirements with extremely low latency and high transmission rate.

Therefore, we can conclude that there is an adherence level of the enabler referring to each scope of the architectural project. Based on studies related to the architectural scopes in our state-of-art (Subsection IV-C), we mapped 4 DSs (DS1-DS4). Finally, by using these information, we can analyze the adherence level for each enabler in the 4 DSs previously classified. The metric adopted for scoring this VRA will be detailed in Subsection V-F.

B. VRA 2: POPULARITY

Popularity is a VRA considered for our relevance analysis, since its variable is capable of quantifying how popular an enabler is concerning the literature review presented in Section IV. This approach can be considered as an influencing variable for analysing the relevance of an enabling technology, since it can indicate how widespread and established this technology is in a research area or industrial sector. In our case, if an enabler is widely cited in many papers related to 6G, it is likely to be considered an important or essential tool for performing certain tasks or activities in this context.

Furthermore, if a technology is cited in many relevant and high-quality 6G papers, this can indicate that it is seen as an important innovation that has the potential to cause significant changes in the sixth generation of mobile communications. In addition, its popularity over time can be an indicator of its evolution and development, since it has possibly been the topic of continuous improvement and research, making it increasingly relevant and useful for solving specific 6G problems and challenges.

In our relevance analysis, the popularity level is assessed by taking into account the number of papers mentioning the enabler relative to the number of surveyed paper.

C. VRA 3: INNOVATION

Innovation is another conditioning variable for the relevance analysis of an enabling technology. Innovative technologies often present new ways of solving problems, improving processes and optimizing resources. In addition, an innovative technology may have disruptive potential, which means it can cause significant changes in 6G networks, impacting in the market and society.

An innovative technology can also offer competitive advantages for companies or organizations that use them by achieving superior performance. Furthermore, since innovative technologies generate more interest and curiosity in the scientific and industrial community, it can be an indicator to lead to greater investment in research and development, consequently improving and expanding their use.

In contrast, it is necessary to evaluate the practicality and feasibility of some innovative technologies for widespread implementation, which can be a limiting factor for their relevance in the context of 6G. Also, the innovation level can be estimated based on a range of values whose low scores refers a mature technology, while high scores can be considered as a fully disruptive one. The metric adopted for scoring this VRA will be described in more details in Subsection V-F

D. VRA 4: SYNERGY

Synergy can be considered as an influencing VRA, since when two or more technologies are combined synergistically, they can work together to create more efficient and effective 6G solutions. Then, we can conclude that, if an enabler has more synergy with other technologies, this synergy will probably bring more benefits to a 6G architecture. So we can conclude that the fact of an enabler has more synergy with other technologies will likely bring more benefits to a 6G proposal.

For example, the combination of AI and Big Data analysis technologies can lead to a better understanding of data, and consequently, the discovery of more accurate patterns, which can lead to more informed decisions. In addition, DLT presents a high synergy level as it can impact in many functionalities of a 6G network and its software layers. The combination of technologies can also allow the development of completely new products or services, which would not be possible using just one of the enablers, separately.

Furthermore, another conditioning indicator of the synergy for the relevance of an 6G enabling technology is that, enablers which have greater synergy with other ones may be easier to implement and used in larger systems, as they are designed to work seamlessly with other technologies. This can lead to greater practicality and efficiency in implementing business processes and 6G architectural components.

Similar to the Innovation VRA, the synergy level can be estimated based on a range of values whose low scores refers an enabler in which few or no other one can exploit it, while high scores can be seen as a technology whose most part of enablers exploit this one directly. The metric adopted for scoring this VRA will also be detailed in Subsection V-F.

E. VRA 5: SUPPORT TO REQUIREMENTS

The Support to Requirements is the VRA responsible for quantifying how much an enabler helps to meet 6G requirements. Remarkably, the applications and consequently use cases are essential for designing a next-generation mobile network as they drive its requirements to new capabilities. Therefore, to better understand which enabling technologies are essential for deploying 6G architectures, it is necessary to assess the importance of such enablers to fulfill this implementation and support the 6G potential use cases and their requirements.

Through 6G use cases, we can identify their respective primary requirements to be met. Consequently, we can rank the enabling technologies that support the highest number of requirements as the most relevant for meeting 6G applications. Based on the state-of-art related to use cases and network requirements performed in Subsections IV-B1 and IV-B2, it is possible to score the Support to Requirements VRA of the enablers based on the number of requirements previously mapped that are supported by each of them. The metric used to score this VRA for the relevance analysis of enabling technologies, such as the other ones, is discussed in Subsection V-F.

F. METRIC FOR SCORING VRAs

Before applying the optimal methods selected in our analysis for ranking the relevance of an enabling technology for 6G, we need first to score these enablers according to each VRA. These scores will be later used as input parameters in our proposed methods to finally rank the enablers.

To evaluate the enablers concerning the 5 VRAs, we developed a methodology described in Fig. 3. This methodology applies straightforward rules seeking homogeneity among the team of researchers responsible for performing the evaluation. Such homogeneity is relevant as most of the VRAs (e.g., Adherence, Popularity, Innovation, Synergy, and Support to Requirements) are analyzed qualitatively.

First, we adopted a range of values from 0 to 10 for each VRA scoring. All these variables have the same weight in our relevance analysis. Regarding to Adherence, as previously described in Subsection V-A, the DSs are conditioning indicators to change its value. Consequently, an enabler may have different levels of adherence for different DSs. Consequently, the Adherence (VRA) of an enabling technology can be estimated by averaging the individual adherence of each of the four previously defined domains (e.g., Universal, Telecommunication, Computing, Specialized), as depicted in Figure 3. The value 0 refers to an enabler that can not be applied in the DS, while 10 indicates that an enabler is fully adherent to its DS. Finally, values within these limits can be considered partially adherent to a certain DS.

The Popularity scoring can be quantitatively obtained by the percentage of the number of papers that discussed about an enabling technology, taking into account the total amount of papers surveyed in our review of state-of-the-art in 6G. For our analysis, this percentage is normalized for varying from 0 to 10. Then, if an enabling technology was considered in 0% of the surveyed papers, its popularity is 0. In contrast, if 100% of the selected articles considers the enabler in a 6G architecture, it can be scored as 10.

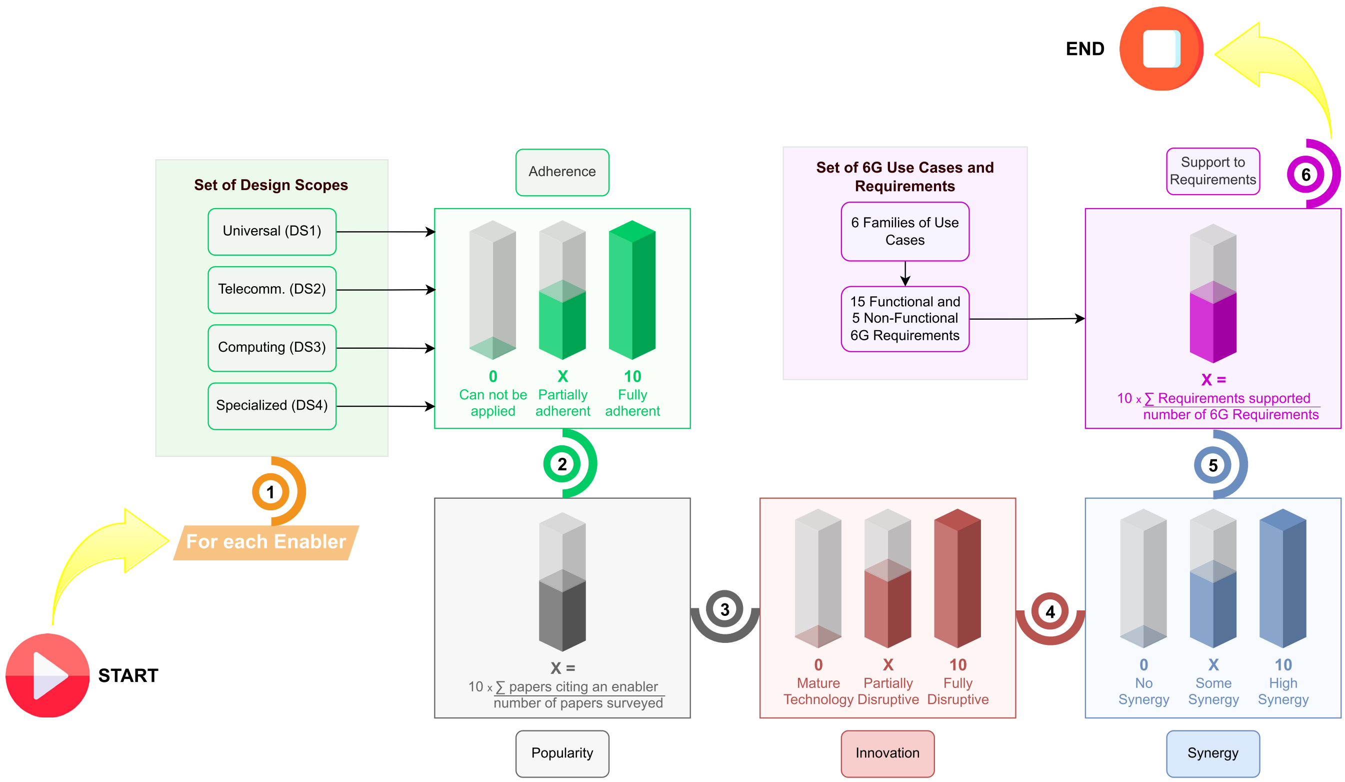

FIGURE 3. Metric developed for scoring VRAs to later applying it on the relevance analysis of the potential 6G enablers.

For Innovation and Synergy VRAs, the scores applied for each technology were adopted based on the knowledge of the researchers involved in this work. For such, values from 0 to 10 were arbitrated for scoring the Innovation VRA of an enabler, in which 0 refers to a mature technology, intermediate values are considered as partially disruptive technologies, and finally 10 as fully disruptive ones. In the same way, values from 0 to 10 were also used for scoring the Synergy VRA of an enabler. In this scenario, a technology with a score of 0 has no synergy with others, intermediate values indicate some synergy, and a score of 10 represents strong synergy with a majority of other enablers.

