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A Complex Insight for Quality of Service Based on Spreading Dynamics and Multilayer Networks in a 6G Scenario

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Abstract: Within the 6G vision, the future of mobile communication networks is expected to become more complex, heterogeneous, and characterized by denser deployments with a myriad of users in an ever-more dynamic environment. There is an increasing intent to provide services following the microservice architecture, thus gaining from higher scalability and significant reliability. Microservices introduce novel challenges and the level of granularity impacts performances, due to complex composition patterns. This openness in design demands service requirements be heterogeneous and dynamic. To this end, we propose a framework and a mathematical approach to investigate the complex quality of services. We exploit the temporal multilayer network representation and analysis jointly, with the spreading dynamics of user experience. We study the joint impact of structural heterogeneity and the evolutionary dynamics of the temporal multilayer quality network, composed of networked parameters, and a temporal multilayer social network, populated by a social layered structure of users. We conducted simulations to display our findings on how this modeling approach enables evaluation of otherwise-overlooked information on quality arising from a profound investigation of the structural-complexity and social-dynamics measurements.

Keywords: quality of service; multilayer social networks; temporal networks; epidemic spreading; 6G; microservice architecture

MSC: 05C82

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1. Introduction

1.1. Contextualization

Communication networks evolved from the 1st to the fifth generation (5G) by introducing innovative ideas and addressing fundamental problems, from higher system capacity to the quality of service (QoS) [1]. Currently, 5G mobile networks have been deployed around the world, reaching a very large scale in many countries [2–5]. Both academia and industry are shifting their attention beyond 5G (B5G) or to sixth-generation (6G) systems, to meet the future demands for information and communication technology (ICT) in 2030 [1]. While 5G systems will include significant improvements, they will not be able to meet the demands of future emerging intelligent systems, and provide everything as a service [6]. For this reason, there is great interest in studying new paradigms of communications such as 6G, which is expected to be implemented between 2027 and 2030 [7]. The development of 6G is driven by the growth in mobile traffic, subscriptions and new disrupting services and applications [1,8]. It will represent a pivotal point for the enabling of intelligence and complexity within future networks [8–11]. Due to the exponential increase in connected devices, and interactive and intelligent services, there is an emerging need to overcome the traditional architectures to enable the deployment of reliable systems [1,12]. Microservices are attracting significant interest due to their capability in improving the performances of

IoT services, especially in the case of environments characterized by heterogeneity and distribution in computing [12]. They represent an approach to developing a single application as a set of small services, each running as independent processes and communicating with lightweight mechanisms. Microservices, which are fine-grained compared to traditional services, are independently deployable, scalable and connected components which can be easily integrated to create complex applications. The level of granularity directly impacts performance, due to the dependencies of the complex composition patterns which results in composite services. This openness in design allows the reausability of microservices, by asking for as heterogeneous and dynamical QoS requirements as possible [13,14]. In order to provide a novel assessment system which enables scalability and reliabilty and, moves the systems from closed hierarchical structures towards open, distributed and dynamical networks, a QoS methodology for this kind of service, within the 6G scenario, is a critical task.

1.2. Problem Motivation

In the roadmap to 6G, researchers, companies, and governments are pushing towards an ever-increasing trend in novel vision, scenarios and disruptive technologies to develop the future of wireless communication networks through complex paradigms [8,15,16]. It is expected that networks will become completely dynamic, with the ambition to introduce interconnected elements, a set of heterogeneous things (human beings, devices, etc.), which can dynamically interact in an unpredictable and unplanned way [17,18]. With the rapid growth in large-scale networks, the complex approach has become a key feature to investigate innovative perspectives, and to provide high-speed data transmission and large system capacity, through several appealing technologies, such as massive multiple-input multiple-output (MIMO), device-to-device (D2D) communications, full-duplex (FD) transmissions and mobile edge computing (MEC) [19,20]. It is becoming increasingly clear that this scenario can be viewed as a networked world of heterogeneous constituents and can be classified as a complex system [18,21]. Following the evolution of these systems, the microservices architecture and the evaluation of its quality can also benefit from integration with the complex approach. The fine-grained, independently deployable and scalable nature of a microservice has the potential to enhance performances, in terms of resilience, scalability, security and QoS, if novel algorithms are appropriately exploited, and complexities handled efficiently. The microservice architecture can dynamically move the shared resources to the edge, with a placement method influenced by several factors within a socio-technical, dynamical and heterogeneous environment and time-changing requirements. Thus, identifying ”good” microservices does not focus only on partitioning the system, but also concerns evolution and scaling capabilities [22].

1.3. Contribution

Modern telecommunication networks represent a large-scale revolution with continuously renovations occurring consistently. During the last decades, the resulting networks consist of heterogeneous entities (from people to devices) commingled with a complex ecosystem. The modeling of heterogeneous networked dynamical systems is attracting ever-growing interest in bringing together complex systems and networking theorists [21]. Some existing surveys provide reviews of basic models of complex networks from a communication-networks perspective in order to present concepts and properties of complex systems [8,23]. Other works attempt to design alternative network protocols based on the integration of these theories [21]. In this paper, we propose a complex approach for a novel methodology in order to mine a complex QoS esteem. Indeed, 6G will allow us to usher in an era in which ubiquitous computing becomes long-predicted, encompassing both the pervasive aspects that span multiple levels of interaction and the persuasive aspects that manifest themselves in changing user behavior through social influence [24]. It is consistent with this trend to adopt a complex approach, both in terms of the representation and analysis of interacting structures and social dynamics. Our work dovetails with the 6G environment in that it proposes a multi-layered representation and analysis of an interconnected dynamic scenario characterised by human-centeredness, and a dynamic topology with pervasive and persuasive aspects. Based on this approach, we design a framework based on temporal multilayer networks and spreading dynamics [25,26]. This would provide future research with an opportunity to comprehensively address the challenges of the QoS in a dynamic and heterogeneous environment through novel algorithms, providing suitable methods for complex ecosystems.