Finally, the Support to Requirements VRA was estimated in a quantitative way based on the functional and non-functional requirements defined in Subsection IV-B2. Similar to Popularity VRA, the percentage of requirements supported by an enabling technology was normalized in order to vary from 0 to 10. For this, 0 indicates that an enabler does not support any requirements, while 10 refers to a technology that support all the functional and non-functional requirements mapped in our work.

After defining this metric, we must score the 6G enabling technologies described in Section IV-A2 considering each of the 5 VRAs and finally use these scores as input parameters for computing the relevance of each enabler. The score of the VRAs for the 6G enabling technologies, the methods employed for the relevance analysis and the relevance ranking of the enablers will be introduced in the following Section to answer SQ5 and consequently MQ, described in Table 3, which is the main goal of our article.

VI. RELEVANCE ANALYSIS

In previous sections, we examined the enabling technologies, which have been categorized into different clusters of key roles to be performed by 6G architectures, and the VRAs factors that can impact the relevance analysis of an enabler. We also developed a new metric for scoring the VRAs for each enabling technology, whose results can be later applied as inputs parameters in our chosen methods for performing our relevance analysis. Figure 4 illustrates an overview of the results obtained by the methodology proposed in Section III. In addition, Tables 17 and 18 present these results with more details, summarizing the relevance analysis of the enabling technologies for the 6G design, with the scores generated for the VRAs considered for each enabler, in addition to the relevance scores adopted by using the AVG and AHP methods.

For the better understanding of our relevance analysis, in addition to a in-depth interpretation and discussion about the Figure 4 and the Tables 17 and 18 previously mentioned, this Section is organized as follows: Subsection VI-A scores and justifies the VRAs adopted for each enabling technology; Subsection VI-B presents some possible methods that can be applied for the relevance analysis following VRAs' scoring of each enabler as input parameters, and justifies the selection of the chosen AVG and AHP methods; and

Subsection VI-C finally presents the ranking of the most relevant enabling technologies for a 6G architecture obtained by the AVG and AHP methods proposed.

A. SCORE OF THE VRAS FOR THE 6G ENABLERS

Based on the VRAs previously considered, Tables 17 and 18 present the analysis of the critical 6G enablers. In this Subsection, we will discuss about the scores of the VRAs obtained for each enabling technology, which encompasses the columns DS1, DS2, DS3 and DS4 of Adherence, in addition to Popularity, Innovation, Synergy and Support to Requirements, detailed in Tables 17 and 18.

For this, the scores generated for the VRAs are divided into Clusters of Enablers in the following items.

1) ENERGY

Energy Harvesting is a highly specialized enabler and depends on application scenarios. Therefore, this enabler can be classified as highly adherent to the DS4 scope (10). In addition, it has an adherence level of 7 for the other Design Scopes, as it is an enabler that can be applied immediately. Also, a score of 3 has been applied to innovation, as its feasibility, usage, and application have been known for a long time. Our analysis shows that the popularity of Energy Harvesting is low (2), mentioned in only 20% of the revised papers. It also presents a low degree of synergy (3) and provides support to just a few 6G requirements (1). WPT does not adhere to the DS1 and DS3 scopes, since this type of communication is not directly related to the usages and applications envisaged in these scopes. The adherence of this enabler to scopes DS2 and DS4 is also low (4). This enabler is not popular, mentioned in only 10% of the studied papers. Regarding innovation, this enabler presents some challenges for 6G, not been used in legacy networks (7). WPT does not present a high degree of synergy (5) and can help with just a few 6G requirements (1). Green technologies can be applied in all Design Scopes to a greater or lesser extent. Thus, a score of 7 has been applied to all scope adherence. Based on the studied literature, we noticed that Green technologies present low popularity (1), mentioned in only 10% of the papers. Since this enabler can comprise new solutions, especially in the RAN domain, a score of 7 has been applied to innovation. Green technologies do not present a high degree of synergy (4) and can support just a few 6G requirements (4).

2) SENSING

Two enablers represent the Sensing Cluster: Ubiquitous Sensing, which means universal ways of capturing perceptions of the physical world; and IoT-Based Sensing, which focuses on the interconnection of devices that can work collaboratively with a common purpose. However, despite the undeniable density of devices that promote sensing, these enablers show low popularity (1) in the reviewed literature, being present in less than 15% of the studied works. Ubiquitous detection has significant adherence to DS1 (9) and DS4 (8) scopes, exploring sensors to enable fully connected environments and their virtual representations. In addition, it covers a range of use cases, such as localization, imaging, environment reconstruction, environment monitoring, and gesture and activity recognition, among others. On the other hand, there is low adherence to the DS2 (2) and DS3 (2) scopes, integrating part of the user plane architecture, usually in the portion associated with edge computing. The degree of synergy is high (8), especially with enablers that promote the abstraction of the ICT infrastructure, such as connected things that can be sensed, represented by DT and software. Several applications have exploited this enabler for a long time. In addition, its degree of innovation is defined as a medium (5) due to the significant impact on the architecture of 6G networks, meeting 46.67% of the requirements listed in Table 15 (score 5), namely: Latency, Energy Efficiency, Privacy, Security, Density, Spatial Accuracy, and RF/Image Resolution.

With few citations in the literature reviewed, about 14.81% of the 54 works analyzed, IoT-Based Sensing is an enabler with low popularity (1). However, the literature attributes high adherence to the DS1 (9) when pointing to sensing and detection as a primitive task for 6G networks (e.g., spectral sensing). Notwithstanding, for the DS4 scope, this technology is popular (8) by promoting, for instance, the implementation of massive IoT and the integration of uHSLo sensor networks. On the other hand, its adherence to DS2 and DS3 scopes is low (2), as this enabler usually is treated as an end device. This enabler is quite synergistic (8) by promoting the interaction of the physical, digital, and biological worlds through biosensing and nanosensing. However, this enabler is not novel (5), given the available applications with IoT-based Sensing. However, it contributes to about 53.33% of the 15 requirements in Table 15 (score 5) for 6G: Latency, Energy Efficiency, Privacy, Security, Density, Spectrum Access, Spatial Precision, and RF/Image Resolution.

3) COMMUNICATION

Since the Communication Enablers Cluster comprises several enablers, we will highlight only the one with top scores concerning popularity, innovation, synergy, and support to requirements. We also highlight the scores of those enablers with high adherence to Design Scope DS2 since it represents the original scope for most of the enablers in this cluster and to Design Scope DS1 due to its relevance. We split the discussion into two groups. The first group comprises THz Communications, Ultra-Massive MIMO, IRS/RIS, and Cell-Free Networking, while the second one is composed of VLC, OWC, D2D, and Disruptive Waveforms.

The enablers of the first group have perfect adherence (10) to DS2 and they have the potential to increase the wireless network capacity noticeably. In general, these four enablers have high scores in DS1 (ranging from 6 to 9), since wireless network capacity is also significant in this scope. Additionally, they can provide other contributions, e.g., THz can also be used as a powerful sensor, and IRS/RIS also improves security. While none of these enablers present high popularity (less than 5), all of them exhibit high innovation, synergy,

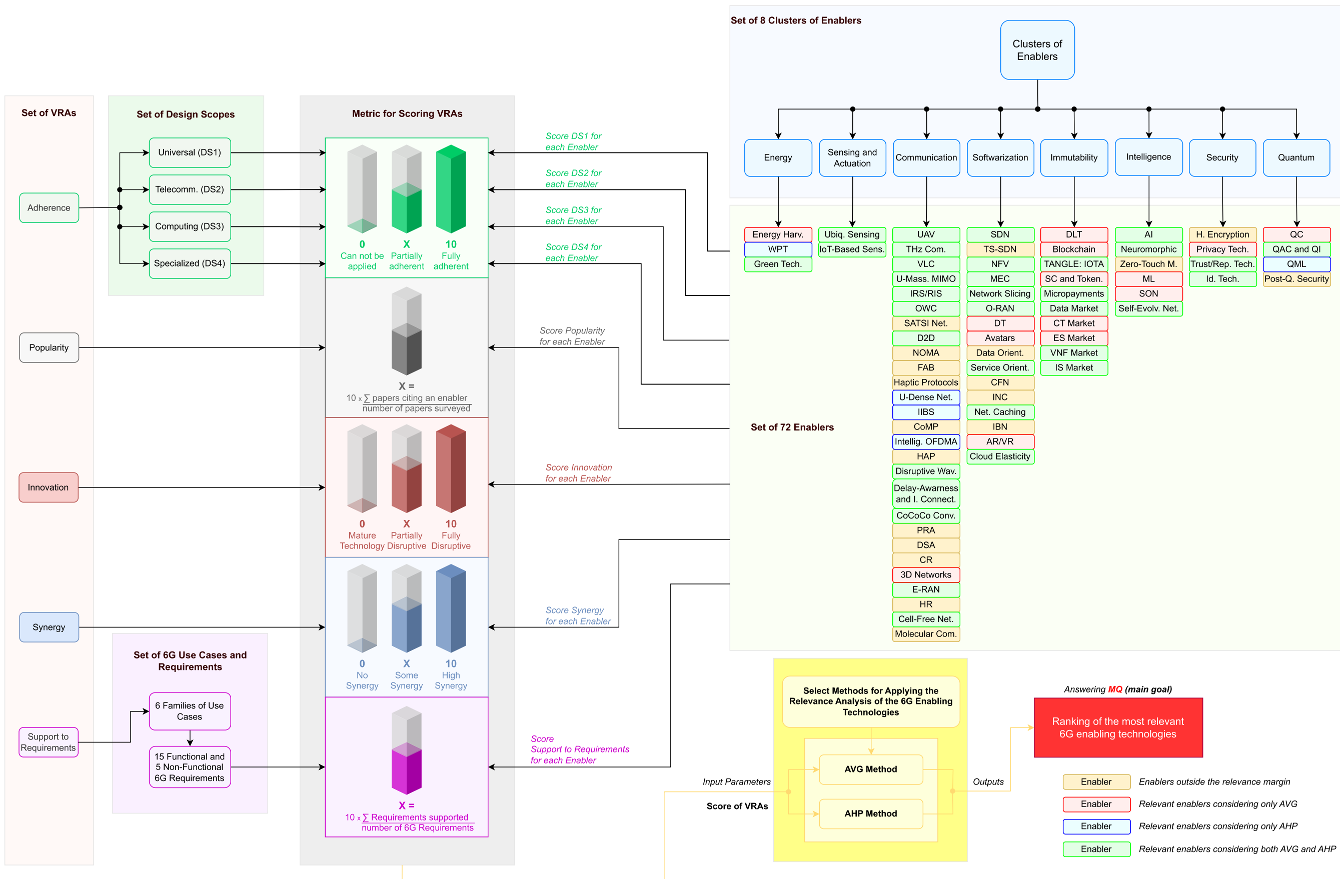

FIGURE 4. **Overview of the results obtained by the proposed methodology in our paper.**

and support to requirements' scores. Similar to mmWave in 5G, THz Communications seeks to explore not only a new spectrum band in higher and challenger frequencies, but also the potential for large increasing network capacity. Ultra-Massive MIMO seeks to repeat the success of Massive MIMO in 5G and, earlier, MIMO in 4G, increasing the number of antennas. Similarly, Cell-Free Networking is also based on Massive MIMO but employs many distributed antennas to serve a smaller number of user devices. Thus, among these four enablers, Ultra-Massive MIMO and Cell-Free Networking have the lowest scores in innovation (7). On the other hand, IRS/RIS is a disruptive enabler that became viable only recently and received the highest innovation score (10).

The enablers of the second group have high adherence to DS2 (greater than 8), but VLC and Disruptive Waveforms also have increased adherence to DS1 (ranging from 8 to 9). Both VLC and OWC present high scores in synergy (9) and support to requirements (8), with a high potential for adoption in indoor scenarios, mainly VLC, which is receiving considerable interest from the industry. On the other hand, both show low adherence to DS3 and DS4 (less than 5) and low scores in popularity (3) and innovation (5). D2D exhibits a high adherence to DS3 (8) and an average score in popularity (6), since it is a well-known enabler, introduced originally in 4G networks, with many possible applications. Thus, D2D has a medium score in innovation (5) but can contribute to satisfying many requirements of 6G (8), similar to VLC and OWC. Disruptive Waveforms were unpopular in our literature review (0), despite being the enabler of this group with the higher score in innovation (7). Since this enabler is significantly related to the physical layer of the wireless channel, its scores on synergy (6) and support to requirements (4) are not very high, and similar behavior can be observed concerning the adherence to DS3 and DS4.

4) SOFTWARIZATION

SDN, NFV, MEC and NS are popular enablers, mentioned in, respectively, 54%, 54%, 56% and 52% of the researched articles, resulting in a score of 6 for the Popularity VRA. These enablers also adhere to practically all Design Scopes studied (scoring above 5 in most of the cases) and have a high degree of synergy (greater than 6), supporting several other more complex technologies, such as E-RAN, O-RAN, Cloud Elasticity, IoT-based Sensing, DT, Green Technology, SATSI, AR/VR. Therefore, they can leverage several requirements mentioned in Table 15 (scoring above 5 in most of the cases). SDN and NFV are mature technologies with a low impact on innovation (less than 3). In contrast, MEC and NS were proposed in the context of 5G, being more

TABLE 17. Part 1: Analysis of the relevant 6G enabling technologies using two methods: (a) AVG - Average Method; (b) AHP - Analytic Hierarchy Process Method. Each row in the table is a 6G enabler. Adherence, popularity, innovation, synergy and requirements are Variables for Relevance Analysis (VRAs). VRA scores are from 0 up to 10. DS1 means universal scope. DS2 means telecommunications scope. DS3 means computing scope. DS4 means specialized scope. AVG relevance is from 0 up to 10, while AHP relevance is from 0 up to 1. Red text means a 6G enabler considered relevant in AVG analysis, while blue text means a relevant enabler when AHP is employed.

	Enabler		Adherence				Popularity	Innovation	Synergy	Requirements	Relevance	
	#	Name	DS1	DS2	DS3	DS4					AVG[1]	AHP[2]
Energy	1.1	Energy Harvesting	7	7	7	10	2	3	3	1	**5.000**	0.291
Energy	1.2	Wireless Power Transferring	0	4	0	4	1	7	5	1	2.750	**0.317**
Energy	1.3	Green Technology	7	7	7	7	1	7	4	4	**5.500**	**0.392**
Sens.	2.1	Ubiquitous Sensing	9	2	2	8	1	5	8	5	**5.000**	**0.500**
Sens.	2.2	IoT-based Sensing	9	2	2	8	1	5	8	5	**5.000**	**0.500**
Communication	3.1	UAV	10	9	1	7	4	0	8	5	**5.500**	**0.040**
Communication	3.2	THz Communications	9	10	3	4	4	9	9	8	**7.000**	**0.051**
Communication	3.3	VLC	9	10	3	4	3	5	9	8	**6.375**	**0.049**
Communication	3.4	Ultra-Massive MIMO	6	10	3	8	4	7	9	7	**6.750**	**0.049**
Communication	3.5	IRS/RIS	9	10	3	4	1	10	9	8	**6.750**	**0.050**
Communication	3.6	OWC	6	9	2	4	3	5	9	8	**5.750**	**0.048**
Communication	3.7	SATSI	8	2	1	8	2	8	6	4	4.875	0.032
Communication	3.8	D2D	5	10	8	3	6	5	6	8	**6.375**	**0.045**
Communication	3.9	NOMA	5	8	0	0	1	0	4	2	2.500	0.023
Communication	3.10	FAB	0	10	0	5	1	0	0	6	2.750	0.018
Communication	3.11	Haptic Protocols	6	4	0	0	2	8	6	1	3.375	0.029
Communication	3.12	Ultra-Dense Networks	8	9	2	0	2	0	7	5	4.125	**0.037**
Communication	3.13	IIBS	7	10	2	2	2	4	7	4	4.750	**0.038**
Communication	3.14	Coordinated Multi-Point	5	8	0	0	1	0	2	3	2.375	0.019
Communication	3.15	Intelligent OFDMA	1	9	0	9	1	1	9	9	4.875	**0.045**
Communication	3.16	HAP	8	8	0	7	1	2	7	3	4.500	0.034
Communication	3.17	Disruptive Waveforms	8	10	5	6	0	7	6	4	**5.750**	**0.037**
Communication	3.18	Delay-awareness and Intermittent Conn.	5	8	5	6	2	2	7	5	**5.000**	**0.039**
Communication	3.19	CoCoCo Convergence	2	7	10	4	2	7	7	4	**5.375**	**0.042**
Communication	3.20	PRA	3	8	4	7	1	5	2	3	4.125	0.023
Communication	3.21	DSA	7	8	4	6	1	3	5	4	4.750	0.032
Communication	3.22	CR	4	3	3	0	1	7	8	2	3.500	0.035
Communication	3.23	3D Networks	7	6	2	6	2	7	5	5	**5.000**	0.033
Communication	3.24	E-RAN	7	8	8	10	3	8	7	6	**7.125**	**0.045**
Communication	3.25	HR	6	8	6	2	1	8	5	3	4.875	0.033
Communication	3.26	Cell-Free Networking	7	10	7	4	1	7	9	8	**6.625**	**0.051**
Communication	3.27	Molecular Communications	5	7	2	7	1	10	3	0	4.375	0.023
Softwarization	4.1	SDN	7	7	6	6	6	1	9	5	**5.875**	**0.072**
Softwarization	4.2	TS-SDN	9	9	2	2	1	9	2	4	4.750	0.042
Softwarization	4.3	NFV	7	8	7	5	6	2	9	6	**6.250**	**0.076**
Softwarization	4.4	MEC	5	6	9	4	6	6	7	9	**6.500**	**0.073**
Softwarization	4.5	Network Slicing	6	7	6	6	6	5	8	5	**6.125**	**0.070**
Softwarization	4.6	O-RAN	8	8	8	10	3	8	8	6	**7.375**	**0.074**
Softwarization	4.7	DT	3	3	8	8	1	6	8	5	**5.250**	0.065
Softwarization	4.8	Avatars	2	8	8	8	1	10	5	7	**6.125**	0.062
Softwarization	4.9	Data Orientation	2	10	8	8	5	0	3	0	4.500	0.039
Softwarization	4.10	Service Orientation	8	4	10	8	6	3	9	7	**6.500**	**0.075**
Softwarization	4.11	CFN	1	4	10	4	2	7	4	5	4.625	0.049
Softwarization	4.12	INC	1	4	10	4	2	7	4	5	4.625	0.049
Softwarization	4.13	Network Caching	4	7	10	7	4	4	7	7	**6.250**	**0.069**
Softwarization	4.14	IBN	8	6	6	9	0	2	2	2	4.375	0.033
Softwarization	4.15	AR/VR	7	3	10	8	2	8	7	8	**6.625**	0.068
Softwarization	4.16	Cloud Elasticity	8	6	9	7	9	6	9	9	**7.875**	**0.084**

[1] AVG - Average Method [2] AHP - Analytic Hierarchy Process Method (Percentages computed by enabler cluster)

innovative technologies. O-RAN strongly adheres to the DS1, DS2, and DS4 scopes (greater than 7), with mentions in approximately 29% of the analyzed articles. This enabler also has an important degree of synergy (8), not only because of the revolution it causes in RAN, but also due to its importance in 6G, being able to support 60% of the requirements listed in Table 15 (score 6). DT, Avatars, and AR/VR are technologies driven by 5G/6G, with great adherence to scopes DS1, DS3, and DS4. These enablers are still not very popular, with citations in less than 8% of the surveyed works (score 1). However, such technologies present several innovations for 6G (ranging from 6 to 10), providing sophisticated environments for cross-realities and digital representation of things. Indeed, the representation of the physical and virtual worlds

TABLE 18. Part 2: Analysis of the relevant 6G enabling technologies using two methods: (a) AVG - Average Method; (b) AHP - Analytic Hierarchy Process Method. Each row in the table is a 6G enabler. Adherence, popularity, innovation, synergy and requirements are Variables for Relevance Analysis (VRAs). VRA scores are from 0 up to 10. DS1 means universal scope. DS2 means telecommunications scope. DS3 means computing scope. DS4 means specialized scope. AVG relevance is from 0 up to 10, while AHP relevance is from 0 up to 1. Red text means a 6G enabler considered relevant in AVG analysis, while blue text means a relevant enabler when AHP is employed.