The main contributions of our work are as follow:

- We discuss a background scenario for 6G and microservices. We argue why a complex approach may become a pivotal aspect in modeling and analyzing future networks and services. To this aim, we exploit temporal multilayer networks and spreading dynamics in a social network, identifying features and requirements that benefit these areas from their integration, to profounding investigate the QoS.
- We propose a novel framework for a complex QoS, by exploiting the mathematical representation and analysis of temporal multilayer networks and spreading dynamics. We study the structural heterogeneity of a temporal multilayer quality network, composed of heterogeneous networked quality parameters, jointly with the spreading dynamics of user experience in a temporal multilayer social network, populated by users.
- We quantify the dynamical interdependence between the temporal multilayer quality network and the temporal multilayer social network through the quality of experience (QoE), perceived as a social marker of a network able to highlight the trend of QoS.
- We detail the proposed mathematical model, the representation of the novel complex methodology and the conducted simulations.

1.4. Organization of the Paper

The rest of the paper is organized as follows:

- In Section 2, we review recent research and background on 6G, microservices, temporal multilayer networks and spreading dynamics in social networks.
- In Section 3, we describe the high-level abstraction of the system by detailing the proposed framework.
- In Section 4, we comprehensively detail the mathematical modeling of the proposed methodology.
- In Section 5, we discuss the conducted simulations and the numerical results, shedding light on the findings of the proposed method.
- Finally, in Section 6, we outline our conclusions and we identify future research directions.

2. Background: Paradigms, Concepts and Methods

2.1. Towards 6G

Within the ongoing process of telecommunication evolution, 6G is a promising paradigm that will support more use cases and more stringent requirements [27]. Most surveys are focused on investigation into use cases and usage scenarios, proposing a roadmap of definitions and standardization, advantages and challenges [1,28,29]. Accordingly, 6G will be the generation of mobile networks with the ambition of immersing the digital into the physical reality, making requirements more stringent and bringing them a new level of complexity [30]. The study of future wireless systems clearly shows how technological trends embrace new functionalities and paradigms in B5G and 6G, such as the integration of sensing and communications, paving the way for complex perspective networks [31]. The European Commission has announced a strategy for the investment in 5G and 6G to shape Europe's digital future [32]. The international telecommunication union radiocommunication sector (ITU-R) supports the study of the future of international mobile telecommunications (IMT), confirming the significant interest in establishing guidelines for research and development. While 5G shifted from a communication-centric architecture to a service-centric architecture, 6G will pay greater attention to security and privacy as key features [33]. The interest in an intelligent 6G grows faster, and in many works the authors shed light on enabling technologies and paradigms, as machine learning drives, in a new way, communication, networking, computing and security [9,34] or AI for 6G [35]. There is an attempt to draw a picture of drivers, usage scenarios, requirements, performances, architecture and enabling technologies with the aim of detecting novel paradigms, by underlining the reasoning behind what motivates 6G. Most of the surveys confirm a common vision of requirements, trends and challenges regarding coverage, data rate and mobility [16,36]. Other works shed light on use cases and enabling technologies, and relevant unresolved research issues [37,38]. Additionally, 6G will be more human-centric, implementing social structured networks and collective dynamical processes, exploiting the complex-system approach in many important aspects [8,21,39]. Some pivotal points of complexity are linked to emergence, adaptability, decentralization and self-organization, which may become key factors for the future of mobile communication characterized by an increasing of level of interdependence among the heterogeneous interconnected constitutive elements [18,21]. To facilitate a clearer explanation of the research trends and the roadmap towards the introduction of a novel approach as a set of tools and methodologies based on complex systems and network science, we chronologically listed major contributions linked to 6G communications, complexity and quality in Table 1.

Table 1. Summary of state-of-the-art contributions related to 6G paradigm, complex approach to the future of mobile communications and the QoS.