	Enabler		Adherence				Popularity	Innovation	Synergy	Requirements	Relevance	
	#	Name	DS1	DS2	DS3	DS4					AVG[1]	AHP[2]
Immutability	5.1	DLT	9	5	10	10	1	5	9	2	6.400	0.093
	5.2	Blockchain	2	8	8	10	4	1	9	2	5.500	0.097
	5.3	Tangle: IOTA	6	6	10	10	0	10	9	4	6.875	0.104
	5.4	Smart Contracts and Tokenization	2	2	4	9	2	10	10	2	5.125	0.092
	5.5	Micropayments	7	7	10	10	1	10	9	4	7.250	0.108
	5.6	Data Market	7	7	10	10	0	9	9	3	6.875	0.101
	5.7	Connected Things Market	6	6	4	10	0	9	9	2	5.750	0.091
	5.8	Electromagnetic Spectrum Market	8	8	0	10	1	9	9	2	5.875	0.093
	5.9	Virtual Network Functions Market	7	8	10	10	0	9	9	3	7.000	0.103
	5.10	Infrastructure and Slices Market	9	8	10	10	1	8	9	6	7.625	0.118
Intelligence	6.1	AI	7	10	10	8	8	6	7	7	7.875	0.186
	6.2	Neuromorphic Computing	4	6	8	10	0	10	7	10	6.875	0.178
	6.3	Zero-Touch Management	2	8	0	6	1	7	5	5	4.250	0.126
	6.4	ML	6	8	7	4	4	2	8	5	5.500	0.167
	6.5	SON	4	9	5	3	1	4	8	7	5.125	0.171
	6.6	SEN	7	8	8	6	0	3	8	7	5.875	0.172
Security	7.1	Homomorphic Encryption	3	5	5	8	0	2	2	1	3.250	0.141
	7.2	Privacy Tech.	5	5	5	10	2	4	8	2	5.125	0.273
	7.3	Trust/Reputation Tech.	4	6	8	10	1	5	8	2	5.500	0.282
	7.4	Identification Tech.	4	6	8	10	1	7	9	2	5.875	0.304
Quantum	8.1	QC	2	2	10	6	2	10	5	5	5.250	0.239
	8.2	QAC and QI	2	3	4	6	2	9	9	8	5.375	0.323
	8.3	QML	3	4	5	5	1	10	5	5	4.750	0.241
	8.4	Post-Quantum Security	5	0	0	4	2	9	7	1	3.500	0.197

[1] AVG - Average Method [2] AHP - Analytic Hierarchy Process Method (Percentages computed by enabler cluster)

can contribute significantly to other enablers, consequently presenting a high degree of synergy (ranging from 5 to 8). DT Avatars, and AR/VR can also contribute to the majority of the requirements listed in Table 15, obtaining scores 5, 7, and 8, respectively.

CFN and INC present high adherence to DS3 (10) since they have a high degree of synergy with computing. These enablers support approximately 50% of the requirements listed in Table 15. However, they are not very popular, with mentions below 5% (score 1). IBN, in its turn, is strongly related to infrastructure management, showing high adherence to all scopes. In contrast, this enabler was not mentioned in any of the surveyed articles, receiving 0 in popularity. Furthermore, IBN is an enabling technology with low innovation (2) and a degree of synergy (2), although it enables the conditions that lead AI/ML and SON to configure low-level technologies. This enabler can contribute to 20% of the requirements listed in Table 15 (score 2).

Finally, Cloud Elasticity has high adherence to all scopes (scores ranging from 6 to 9), as the scalability and plasticity provided by cloud computing are essential features for the next generation of mobile networks. Although the term Cloud Elasticity was not always applied, we noted that the fundamentals of this enabler were mentioned in 90% of the reviewed works. This technology is not innovative nowadays, but considering that elasticity problems remain open, it presents an average degree of innovation (6) concerning network architectures. There is a high degree of synergy (9) between this enabler and the others since cloud computing, as well as the elasticity capacity, facilitates scalable provisioning of components. This enabling technology can support many of the 6G requirements, especially those concerning scalability and efficiency (score 9).

5) IMMUTABILITY

Despite having low popularity (1), especially in the DS1-DS3 Design Scopes, DLTs have high adherence to DS1, DS3, and DS4 (greater than 8). DLTs can drive the evolution of network softwarization with digital payments. In DS3 and DS4, DLT should motivate the integration of new 6G markets, with requirements for decentralized deterministic computing and immutable information recording. DLT has a high degree of synergy (9) with a significant contribution towards the reliability, security, and privacy requirements. Blockchain is a DLT with the maximum degree of adherence to DS4 (10), being widely implemented in specific use cases. In addition, Blockchain also has a high level of adherence to DS3 (8), being present in most works whose computation is the focus of the architecture, and to DS2 (8), where it can be used to solve problems in a decentralized way. Its popularity is considerable (4), with mentions in 21 of the 54 articles reviewed, but its degree of innovation is low (1) since this enabler has been explored in several applications.

IOTA is another DLT more adherent to DS3 (10) and DS4 (10), respectively. Although it is being used in various industries, IOTA in telecommunications is an opportunity to be exploited. In this context, the adherence to a global scenario is also possible. IOTA can be applied in any context that involves tokenization and smart contracts. Even though, this technology does not appear directly in any of the 54 analyzed works (0). Synergy with IOTA is understood to be high (9). In terms of requirements, it is related to the following ones: reliability, privacy, security, spectrum access, and energy efficiency (since it uses less energy than Blockchain) (4). Both Blockchain and IOTA support smart contracts. Nowadays, this enabler has little adherence to the DS1 and DS2 Design Scopes, but it can be adopted in disruptive 6G. For DS3, which has a strong computing component, adherence was considered higher (10), while in DS4 it is ready to be applied (10).

Smart Contracts are disruptive for 6G since they solidly contribute to the security requirement. Micropayments are related to tokenization, that is, the use of enablers to monetize transactions, data access, computing, etc. Most of the work related to micropayments is found in DS3 (4) and DS4 (9). DLTs can be immediately applied to support digital payments, although many of them have considerable transaction costs. Of course, there are some with low or even no cost (IOTA). There are also multiple initiatives of CBDC that are being developed around the world. Even though telecommunication micropayments (DS2) did not appear in the works reviewed, digital micropayments are being used in all scopes, fostering several digital markets for data, things, RF spectrum, virtual functions, and infrastructures (a must due to the high cost of 5G/6G).

6) INTELLIGENCE

This cluster comprises enablers related to AI and ML. Among them, there are new and familiar concepts since AI techniques have high optimization capabilities in 6G network architectures. This enabler can be classified as popular (8) in the scientific and technological environment. Regarding the Adherence VRA, it can be categorized with a high adherence in DS1 (7) and DS4 (8), and maximum (10) adherence in DS2 and DS3. Although this enabler has been known for a long time, recent innovations justify an excellent capacity for innovation (6) and synergy (7) with all 6G components. Therefore, this topic can be approached in several areas for predicting machine performance or even as a security mechanism to prevent digital attacks.

Neuromorphic Computing is a new technology that accommodates AI/ML algorithms in hardware with significantly reduced power consumption. Its massive usage still depends on many factors. The adherence of this enabler decreases as we move from specialized to global Design Scopes, i.e., DS4 to DS1. In DS4, it could already be selected in proof-of-concept proposals and therefore has maximum adherence. Despite being a disruptive and radical innovation (10), its popularity in the studies is 0%. This enabler impacts other enablers as far as AI/ML is concerned, getting a high score for synergy (7).

Zero-Touch Management has low popularity (less than 4% of the surveyed works), scoring 1 concerning this VRA. However, it presents a substantial innovation degree (7), in contrast to a medium (5) degree in terms of synergy. A use case frequently employed to demonstrate the properties of this enabler is Network Slicing management. Hence, the adherence to this enabler is higher in DS2 (8). It also adheres to DS4 (6) due to its usage in specialized architectures focused on network management.

ML is already an enabler with adherence to all Design Scopes. In DS1 and DS3, this enabling technology has a medium score. On the other hand, it has a higher adherence to DS2 (8) since most studies adopted this enabler. Finally, ML has low adherence to DS4 since the architectures in this scope are goal-specific and may not typically include ML. Regarding popularity, we noticed occasional occurrences of this enabler in the studied works, resulting in a low score (4) for this VRA. ML a has high degree of synergy (8) since it permeates and directly supports numerous other enabling technologies.

SON proposes concepts of autonomous computing applied to radio management in mobile networks. A higher degree is pointed out for DS2 in terms of adherence (9) since it is a technique employed in mobile networks since 3G. In addition, an average level of adherence is perceived in DS3, while a low one is adopted in DS1 (4) and DS4 (3). Although the Popularity VRA is declining (1) and its innovation degree is low (3), SON has a high degree of synergy (8) with other enablers in general since it is an enabler that covers the management plan as a totality.

Finally, SEN uses AI techniques to create networks capable of making decisions without human intervention by learning and adapting to the environment. Like SON, this enabler presents a high degree of synergy with the other enablers (8). It also presents high adherence to all scopes (7, 8, 8, and 6 for DS1, DS2, DS3, and DS4, respectively). In contrast, this enabling technology presents shallow popularity (0) and innovation degrees (3).

7) SECURITY

The adherence of the Homomorphic Encryption enabler to DS1 (3) may not be a reality for 6G networks, mainly due to the adoption of already established security protocols. For DS2 and DS3 Design Scopes, the relevance of this enabler increases (5), but only for specific applications and contexts where data security must be high. In contrast, Homomorphic Encryption is a promising tool for networks where security is the most relevant factor (8).

In terms of innovation, the enabler's usage is already known, which led to a lower score (2). Its synergy is also low (2) but similar to the Adherence VRA. It has great potential for networks where security is the main requirement. Finally, Homomorphic Encryption can contribute to a few requirements of 6G (1). Also, according to the analysis of the 54 surveyed articles, the popularity of this enabler is low (0).

Privacy Technology is an enabler that adheres to all scopes. In DS1, DS2 and DS3, there is a demand for privacy and security, but they are not the main focus of these scopes (5). However, in DS4, the Adherence VRA received the highest score (10). Although security and privacy are important topics for 6G technologies, these enablers are not very popular (2), appearing in only 20% of the surveyed articles. On the other hand, it presents a high degree of synergy (8) with the other enablers, as security aspects are present in the entire 6G architecture. Since this topic has been discussed in the previous mobile generations, its innovation degree is considered low (4), along with its Support to Requirements VRA (2), since this technology does not explicitly contribute to meeting 6G requirements.

Similar to the other enablers from the Security Enablers Cluster, the specialized architectures of the DS4 scope are the ones that most exploit Trust/Reputation technologies with a maximum adherence degree (10). Then, we also observed a greater adherence to DS3 (8), given that many techniques are computational. In addition, the Adherence VRA in DS2 is still increasing (6), given a more significant concern with trust and reputation as software evolves while not being implicitly introduced in DS1 (4). Since the reviewed works related to 6G pointed to exciting innovations in Trust/Reputation technologies, they present a medium level of innovation (5). Regarding the degree of synergy, such techniques have an important impact on proposals for open networks, i.e., O-RAN and Software-Defined RAN (SD-RAN), and eventual open cores that may appear in 6G. SDN and NFV can also benefit from this enabler when estimating the trust and reputation of controllers and orchestrators in an open ecosystem. Although Trust/Reputation technologies have high synergy with many other enablers (8), discussions regarding the importance of this technology for 6G networks and 6G requirements are not frequent. This justifies the low popularity and support to requirements for this enabler, with score values of 1 and 2, respectively.

With the advent of IoT, things' identification techniques, i.e., RFID and QR codes, have advanced to the global scope. Based on this context, Identification Technologies can be immediately applied across all Design Scopes to identify things within an infrastructure, powering DTs and other services. Regarding adherence, Identification Technologies have similar behavior to the Trust/Reputation technologies since the maximum score value is applied for DS4 while it decays for DS3, DS2, and DS1. This enabler is mentioned in only 1 of the 54 reviewed articles, which explains its low popularity (1). In terms of innovation, this enabler contemplates both old and new techniques [238], [239], such as RFID and self-verifying naming (considered by 3GPP for ICN), increasing its score to 7.

The degree of synergy is high (9) since these techniques allow better identification of physical and virtual entities. On the other hand, its score for requirement support is low (2) as, in general, it is not an essential enabling technology for meeting the 6G requirements.

8) QUANTUM

QC stands out for its adherence to computing, resulting in the highest score (10) for DS3. In addition, it has a relevant degree of adherence to DS4 (6), given its use in the technical scope. In DS1 and DS2, quantum computing could be applied to solve some problems to minimize the use of resources or other digital communication. However, the adherence of this enabler faces the inherent difficulties of introducing new optimization techniques. For this reason, we consider the application of quantum computing in the DS1 and DS2 scopes open to research (2). It has a low degree of popularity (2) since it is covered in 8 of the 54 articles researched. On the other hand, it is a highly innovative technology, with research and studies in development for greater exploitation, receiving the maximum score (10) for the innovation degree. In addition, it has a medium (5) degree of synergy, given the need to work with other enablers to make quantum computing a reality in 6G networks. Regarding support to requirements, it contributes to 7 of the 15 listed in Table 15, receiving a score of 5.

QAC is an important enabler for future information architectures but may play a small role in 6G. The adherence of these technologies in practice is relatively small, ranging from 6 (DS4) to 2 (DS1). In terms of popularity, these enablers appear in 6 works out of the 54 studied, scoring 2 in this VRA. This enabler has a high degree of innovation (9) and can affect the 6G design for all the network layers. This enabler can contribute to meeting most of the 6G design requirements described in Table 15, reaching a score of 8.

QML explores the interaction of ideas from QC and ML. This enabler has medium adherence (5) to the DS3 and DS4 scopes as it is the basis for specialized architectures and brings new ideas about computing. Adherence decreases for DS2 and DS1 scopes since its use is still limited. This enabler has low popularity (1), being present in 3 of the 54 researched articles. On the other hand, it is a highly innovative enabling technology achieving the top score (10). QML has a medium degree (5) of synergy related to other enablers involving quantum computing. This enabler contributes to 7 of the 15 requirements in Table 15, receiving a score of 5 in this criteria.

Post-Quantum Security involves security techniques to withstand attacks from quantum computers [232]. This enabler has a specific adherence to the DS1 scope (5) for considering several technologies, such as quantum computing. Due to their focus on traditional computing, there is no adherence to the DS2 and DS3 scopes. For DS4, the adherence score is slightly lower than DS1, decreasing to 4. There are 7 direct citations in a total of 54 works evaluated, resulting in a popularity score of 2. This enabler is innovative and disruptive for 6G and thus its score was set to 9. On the other hand, there is an excellent synergy with QC in general, but a little synergy with other enablers, impacting a score value assigned to 7. Finally, Post-Quantum Security is directly related to only 2 of the 15 fundamental requirements for 6G as per Table 15, so its score was 1.

B. REVIEW OF METHODS FOR THE RELEVANCE ANALYSIS

In the previous Section, we discussed about the scores of the VRAs adopted for each 6G enabling technology. Now, we need to select the best approaches for conducting the relevance analysis of the enablers, using the scores of these VRAs factors as input parameters.

The choice of method for applying a relevance analysis depends on the specific objective of the analysis, in addition to the variables and factors involved in the process. Each of these methods has different strengths and weaknesses, which should be taken into consideration when choosing the most suitable one for a specific analysis.

One of the most commonly employed methods for relevance analysis is the AVG, also known as Arithmetic Mean, which is a simple and useful method for relevance analysis as it allows calculating an average value from a series of numerical data. This method is important because it helps to summarize a large amount of information into a single value, facilitating understanding and decision-making. For our relevance analysis, the AVG method was used to evaluate the relative importance of different factors or criteria (e.g. VRAs), which would allow classifying the 6G enabling technologies in order of importance, helping to guide in the development and design of 6G architectures. We selected AVG method due to its simplicity and applicability.

In the AVG method we analyzed the importance of an enabler having as input parameters the scores of the VRAs defined in Section VI-A. Nonetheless, this analysis evaluates the relevance of the enabling technology with respect to the entire 6G architecture, meaning that the enabler clusters are not taken into account in this method.

Since we classified the 6G enabling technologies into different clusters in Section IV-A, we can also apply our relevance analysis according to these cluster of enablers. In this way, we are considering the importance of an enabler for only a specific cluster responsible for specific tasks of the 6G architecture, and not for the 6G design as a whole. Therefore, we decided to apply a second method in our proposal also based on the score of the VRAs, but including the criterion of importance for different clusters of enablers. Among some known methods to perform this relevance analysis, we can highlight the Scorecard Method, SWOT Analysis, CBA, MCDA and AHP.

In the Scorecard method, 6G technologies can be assessed based on various criteria, with scores assigned to each criterion. However, this method fails to consider the relative importance of each aspect, potentially leading to a subjective analysis.

For the SWOT analysis, the strengths, weaknesses, opportunities, and threats of each enabler can be identified. While it can provide an overview of the factors affecting each technology, this method does not provide a clear structure for comparing the technologies with respect to a specific criteria.

In the CBA method, the costs and benefits of each technology can be evaluated with respect to a particular objective. While it can be useful in evaluating the financial implications of each technology, it may not consider all other relevant criteria for the evaluation.

The MCDA method involves the evaluation of multiple criteria to select the best alternative. While similar to the AHP method, MCDA does not provide a clear hierarchical structure for evaluating the criteria.

Finally, the AHP method can be very useful for analyzing the relevance of different enablers in a 6G architecture, since some of its specific advantages include to identify the most important technologies taking into account different perspectives and compare them in a systematic way, since it provides a logical framework for objectively comparing technologies using predefined criteria and numerical rating scales. Such features can help to avoid decisions based on subjective opinions and ensure that the analysis is based on data and facts. In addition, AHP can provide transparency in decision making as it allows you to document the rationale and criteria used to compare technologies. Consequently, it can help justifying the decisions made and ensure that all stakeholders understand the reasons behind choosing the selected technologies, providing transparency and reason.

Among the methods previously described, AHP can be considered the best for evaluating the most relevant technologies for a 6G architecture, since it provides a clear and systematic hierarchical structure for evaluating the criteria. Additionally, AHP allows decision-makers to weigh the relative importance of each criterion, which helps to avoid non-objective analysis. AHP also allows for the consistent and systematic comparison of alternatives, taking into account their relationships and inter-dependencies. For these reasons, AHP is a reliable and well-established method for multi-criteria decision-making, and it will also be used in our relevance analysis.

In the following Subsection, we describe in more details the chosen AVG and AHP methods, including the parameters adopted for performing our relevance analysis. Furthermore, we present a discussion about the relevance scores obtained by the 6G enabling technologies based on these methods.

C. RELEVANCE RANKING OF THE ENABLING TECHNOLOGIES

After evaluating the enablers concerning the 5 VRAs, we have the input parameters for computing the relevance score of each enabler. We apply two methods to achieve this goal: AVG and AHP. The first method assesses the relevance score of an enabler as the average of its score values obtained in the VRAs. Consequently, the AVG method considers every VRA equally relevant to the 6G design. In the second approach (AHP), the relevance of an enabling technology in a particular aspect is relative to the performance of the other enablers within the same cluster. In AHP, each VRA receives a weight, reflecting its importance to the 6G design. Thus, in the AVG method, the relevance of an enabler is singly considered for the entire group of technologies, while in the AHP, it is computed within a cluster of enablers. Since these clusters refers to the key roles to be performed by 6G architectures, AHP relevance analysis can define an optimal set of enabling technologies for better fulfilling theses responsabilities, consequently making it possible to design an optimized 6G architecture. For this, Subsections VI-C1 and VI-C2 describes the application of AVG and AHP, respectively, in addition to the results obtained based on these methods.