Ref.	Year	Topic	Keywords	Problem	Objective	Approach	Limitations
[15]	2021	Vision	Artificial intelligence, 6G mobile communication, task analysis, sensors, communication-system security, standards	State-of-the-art deep-learning and big-data-analytics-based AI systems require tremendous computation and communication resources, causing significant latency, energy consumption, network congestion, and privacy leakage in both the training and inference processes.	Providing a comprehensive picture for the design of scalable and trustworthy edge AI systems. Proposing a unified framework for resource allocation in edge AI systems and a holistic end-to-end architecture for edge AI systems.	Theory-driven and machine-learning-based; data-driven.	Complexity is not taken into account and no QoS measures are provided.
[16]	2019	Survey	6G mobile communication, driving trends and performance metrics, enabling technologies	Despite recent 6G developments, the fundamental architectural and performance components of 6G remain largely undefined.	Providing a holistic, forward-looking vision of 6G architecture and challenges.	Descriptive analysis	No QoE and QoS metrics or KPIs are provided to evaluate the performance of upcoming networks.
[8]	2020	Complex	Complex systems, 5G/6G mobile communication, wireless communication, complex networks	Systems can be effectively described as complex networks. Basic issues and fundamental principles related to the structural and evolutionary properties of communication networks still remain largely unaddressed. The situation is even more complicated for modeling the 6G mobile communication networks.	Reviewing basic models of complex networks from a communication networks perspective, which may apply when modeling the 6G mobile communication networks.	Review, Descriptive analysis	A framework to represent and model 6G networks with a complex approach is not provided.
[12]	2022	Quality	6G, QoS, IoT, microservices, fog computing, edge computing	Efficient and scalable scheduling algorithms are required to utilise the said characteristics of the microservice architecture while overcoming novel challenges introduced by the architecture.	Providing a comprehensive taxonomy of recent literature on microservices-based IoT applications scheduling in edge and fog computing environments. Organizing multiple taxonomies to capture the main aspects of the scheduling problem.	Literature review	The aspect of complexity and the vision of 6G as a complex ecosystem are not included in the review.
[40]	2020	Complex	6G mobile communication, wireless communication, frequency measurement, satellites, loss measurement, nonlinear optics	Telecommunication networks are evolving towards a distributed and autonomous system.	Proposal of a novel distributed and autonomous network architecture for 6G.	Architecture designing	Complexity, microservices and measures are not considered when calculating QoS

Table 1. *Cont.*

Ref.	Year	Topic	Keywords	Problem	Objective	Approach	Limitations
[41]	2022	Vision	6G communication, artificial intelligence, edge, AI, quality of life, quality of experience, cognitive intelligence, data science, big data	The intelligent network will be fully AI-driven, and the cognitive model of the network architecture will affect every aspect, promising a high QoS and a high QoE to move society towards an AI-driven smart city.	Disclosing the advanced scopes such as quantum machine learning, deep learning, and black-box techniques to support a high-configuration networking system.	Literature review	Complexity is not taken into account and no QoS/QoE measures are provided.
[42]	2022	Vision	6G, 5G, mobile technology connectivity, quantum technology, WCDMA	5G communication is the most trending technology and, nowadays, commercialized to the whole world. Still, now is the time to look forward beyond this technology, which could be more advanced than 6G.	Review of the technology advancement in the 6G network, including comparative analysis of efficient, cost-effective, specific and aggregate efforts toward breakthrough innovations.	Comparative analysis, literature review	Complexity is not taken into account and no QoS/QoE measures are provided.
[43]	2022	Vision	6G communication, future directions THz, smart society, smart healthcare, challenges and applications	The 6G revolution and its growth have a fundamental influence on intelligent communication, including smart connectivity, faster communication, and holographic connectivity.	Providing an overview of 6G, core technologies, basic architecture, challenges, the applicability of 6G in various real-life applications such as smart city, military surveillance, healthcare.	Literature review.	Complexity is not taken into account and no QoS/QoE measures are provided.
[10]	2020	Vision	6G mobile communication, wireless communication, 5G, automation, internet, communication system security	Transformative solutions are expected to drive the surge in accommodating a rapidly growing number of intelligent devices and services. A plethora of emerging use cases that cannot be served satisfactorily with 5G.	Detailing the roadmap for the future of wireless communications and introducing the key performance indicators (KPIs) for 6G designing.	Descriptive analysis, survey	Complexity is not taken into account.
[44]	2020	Complex	Complex approach, 6G, edge intelligence, advanced IoT, artificial intelligence, machine learning, intelligent internet	Intelligent solutions utilizing data-driven machine learning and artificial intelligence has become crucial for several real-world applications, including the development of 6G intelligent edge.	Overview of computing infrastructure and platforms, data and edge network management, software development for edge, and real-time and distributed training of ML/AI algorithms, along with security, privacy, pricing, and end-user aspects.	Descriptive analysis	A framework to model the 6G edge infrastructure with a complex approach is not provided.
[45]	2021	Quality	Quality of service, delays, quality of experience, diffserv networks, wireless communication, cognition	The existing aggregation approaches/QoS mapping methods to provide differentiated sevices are based on quantitative QoS requirements and static QoS classes.	Applying the artificial-intelligence technology of preference logic to achieve an intelligent method for edge computing, called the preference-logic-based aggregation model (PLM), which groups flows with qualitative requirements into dynamic classes.	Quantitative and qualitative approaches.	Complexity is not taken into account.
[11]	2022	Vision	6G communications, networking, wireless communication, healthcare, vehicular technology, robotics communications, internet of things, internet of everything	6G promises high-quality QoS and QoE. 6G will enable internet of everything (IoE), which will also impact many technologies and applications.	Envision the potential applications of 6G communication technology in the near future.	Descriptive analysis	No QoE and QoS metrics or KPIs are provided to evaluate the performance of upcoming networks
[46]	2022	Quality	5G, 6G communication, quality of service, vehicular network, UAV, machine learning	The QoS in 6G enormously depends upon the mobility and agility of the network architecture. Although different mathematical and computation methods have traditionally been used to optimize the allocation of resources, the nonconvexity of optimization issues creates a unique type of challenges.	An insight into how network resources can be allocated to reinforce network communication using optimization and cutting-edge machine-learning techniques.	Designing of machine-learning-based algorithms	Complexity is not taken into account and no QoS/QoE measures are provided.
[47]	2022	Quality	5G/6G; dynamic QoS management, network slicing, software-defined networking, queue management	Developing a more flexible core infrastructure according to more complex QoS requirements.	Providing 6G core flexibility by customizing and optimizing network slices, introducing a higher level of programmability and enabling a higher level of programmability as a prerequisite for dynamic QoS.	Designing of multislice network architecture.	Complexity and microservices architecture are not taken into account.
[27]	2022	Quality	6G mobile communication, autonomous systems, heuristic algorithms, quality of service, communications technology, telecommunications, noise measurement	Providing differentiated services to meet the unique requirements of different use cases. Fulfilling this goal requires the ability to assure quality of service (QoS) end to end (E2E) considering that access networks (ANs) and core networks (CNs) manage their resources autonomously.	A novel framework and a distributed algorithm that can enable ANs and CNs to autonomously "cooperate" with each other to dynamically negotiate their local QoS budgets and to collectively meet E2E QoS goals.	Designing of novel and distributed algorithm for QoS	Complexity and microservices architecture are not considered.