1) AVG METHOD

Based on the score assigned to each VRA (Adherence, Popularity, Innovation, Synergy, and Support to Requirement)s, we performed AVG to analyze the relevance of the enabling technologies in a 6G network. In this analysis, only enablers with a score higher or equal to 5 are considered relevant. Tables 17 and 18 highlight in red the relevant enabling technologies for 6G according to the AVG method. The discussion on the selected enablers is presented below.

According to this evaluation, in the Energy Enablers Cluster, the most important enablers for 6G are *Green Technology* (1.3) and *Energy Harvesting* (1.1). Compared to the latter, the former presents higher innovation potential, degree of synergy, and support to the considered requirements. In the Sensing Enablers Cluster, Ubiquitous Sensing (2.1) and IoT-based Sensing (2.2) are equally relevant, with both technologies achieving the same performance.

Regarding the Communication Enablers Cluster, this evaluation shows that E-RAN is the most relevant enabler in this group (3.24). This result attests that resource elasticity is widely desired in 6G, having a great degree of synergy and being able to support various 6G requirements. The second key enabler is THz Communications (3.2), followed by Ultra Massive MIMO (3.4) and IRS/RIS (3.5). Next, CFN (3.26), VLC (3.3) and D2D (3.8) are presented. This result also shows that there is room for innovations in 6G design, which include new types of networks (3.18 and 3.23) and Disruptive Waveforms (3.17), whose relevance degree is considered high, in addition to UAVs (3.1) and CoCoCo Convergence (3.19). Finally, OWC is also indicated as required (3.6).

In the Softwarization Enablers Cluster, the enabler Cloud Elasticity (4.16) obtains the best performance, proving that elasticity (vertical or horizontal) must be provided for any computing resource in the 6G architecture, regardless of the DS1-DS4 Design Scopes. The second most relevant enabler is O-RAN (4.6), demonstrating that elasticity in RAN is also highly desirable. The next enabler that appears with great relevance in this group is VR/AR (4.15), which is essential to support several advanced immersive applications discussed in [234]. This analysis demonstrates that SDN (4.1), NFV (4.3), and MEC (4.4) will still be important enablers for the 6G design, consolidating the idea of an open, multi-vendor, virtualized (in the edge and the core), programmable and disaggregated of network functions market. Enablers such as Service Orientation (4.10) and Network Slicing (4.5) will also continue to be important for the 6G design, integrated with other modern service-centric paradigms such as service description, expressiveness, intent, coordination, services graph, etc. Next, Network Caching (4.13) can be used, which can be generalized to storage anywhere on the network (e.g. core, regional, edge, device). Finally, there are enabling technologies related to the fusion of realities, such as Avatars (4.8) and DT (4.7).

For the Immutability Enablers Cluster, the best-evaluated enabler is the Infrastructure and Slice Market (5.10), referring to technologies that allow the creation of markets for 6G resources. The second enabler is related to Micropayments (5.5), while the third one is the Virtual Network Functions Market (5.9). Both can be integrated with new RANs, O-RAN, E-RAN, etc. These enablers are followed by Tangle (IOTA is an alternative to blockchain) (5.3), Data Market (5.6), and DLTs (generic enabler for any immutable transaction and recording technology) (5.1). In addition, there is the Electromagnetic Spectrum Market (5.8), the Connected Things Market (5.7), and Blockchain (5.2). The relative importance of these enablers shows that immutability and technologies for digital markets are needed in 6G. The immutability of transactions not only serves the market but also the perennial record of controls where there can be no adulteration. Finally, it can be considered the immutability of computer programs, such as Smart Contracts (5.4), which offer high security and can be used by all types of services, depending on performance requirements.

Regarding the Intelligence Enablers Cluster, AI (6.1) appears as the most important enabler, since it will impact all layers of the 6G architecture. The second most important enabler is Neuromorphic Computing (6.2), which is related to chips and computing devices that mimic the human brain. The next enabler refers to the SEN (6.6). ML (6.4) and SON (6.5) complete the list of important enablers, having direct application in building automatic pilots capable of optimizing the deployment, operation, and management of networks.

A few enablers were highlighted in the Security Enablers Cluster. The most important of them is related to Identification Technologies (7.4), such as RFID, SVNs, etc., followed by Trust/Reputation Technologies (7.3), which are extremely important in service orientation. And the third enabler in this group refers to Privacy Technologies (7.2). In the era of softwarization, security cannot be relegated to the background. Therefore, Therefore, 6G must integrate identification, trust, reputation, and privacy with DLTs, Smart Contracts, and technologies for the digital market.

Finally, in the Quantum Enablers Cluster, the main enablers considered are QAC and QI (8.2), in addition to QC (8.1), by using quantum technologies to optimize/support digital communication. QAC and QC can be integrated into

TABLE 19. Scale of weights used in determining the relative importance of the considered criteria.

Description	Weight
Same importance	1
Little more important	3
More important	5
Much more important	7
Extremely more important	9

TABLE 20. Analysis of the relative importance of the considered criteria.

Criterion	Adher.	Popul.	Innov.	Synergy	Req.
Adher.	1	7	5	0.33	1
Popul.	0.14	1	0.33	0.11	0.2
Innov.	0.2	3	1	0.14	0.2
Synergy	3	9	7	1	5
Req.	1	5	5	0.2	1

decision-making and AI processes. On the other hand, the QI enablers require more study to be integrated.

2) AHP METHOD

In this Subsection, we present a relevance analysis of the enablers evaluated in Section IV-A according to the AHP method [21]. AHP is often used to rank problems involving multiple criteria. This method is based on pairwise comparisons of decision attributes, allowing the decision maker to determine trade-offs between attributes. AHP operates in three main phases. As indicated in Fig. 5, the first phase decomposes the attribute ranking problem into a hierarchical structure involving three elements: (i) the goal to be achieved, (ii) the evaluation criteria, and (iii) the attributes to be evaluated. The second phase consists of three subphases: (i) a pairwise comparison of the criteria to determine their relative importance; (ii) the evaluation of the attributes concerning each criterion; and (iii) a pairwise comparison of attributes to compute their local ranks. In the final phase, the attributes are ranked according to their performance for each considered criterion. Next, we detail these three phases and the procedure to implement them in our analysis.

In the first phase, we model the ranking problem in a hierarchical structure to determine the most relevant 6G enablers. This analysis is conducted for each enablers' cluster (key roles for 6G architectures) described in Table 6. For instance, we present in Fig. 6 the problem decomposition for the Softwarization Enablers Cluster. The ranking procedure is followed for all the enablers of the respective cluster. The enablers are assessed in terms of Adherence, Popularity, Innovation, Synergy, and Support to Requirements. Due to its subcriteria, the Adherence evaluation is carried out in two stages. First, the enablers are evaluated according to their adherence to the architectural Design Scopes, i.e., DS1, DS2, DS3, and DS4. And then, the enablers are analyzed recursively by following the Adherence criterion. Therefore, in our analysis, the VRAs illustrated in Fig. 2 represent the evaluation criteria while the attributes are represented by the enablers that compose their respective cluster, i.e., SDN, TS-SDN, NFV, MEC, Network Slicing, O-RAN, DTs, Avatars, Data Orientation, Service Orientation, CFN, INC, Network Caching, IBN, VR/AR, and Cloud elasticity for the Softwarization group. The same procedure is applied to the other clusters.

As mentioned earlier, the second phase is divided in three subphases. The first sub-phase determines the relative importance of the considered criteria. Table 19 shows the weight scale suggested by the AHP method and adopted in this evaluation. We assess the criteria's relative importance by performing pairwise comparisons. For instance, let us consider the Adherence and Popularity pair. We analyze whether Adherence is more important for the 6G design than Popularity. If so, the weight value must be above 1. Otherwise, it must assume 1 if they are equally important, or below 1 if less important. The rationale behind each paired comparison is provided as follows and summarized in Table 20.

- **Adherence and Popularity:** We consider it much more important (weight 7) for an enabler to adhere (applicability) to a certain architectural Design Scope than being popular. Therefore, the relative importance of Adherence concerning Popularity is 7, while the opposite is 1/7.
- **Adherence and Innovation:** We consider it more important (weight 5) for an enabler to adhere (applicability) to a certain architectural Design Scope than being innovative.
- **Adherence and Synergy:** We consider Synergy is a little more important (weight 3) than Adherence (applicability). Thus, if the synergy degree of an enabler and all the others is high, we apply this rationale, even if it has low adherence in some Design Scopes.
- **Adherence and Support to Requirements:** We consider Adherence has the same importance (weight 1) as Support to Requirements.
- **Popularity and Innovation:** We consider Innovation slightly more important (weight 3) than Popularity.
- **Popularity and Synergy:** We consider Synergy extremely more important (weight 9) than popularity.
- **Popularity and Support to Requirements:** We consider meeting Support to Requirements more important (weight 5) than Popularity.
- **Innovation and Synergy:** We consider Synergy much more important (weight 7) for the 6G design than Innovation.
- **Innovation and Support to Requirements:** We consider meeting Support to Requirements more important (weight 5) than the Innovation.
- **Synergy and Support to Requirements:** We consider Synergy more important (weight 5) than Support to

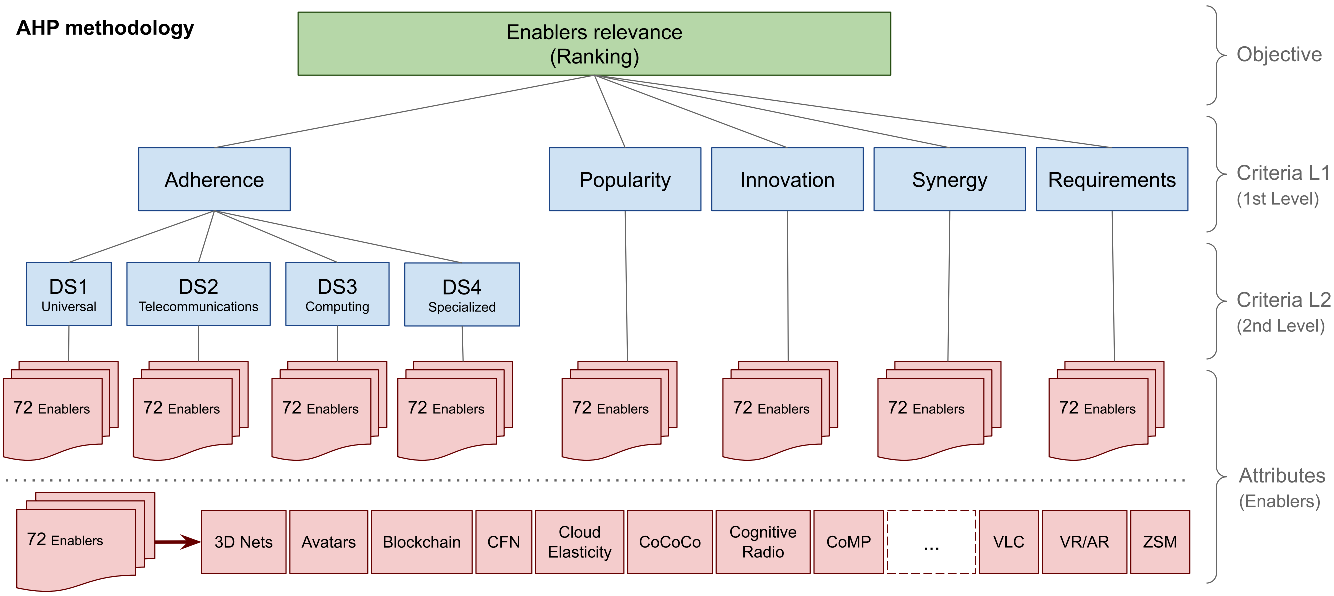

FIGURE 5. AHP Methodology for ranking the 6G enablers.

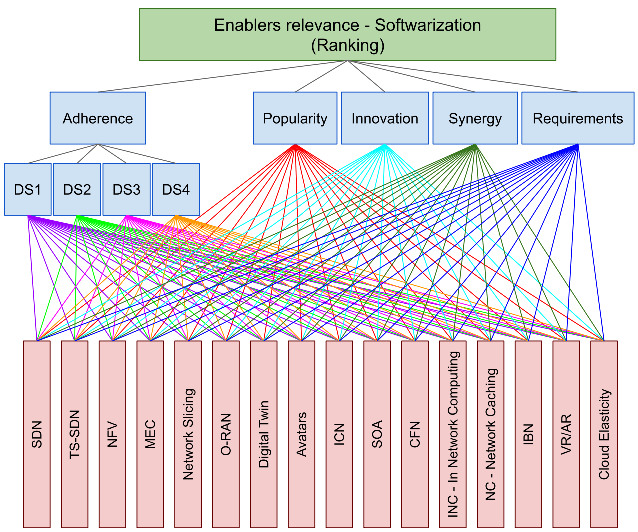

FIGURE 6. Hierarchical structure for the softwarization enablers' cluster.

Requirements. In our understanding, it is better to have an enabler that is more synergistic with the others than one that meets various 6G requirements.

Now to assess the relative importance of the Adherence subcriteria, we applied the reasoning described in Table 21. For this study, we considered Telecommunications (DS2) and Computing (DS3) are the fundamental pillars of 6G architecture. And thus, they received a higher importance level when compared to the other Design Scopes. Between DS2 and DS3, Telecommunications stands with a higher importance level since major 6G requirements are related to the network's capabilities. Finally, DS4 has the lowest importance level as it demands specialized scenarios and architectures.

TABLE 21. Analysis of the relative importance of the subcriteria related to adherence.

Subcriteria	DS1	DS2	DS3	DS4
DS1	1	0.11	0.14	3
DS2	9	1	3	9
DS3	7	0.33	1	7
DS4	0.33	0.11	0.14	1

The second subphase involves the individual assessment of the enablers of a given cluster concerning each criterion. Such analysis was presented in Section VI-A. The third subphase quantifies the enabler's relative importance regarding a certain criterion. This procedure is also performed by comparing two enablers. Here, let E_1 and E_2 be two enablers of the same cluster F. Let V_1 and V_2 be the performance obtained by E_1 and E_2, respectively, concerning the Criterion C. The importance of E_1 in relation to E_2 regarding the criterion C is given by E_1/E_2. Computing the importance of E_i in relation to E_j, $\forall E_i, E_j \in F$ for the criterion C, we obtain a matrix of relative importance involving the enablers of F concerning the criterion C.

Finally, the third phase computes the final ranking of the enablers of a given cluster. First, we calculate the eigenvalues and eigenvectors of the importance matrices generated in the second phase, resulting in an eigenvector for each criterion. Then, the final ranking index is created by multiplying the eigenvectors by their relative importance. The indices within an enablers' cluster add up to 100%.

In the AHP method, we adopted the median of the final ranking indices in each enablers' cluster as the passing score for the relevance of the enabling technologies in a 6G design. Table 22 illustrates the median obtained in each enablers' cluster.

TABLE 22. Median for the enabling technologies in each enablers' cluster.

Enablers' Cluster	Median
Energy	0.3170
Sensing	0.5000
Communication	0.0370
Softwarization	0.0685
Immutability	0.0990
Intelligence	0.1715
Security	0.2775
Quantum	0.2400

The most relevant enabling technologies for the 6G design according to the AHP method are highlighted in blue in Tables 17 and 18.

In the Energy Enablers Cluster, Green Technology (1.3) is the most important enabler, followed by WPT (1.2). Unlike the AVG analysis, in the AHP, WPT performed better than Energy Harvesting (1.1) due to the greater weight given to the innovation criterion.

In the Sensing Enablers Cluster, as observed in the AVG analysis, the Ubiquitous Sensing (2.1) and IoT-based Sensing (2.2) enablers achieve the same performance.

Regarding the Communication Enablers Cluster, the AHP analysis shows that CFN (3.26) and THz Communications (3.2) are the most relevant enablers in this group, followed by IRS/RIS (3.5). Next, we have Ultra Massive MIMO (3.4), VLC (3.3), optical/wireless convergence (3.6), Intelligent OFDMA (3.15), D2D (3.8), E-RAN (3.24), CoCoCo Convergence (3.19) and UAVs (3.1). Finally, Ultra-Dense Networks (3.12), IIBS (3.13), Disruptive Waveforms (3.17), and Delay-awareness and Intermittent Connectivity (3.18) are also highlighted. Considering the most relevant enablers for the Communication group according to the AHP method, only *Intelligent* OFDMA, Ultra-Dense Networks, and IIBS are not considered fundamental in the AVG analysis. In contrast, 3D Networks (3.23), pointed as a relevant enabler in the AVG analysis, does not obtain the minimum score in the AHP method.

In the Softwarization Enablers Cluster, according to the AHP method, the most relevant enabler is Cloud Elasticity (4.16), in addition to other ones with high score values, such as NFV (4.3), SOA (4.10), O-RAN (4.6), MEC (4.4) and SDN (4.1). Network Slicing (4.5) and Network Caching (4.13) also appear as important 6G enablers. We can observe that AR/VR (4.15), DT (4.7), and Avatars (4.8), pointed as relevant 6G enablers in the AVG analysis, are not considered essential in the AHP method.

For the Immutability Enablers Cluster, the enabler with the best score is the Infrastructure and Slice Market (5.10), followed by the Micropayments (5.5), Tangle (IOTA) (5.3), Virtual Network Functions Market (5.9), and the Data Market (5.6). In contrast, the AVG analysis considers the whole group relevant for the 6G design.

Regarding the Intelligence Enablers Cluster, the AHP method and the AVG analysis show similar results. AI (6.1) appears as the most important enabler in this cluster, followed by Neuromorphic Computing (6.2) and SEN (6.6). However, SON (6.5) and ML (6.4) do not score sufficiently to be considered essential enablers in the AHP method.

In the Security Enablers Cluster, the most crucial enabler is related to Identification Technologies (7.4), followed by Trust/Reputation Technologies (7.3). Privacy Technologies (7.2) also performed well in the analysis, but unlike AVG, it did not obtain a sufficient score to be considered a fundamental 6G enabler.

Finally, in the Quantum Technology Enablers Cluster, the main enablers, according to the AHP method, refer to QAC and QI (8.2), in addition to QML (8.3). QC (8.1) also has not been included in the list of essential enabling technologies.

In the next Section, we present a detailed discussion about the most relevant 6G enabling technologies based on the results obtained by the proposed AVG and AHP methods previously described. In addition, future directions and recommendations are also provided.

VII. DISCUSSION, CHALLENGES, FUTURE DIRECTIONS, AND RECOMMENDATIONS

We have developed a complex but effective methodology to rank the best 6G technology enablers. It is a multi-strategy and multidimensional method of analyzing the relative relevance of 6G enabling technologies. The method allows answering several research questions, considering several variables for relevance analysis (VRA), such as adherence to different project scopes (DSs), popularity, degree of innovation ans synergy with other technologies, support for use cases and the 6G requirements associated with them. The application of the two methods (AVG and AHP) according to the metric illustrated in Figure 3 allowed us to rank with good precision the main enablers for 6G as we found in the literature. Someone might take this method and reapply it for 6G or even beyond in the future.

Some difficulties we encountered in this work were: (i) the diversity of articles with all sorts of approaches to presenting 6G enablers, requiring the team to hold frequent alignment meetings; (ii) the enormous complexity in the search for taxonomies and required stages of the proposed method; (iii) many discussions about which method to use and how; (iv) what appropriate comparison variables were required and how they would be calculated or estimated; (v) the application itself of all stages of the methodology was a long and demanding process. A possible future direction is the implementation of the proposed methodology in software, including the use of artificial intelligence tools to automate steps, e.g. ML.