Table 1. *Cont.*

Ref.	Year	Topic	Keywords	Problem	Objective	Approach	Limitations
[48]	2020	Survey	6G mobile communication, 5G mobile communication, robot sensing systems, biology, digital twin, user interfaces	The future of connectivity is in the creation of digital twin worlds which are a true representation of the physical and biological worlds at every spatial and time instant, unifying our experience across these physical, biological and digital worlds.	Painting a broad picture of cognitive-spectrum sharing methods and new spectrum bands; the integration of localization and sensing capabilities into the system definition; the achievement of extreme performance requirements on latency and reliability; new network-architecture paradigms involving sub-networks and RAN-Core convergence; and new security and privacy schemes.	Descriptive analysis	Complexity is not taken into account and no QoS/QoE measures are provided.
[49]	2019	Survey	6G mobile communication, 5G mobile communication, absorption, wireless communication, artificial intelligence, bandwidth, 3GPP	A key enabler for the intelligent information society of 2030, 6G networks are expected to provide performance superior to 5G and satisfy emerging services and applications.	Presenting a large-dimensional and autonomous network architecture which integrates space, air, ground, and underwater networks to provide ubiquitous and unlimited wireless connectivity. The authors also discuss artificial intelligence (AI) and machine learning for autonomous networks and an innovative air-interface design.	Architectural designing	Complexity is not taken into account and no QoS/QoE measures are provided.
[36]	2020	Survey	5G mobile communication, 6G mobile communication, market research, wireless communication	There has not been any officially agreed opinion on what 6G will be; as a future novel generation, 6G will no doubt have ten to a hundred times higher overall capabilities than that of 5G.	Defining the roadmap of 6G; presenting technologies, challenges and future direction for researchers.	Descriptive analysis	A framework to represent and model 6G networks with a complex approach is not provided.
[7]	2020	Survey	5G mobile communication, wireless communication, artificial intelligence, quality of service, market research, sensors	Some fundamental issues that need to be addressed are higher system capacity, higher data rate, lower latency, higher security, and improved QoS compared to the 5G system.	Presenting the vision of future 6G wireless communication and its network architecture and describing emerging technologies.	Descriptive analysis	A framework to represent and model 6G networks with a complex approach is not provided.
[38]	2020	Survey	5G mobile communication, wireless communication, communication-system security, security, physical layer, bandwidth, NOMA	Achieving diverse performance improvements for the various 6G requirements.	Proposing a 6G architecture as an integrated system of the enabling technologies; discussing the potential challenges in the development of 6G technology and identification of 6G core services and KPIs.	Analysis of related works and designing of architecture.	Complexity is not considered and no QoS/QoE measures are provided.
[50]	2020	Survey	Wireless communication, apertures, antenna arrays, optical surface waves, holography, MIMO communication, transceivers	Future wireless networks will be capable of sensing, controlling, and optimizing the wireless environment to fulfill the visions of low-power, high-throughput, massively connected, and low-latency communications.	Providing an overview of HMIMOS (holographic MIMO surfaces) communications, including the available hardware architectures for reconfiguring such surfaces, and highlighting the opportunities and key challenges in designing HMIMOS-enabled wireless communications.	Descriptive analysis	The realistic modeling of metasurfaces is not provided.

2.2. Quality of Microservices in 6G

B5G and 6G have been envisioned as key enablers for many emerging applications that demand high quality, an integration between sensing and communications and highly accurate and robust capabilities [31]. Within the 6G vision, the evolution process includes a growing number of users, large volume of mobile traffic, bandwidth-intensive services and applications with a high data rate, leading to a complex situation [8]. This could be addressed with innovative approaches, based on complexity, to discover tools and methods and design new protocols. We expected that the systems will meet the demands for a fully connected, integrated and intelligent network of users, devices and resources [14]. From a high-level perspective, these aspects can be integrated through modular frameworks that, step-by-step, deepen knowledge discovery, and introduce a complex representation and analysis, leading to the design of new methods [8,14,21]. Microservices are increasingly adopted to keep up with the development of quickly evolving applications [12,16]. Microservices are a software development methodology as well as cohesive, autonomic and deployable independent processes interacting with each other, through a well-defined lightweight mechanism, with the advantage of being reusable across several applications.