Fig. 7 presents the essential 6G enabling technologies selected in our work according to the AVG or the AHP methods and considering the adopted VRA (Adherence to DS1-DS4 Design Scopes, Popularity, Innovation, Synergy, and Support to Requirements). In total, 53 enablers are considered relevant for designing a 6G network, 33 of them

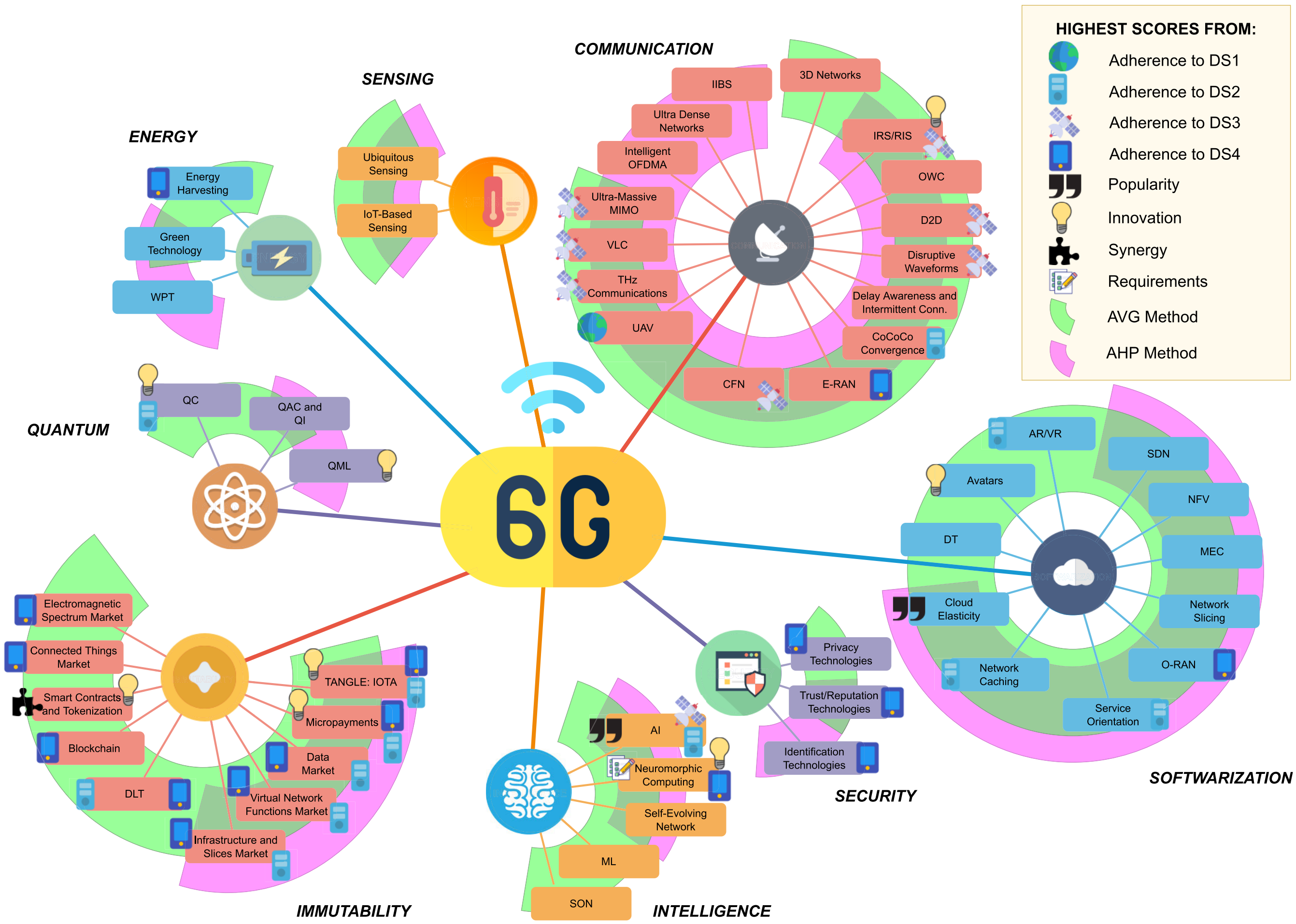

FIGURE 7. Overview of the analysis of the 6G enabling technologies.

deemed in both AVG and AHP. As top-ranked enabling technologies according to the AVG analysis, we highlight AI and Cloud Elasticity. These enablers can support all 6G architectural layers. In contrast, the AHP analyzes the technologies within a cluster, which classifies possible enablers capable of fulfilling specific key roles to be performed by 6G architectures. Therefore, we can apply the AHP analysis to define a set of optimal enabling technologies capable of fulfilling the 6G key roles, and consequently designing an optimized 6G architecture. In such analysis, the top-ranked enablers are Green Technology (Energy), THz communications and CFN (Communication), Cloud Elasticity (Softwarization), Infrastructure and Slices Market (Immutability), AI (Intelligence), Identification Technologies (Security), and QAC and QI (Quantum).

The next step in our work is to leverage these 53 enablers to design evolutionary and disruptive 6G architectures. Some of them fit better in evolutionary proposals that evolve from current 3GPP standards and 5G implementations. Examples are Ultra Massive MIMO, OWC, E-RAN, UAVs, Cloud Elasticity, NFV, SOA, O-RAN, MEC, SDN, Network Slicing, Network Caching, AI/ML, Neuromorphic Computing, Security, and QAC. However, other enablers are better suited for disruptive architectures, such as: CFN, IRS/RIS, VLC, D2D, Disruptive Waveforms, Delay-awareness, Intermittent Connectivity, DT, Digital Markets, IOTA, SON, SEN, QI, and QML. Of course, hybrid proposals can be made, bringing some of these more disruptive enablers to match the evolutionary approach. This seems to be the preferred path for many. Innovate where possible, but do not break with everything that already exists.

Regarding the adherence to the architectural Design Scopes, most of the enablers in the Communication Cluster have great adherence to DS3, except for the UAV, which adheres to DS1 since it can support global coverage. Furthermore, most of the enablers of the Immutability Cluster adhere to DS2 and DS4, showing the increase in approaches associated with immutable register of information and decentralized deterministic computing. The role of computing continues increasing not only in evolutionary 6G, but also on disruptive. Therefore, a recommendation for anyone that wants to take advantage of this study to design 6G architectures is to start with softwarization and DTs, controllers, and orchestrators that could interact with physical enablers at the service layer.

AI and Cloud Elasticity are the most popular enablers, mentioned in most of the studied works. Most of the Quantum enablers (66,67%) obtain the highest scores in the Innovation VRA since this cluster represents an emerging field of physics and engineering that relies on quantum mechanics. Furthermore, Smart Contracts and Tokenization present the highest score for Synergy, highlighting the trend for digitally implementing automatic transactions in the entire 6G environment. This is another important recommendation: to design for an open digital market of infrastructure, services, virtual functions, RF spectrum, and data.

Neuromorphic Computing was the most relevant enabler regarding the Support to Requirements VRA. This technology promises to combine neuroscience, biology, physics, mathematics, computer science, and electrical engineering to design an emerging architecture that meets increasingly challenging requirements. Soon, AI/ML is going to be performed in more energy efficient and capable neuromorphic hardware. Therefore, a recommendation for 6G architects is to consider Neuromorphic Computing as a key infrastructure asset.

Another relevant aspect for the next steps of this work is the definition of design principles that guide the design towards a cohesive, efficient, flexible, and adequate 6G. The ingredients must be integrated in a cohesive, uncoupled and synergistic way. Virtualization and softwarization should be used extensively. Digital twins are recommended to represent physical resources that can not be virtualized. Interfaces should be precisely and flexibly defined. Autonomous control and management is also a must. Services abstractions are required to empower the digital market. Sustainability via green technologies is another design principle to be followed. Security and immutability should also be accommodated. Context-awareness in a requirement to deal with adaptability. Any 6G architecture should foster new business models and future applications. The 6G architecture should encompass all these design principles, being simple, scalable, and elastic.

VIII. CONCLUSION

As can be seen, the next generation of mobile communications is already under extensive investigation. 6G design takes into account new cases, requirements, and a set of enabling technologies that together will shape the whole architecture. With this in mind, we presented some use cases not covered by 5G but essential to drive 6G implementations. In our analysis, we separated the use cases into families of applications. From these families, we established a set of critical requirements related to each other from a functional and non-functional point of view. Furthermore, we envisaged four architectural design scopes (Universal, Telecommunications, Computing, and Specialized) that explore and propose a network with multiple design focus. The enablers were classified into different clusters, following their purpose to be capable of performing a specific key role on a 6G architecture. Then, we presented a comprehensive analysis of the enabling technologies and proposed an innovative approach to scoring them according to Adherence to architectural design scopes, Popularity, Popularity, Innovation, Synergy, and Requirements Support. The scores were analyzed following AVG and AHP methods. Both methods provided a robust analysis, pointing out the more significant technologies that will directly impact the 6G network.

The AVG approach highlighted AI, Cloud Elasticity as the most relevant enablers for 6G. For each enablers' cluster, the AHP method presented Green Technology, Ubiquitous and IoT-based Sensing, THz Communications and CFN, Cloud Elasticity, Infrastructure and Slices Market, AI, Identification Technologies, and QAC and QI as essential 6G enablers. Although the two methods propose an enablers' analysis from different points of view, the scores used to measure the most impacting enabling technologies for 6G were similar. Also, these results contribute by suggesting research approaches toward the most promising technologies. Furthermore, this analysis can help fellow researchers select the ideal enablers for proposing new 6G designs based on particular architectural aspects. However, the AHP method has an advantage over the AVG one, since it conducts an analysis of the enabling technologies using as a criterion their respective importance levels to fulfill key roles to be performed by 6G architectures. Consequently, the AHP relevance analysis can define an optimal set of enablers to design a 6G architecture.

ACKNOWLEDGMENT

The authors thank CNPq, FAPEMIG, and Vivavox Telecom.

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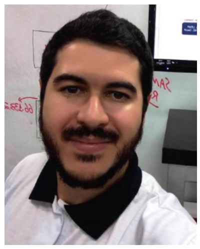

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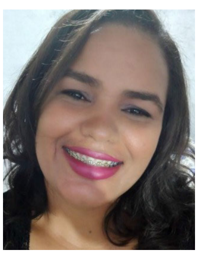

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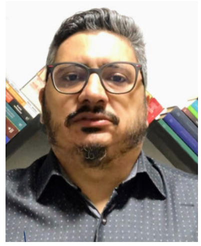

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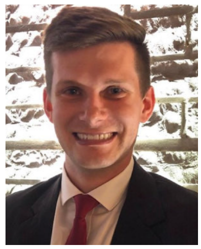

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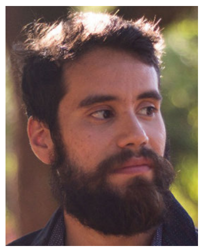

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