A set of microservices serves a certain business goal/task [14]. This includes the possibility to create mashups, where services/data are combined as a set of heterogeneous resources. Microservice architectures introduce several challenges to design, development, and orchestration of the management of dependencies, among microservices, and, consequently, for the composition pattern of mixed services [12]. They represent an architectural and organizational approach to software development. They make applications easier to scale, enabling innovation and accelerating time to market for new features [51]. Since the resulting architectures strongly benefit from breaking monolithics and increasing flexibility and robustness, a dynamical evaluation scheme of the different networked parts is needed. Microservice architectures introduce novel challenges and one of them is the granularity level, which creates dependencies and composition patterns [12,52]. The granularity of a microservice directly affects the application's quality attributes and the use of computational resources [53]. The quality of a microservices-based system is influenced by the granularity of its microservices, because their number directly impacts the system's quality attributes [52]. The openness of this architecture enables the reausability of microservices between the composite services and the granular scalability creates some of the challenges, such as the complexity of managing distributed systems. This scalable and complex nature have the potential to improve performance, but novel algorithms are required to handle QoS requirements [1,12]. Since the future of mobile networks puts users and their interactions at the center of any assets, to better understand, quantify and predict the quality of a service, it becomes crucial to consider the overall aspects that impact the users' perceived quality of a service, and what can affect their experience. QoE represents the degree of delight or annoyance at a service, as a result of user perception [54]. QoE is an overall measure of quality from the perception of users, paving the way for proactive and reactive actions such as in terms of quality monitoring or cases of over-engineering. There are different approaches in the literature based on a collection of methodologies for different types of services [55,56]. In [54], the authors introduce a primary classification of approaches based on subjective tests or objective models, respectively, identifying whether the QoE is assessed by humans or through technical methodologies. Subjective tests are described as a passive or active/interactive method of assessment and based on controlled real-life experiments to directly assess experiences of a service [54]. Among the various methodologies used for subjective assessment, some of them exploit users' score of quality with a rating scale or the comparison of different objects such as images, videos or other resources. The results are based on mixing various factors such as user opinions, perceptions and satisfaction degree when using a service. Focusing on aspects of QoE concerning opinions [45] jointly with the impact of social networks on human behavior, it becomes interesting to shed light on the fact that, through interconnections, personal experiences and perceptions can shape beliefs, attention, interests and behaviors [57–59]. An opinion is a description of a personal point of view of certain objects or aspects but it is biased by experience, beliefs and interconnections within a social network. In terms of QoS and QoE, the process of opinion formation and evolution depends on the developed perception of observable attributes and, through the accumulation of that experience over time, a belief is developed. An opinion could change as the user accumulates experiences, refines perceptions or when interacting with others who have different experiences [60]. This can happen in social networks where users, by coming into contact with others, acquire new information that reshapes beliefs and affects behavior. For the above, the QoE and QoS ratio is also defined by the complex input inherent in the structure of the interconnections between networked users and their temporal evolution.

2.3. Temporal Multilayer Networks and Spreading Process

The complex approach is useful to fully describe and exploit the connectedness of different elements that interact to each other via several links of different types. The relationships between nodes in networked systems can be different, according to relevance, context, weight and meaning [25,61,62]. To preserve the knowledge that is derived from multiple interactions, we consider the multilayer and its mathematical representation and analysis [21,25]. This enable us to fully characterize the complex structure of heterogeneous nodes and their behavior by unveiling pivotal and hidden properties and paths [18,60,63]. In some cases, links, among nodes, are not continuously active but they could represent sequences of instantaneous or interval contacts, such as in human proximity networks. Proximity networks are time-varying graphs representing the closeness among individuals moving in a physical space. They are modelled by interval graphs, which are particular temporal networks, based on data about who is close to whom at what time [64]. The huge amount of data available and the various types of interactions, which co-exist and evolve over time, make it necessary to base a description on the evaluation of temporal and multilayer dimensions [25,26]. Since interest also lies in highlighting how experience and perception can spread within the network, we take into consideration spreading processes. Social behaviors, misinformation, beliefs, opinion and emotions spread interpersonally [57,65]. There is a vast amount of literature that has investigated that these complex dynamics following classical epidemiological models and by involving several research fields in network science [66–73]. We can state that the nature of social ties has a key role in a spreading process on a social network [57,74–78]. Here, we exploit the paradigm of the multilayer network and the spreading process to investigate the multi-dimensional structure of networks, enabling us to fully characterize the behavior of complex systems, to unveil interesting structural properties.

3. System Architecture

Scenario

In Figure 1, we introduce a schematic representation of the model design, in order to describe a high-level abstraction of the overall system and the key aspects of our complex approach, with the aim of investigating the complex QoS system. This starts from a socio-technical system of mobile users and devices exploiting a D2D-MEC system for communication and computing of tasks. We assume that a set of services accessed by end users, as in Figure 1a, is represented as a set of microservice applications which consist of multiple composite services, Figure 1c. Since this scenario requires heterogeneous QoS requirements, we consider a graph of heterogenous networked QoS parameters, Figure 1b, belonging to different categories such as acceptabilty (Ac), usability (Us) and user experience (Ue). In the left panel of Figure 1d, we show the temporal multilayer representation for both environments and we consider the temporal multilayer of the system characterized by two layers—a proximity network and a social network—jointly with the spreading-dynamics process (SI model). In the right panel of Figure 1d, we detail the temporal multilayer representation of the graph in Figure 1b. The analysis of both complex structures, their interdependence and dynamics leads to the complex systems of QoS and QoE, whose algorithm is detailed in the scheme in Figure 1e. The analysis of the spreading dynamics of user experience, as a collective phenomena of the social network of users, impacts both QoE and, consequently, the overall QoS. The D2D-MEC system, as shown in Figure 1, in the socio-technical environment, is a pivotal design assumption in accordance with the 6G scenario, since it allows for greater flexibility in computing by exploiting the D2D and the MEC gain, through offloading, in order to improve the computation capacity of the whole system [20]. We assume that at each time step $t_i \in T$, each device has a computation task to be accomplished, following the assumptions in [20], with a load to be computed corresponding to its task. The D2D-MEC system enables three possible computing procedures such as local, edge or D2D offloading. Every component as data, computing and storage capability constitutes a resource, and the mashup of the resources can implement processing or decision tasks [14]. This approach is useful for the microservice applications that consist of interconnected microservices collaboratong to perform in specific domains. The granularity level of microservices creates composite services with different patterns, as shown in Figure 1. An application consist of multiple composite services leading to a heterogeneous QoS environment. In the next section, we describe the mathematical modeling and, for the sake of clarity, a complete list of symbols with their meanings is summarized in Table 2.

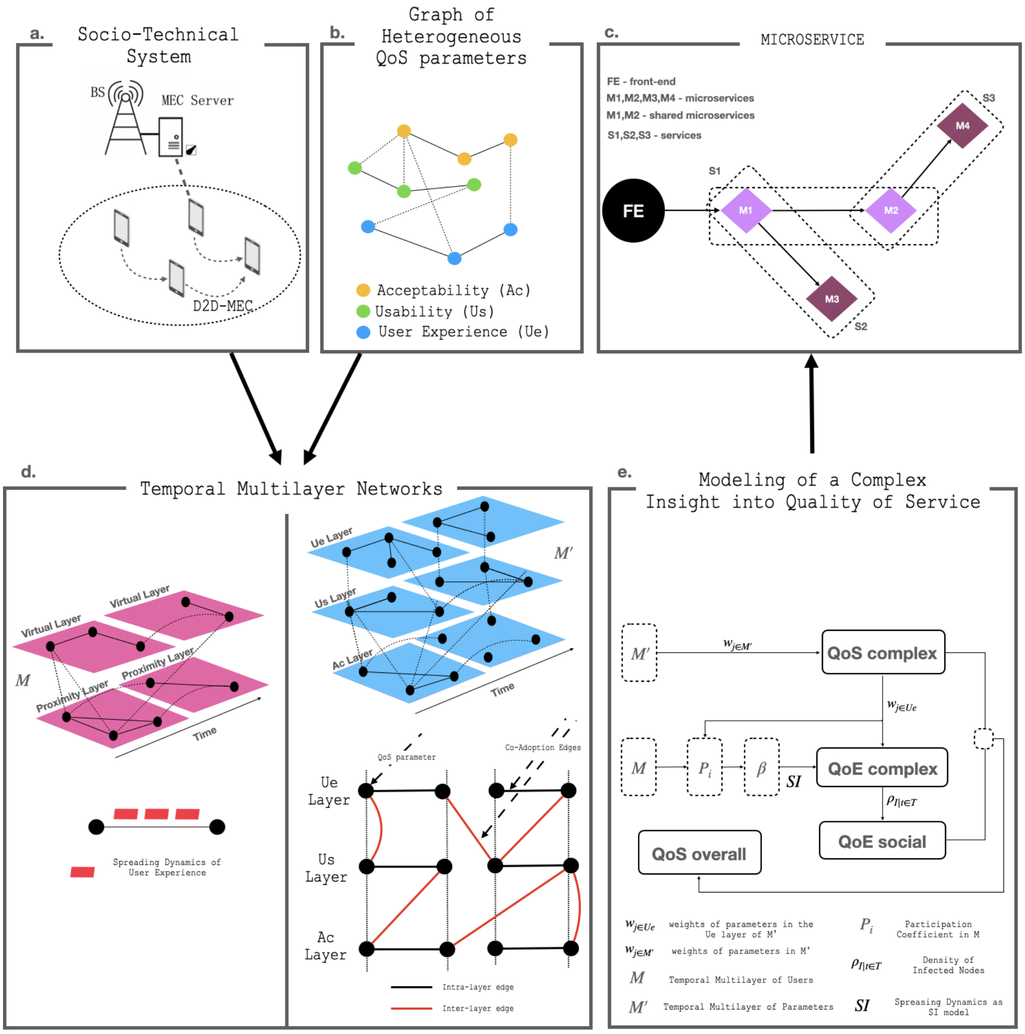

Figure 1. Bringing complexity to 6G to assess the quality of microservices. The figure schematically describes the main aspects of our proposed modeling approach. We consider a socio-technical system of mobile users and devices (**a**) exploiting a D2D-MEC system for communication and computing of tasks. We assume that a set of services accessed by end users, as in (**a**), is represented as a set of microservice applications which consists of multiple composite services (**c**). We consider a graph of heterogenous networked QoS parameters (**b**), belonging to different categories (Ac, Us, Ue). In (**d**), we show the temporal multilayer representation for both environments. The analysis of both complex structures, their interdependence and dynamics leads to the complex systems of QoS and QoE, whose algorithm is detailed in the scheme in (**e**).

Table 2. Main notations.

Symbol	Description
$\mathcal{M}$	Temporal multilayer social network.
V_M, E_M	Set of vertices and set of edges for $\mathcal{M}$.
L	Set of elementary layers for $\mathcal{M}$, with $L = L_1, L_2$, respectively, the interconnections based on proximity networks and virtual social networks.
$\mathcal{M}'$	Temporal multilayer quality network.
T	Temporal window of observation.
N	End users, population of $\mathcal{M}$.
J	Heterogeneous quality parameters and population of $\mathcal{M}'$
w_j	Weights of $j \in J$ in $\mathcal{M}'$.
k_j^{α}	Intra-layer degree of j on a layer α in $\mathcal{M}'$.
$k_j^{\alpha\beta}$	Inter-layer degree of j through layers α and β in $\mathcal{M}'$.
$P_{\alpha\beta}(k, k')$	Probability of having edges that connect node of degree k in a layer α to node with degree k' in a layer β in $\mathcal{M}'$.
S	Susceptible state of the SI model.
I	Infected state of the SI model.
β	Infection rate.
$\overline{P}$	Mean value of the participation coefficient of node i in $\mathcal{M}$.
$QoS_{complex}$	The measure of quality depending on weighing the co-adoption of heterogeneous parameters in $\mathcal{M}'$.
QoE_{social}	The measure of quality based on user-experience spreading dynamics in the social network jointly with its complex values weighted in $\mathcal{M}'$.
$QoS_{overall}$	The overall complex measure of QoS, computed as the sum of $QoS_{complex}$ and QoE_{social}.

4. Mathematical Modeling

4.1. Temporal Multilayer Social Network

Let us consider a temporal multilayer social network $\mathcal{M}$ defined as a quadruplet, $\mathcal{M} = (V_M, E_M, V, L)$, where V is the set of vertices, representing users of the socio-technical environment of Figure 1a, as detailed in the left panel of Figure 1d [26,61,79]. The set of elementary layers is $L = L_1, L_2$. The L_1 identifies two types of interconnections among vertices V, which are a proximity network and a virtual social network. The L_2 identifies the variation in interactions for each time step t_i within the temporal window T [64]. We assume $\mathcal{M}$ to be node-aligned, which means that all layers contains all nodes, with $V_M = V \times L_1 \times L_2$ and E_M their edges. Furthermore, the couplings of $\mathcal{M}$ are diagonal, meaning that all the inter-layers edges are between nodes and their counterparts in another layer. Furthermore, they are also categorical, due to the fact that each node is adjacent to all of its counterparts in the other layers [25].

4.2. Temporal Multilayer Quality Network

Let us consider the quality graph shown in Figure 1b, represented in a temporal multilayer network $\mathcal{M}'$, as in Figure 1d, whose vertices V' are the networked heterogeneous parameters J referring to the QoS. Representing this graph as $\mathcal{M}'$, we assume three distinct layers (Ac, Us, Ue), as detailed in right panel of Figure 1d, in accordance with the three categories, as assumed in [80]. The edges among nodes in $\mathcal{M}'$ are referred to as their "co-adoption", which denotes the relative frequency of using a pair of parameters for the quality esteem. In order to mine a complex esteem of QoS, we define the structural-based weights, $\forall j \in J$ in $\mathcal{M}'$, as follows:

$$w_j = k_j^{\alpha} + P_{\alpha\beta}(k,k') \times k_j^{\alpha\beta}, \tag{1}$$

where k_j^{α} is the intra-layer degree of a node $j \in J$ in a layer α in $\mathcal{M}'$, $k_j^{\alpha\beta}$ is the inter-layer degree which considers the inter-layer edges of a node $j \in J$ between a pair of layers in $\mathcal{M}'$, and $P_{\alpha\beta}(k,k')$ is the probability of having edges that connect nodes with degree k in a layer α with a node with degree k' in a layer β [25,26,61]. The degree of each node is computed following the mathematical approach presented in [61]. Taking into consideration a microservice s and a set of parameters with w_j in $\mathcal{M}'$, we define the complex QoS as follows:

$$QoS_{complex} = \sum_{j \in \mathcal{M}'} w_j \tag{2}$$

This represents a measure depending on how the "co-adoption" of heterogeneous parameters, belonging to different categories, can contribute as an extra aspect that could be added to the well-known and traditional ones.

4.3. Spreading Dynamics of Experience in Social Networks

The spreading dynamics are modeled as an SI epidemic spreading process, which describes how the user experience can spreads in the network $\mathcal{M}$, impacting on quality esteem in $\mathcal{M}'$ [21,65] . The spreading process is diagrammatically expressed in terms of a reaction-diffusion equation, as follows:

$$SI \Rightarrow S \xrightarrow{\beta} I \tag{3}$$

The SI model is governed by the above reaction where β is the transition rate for infection. Many more epidemic models can be defined analogously to the classical SIS and SIR models. A useful variant is the SI model, which only considers the first transition, i.e., individuals becoming infected and never leaving this state [65]. In accordance with the microservice scenario, the rate β represents the probability that a microservice is accessed by the end users in $\mathcal{M}$, following the social influence jointly with the awareness of the computed complex esteem of QoS. A user acquires experience and performs a judgement process concerning quality. In accordance with this assumption, we define the β as follows:

$$\beta = \overline{P} \cdot (QoS)_{complex} \tag{4}$$

where $\overline{P}$ is the mean value of the participation coefficient of nodes in $\mathcal{M}$, and represents a measure of the distribution of the edges across the layers [61], while $(QoS)_{complex}$ is the computed contribution to quality mined from the $\mathcal{M}'$, as in Equation (2). The dynamic microscopic Markov chain approach (MMCA) enables us to explore the spreading dynamics in $\mathcal{M}$ [21]. We quantify the probability of each node being in one of the states at time step t_i. In our work, the threshold model depends on the complex dynamical interplay, since the values of β changes accordingly to the network structure of the $\mathcal{M}$ network and the complex QoS. Since the SI model determines the user-experience spreading process in $\mathcal{M}$, it contributes to changing the complex QoE. We define a social dynamical esteem for QoE as follows:

$$QoE_{social}|_{t \in T} = (\rho_I)|_{t \in T} \cdot \sum_{j \in \mathcal{U}]} w_j \tag{5}$$

This is the product of the ρ_I, which is the density of infected nodes in T, and $(QoS)_{complex}$ is the complex QoS, as in Equation (2). This value changes in time, depending on the spreading dynamics of user experience jointly with the complex values mined from $\mathcal{M}'$, where the structural heterogeneity of the quality evaluation is weight.

5. Numerical Results

5.1. Simulations Setup and Pseudo-Code

Simulations were conducted taking into consideration the two multilayer structures $\mathcal{M}$ and $\mathcal{M}'$, respectively, representing the temporal multilayer social network and the temporal multilayer quality network, by varying in a temporal window T, as discussed in Section 4. We assume that, in $\mathcal{M}$, the virtual social layer follows a scale-free topology [21,81], while the proximity layer is a temporal exponential-family random graph model (TERGM) dynamic proximity network with random edge formation and dissolution effects [82]. For the network $\mathcal{M}'$, we consider a set J of parameters, and we assume that the topology that describes the edge formation in terms of intra-layer and inter-layer edges may follow the scale-free or the small-world hypothesis, enabling us to vary different degrees of structural heterogeneity for the distribution of "co-adoption" edges. To build the model, perform computation and obtain our results, we used the programming language R and the IDE RStudio [83,84]. The findings were generated thanks to the packages EpiModel [85] and TERGM [86]. Table 3 summarizes the major simulation parameters. The pseudo-code of our proposed model, in accordance with the mathematical approach explained in Section 4, is detailed in Algorithm 1.

Table 3. Simulation parameters.

Parameter	Value
Time steps $t_i \in T$	ranges in [1:500]
Number of layers in $\mathcal{M}$	2
Number of layers in $\mathcal{M}'$	3
Number of nodes in $\mathcal{M}$	N ranges in [200:1000]
Number of nodes in $\mathcal{M}'$	J ranges in [30:180]

Algorithm 1: Complex Quality Esteem.

Input: $N;J$.
Results: $QoS_{complex}$; QoE_{social}; $QoS_{overall}$.
Set T; $t_i \in T$; $\mathcal{M}$; $\mathcal{M}'$.
Compute: $\forall j \in J$ in $\mathcal{M}'$ calculate w_j and $QoS_{complex}$.
COMPUTE: in α virtual social layer of $\mathcal{M}$ we calculate $\overline{P}$.
for $t_i \in T$ **do**
  SIS dynamics in $\mathcal{M}$.
  compute ρ_I; QoE_{social}.
  compute $QoS_{overall} = QoS_{complex} + QoE_{social}$
endfor

5.2. Discussion

The simulations conducted were based on the proposed modeling approach described in Section 4, leading to the following results. The selected findings were properly chosen to extract the most relevant findings. As explained in previous sections, we designed a temporal multilayer social network $\mathcal{M}$ with two types of topologies, the scale-free network (SF) [81] for the social-network layer topology and a TERGM dynamic proximity network with random edge formation and dissolution effects [86] for the proximity network layer. In Figure 2, we display the temporal multilayer social network $\mathcal{M}$, the evolutionary structure and the spreading dynamics, in the selected time steps t_1, t_{500} within the overall temporal window of observation T. The lower side of the figure shows the time-varying proximity layer of interactions between nodes, differently from the upper portion, which shows the topology of the scale-free network hypothesis, as specified in Section 4.1. The virtual layer does not vary in $t < T$, by displaying the same topology of a scale-free network in the overall observation period, differently from the real proximity network. According to Equation (4), the higher the mean value of participation in $\mathcal{M}$, the higher is the probability of infections emerging from the time-varying proximity and proportional to the $QoS_{complex}$, assumed to be a computed value the users are aware of. In Figure 3, we show the evolution of the overall complex QoS dynamics in T, by varying the population size N of the temporal multilayer social network $\mathcal{M}$. The overall complex QoS is the sum of two contributions, the $QoS_{complex}$ and QoE_{social}, respectively, expressed in Equations (2) and (5). The resulting overall value increases as a function of the quality system mined from $\mathcal{M}'$ in conjunction with the dynamics of the QoE, which follows the spreading dynamics of the user experience during T, in $\mathcal{M}$. The overall value of QoS changes slightly in the temporal window T under the increase in the population size N, due to the aim of being scale-free for the virtual layer, which is a highly heterogeneous network, characterized by a power-law degree distribution with very few hubs in the network. This implies that, regardless of N size, the hubs in a heterogeneous network produce the same acquisition of experience over time. In Figure 4, we display the variation in the complex QoS as a function of the number of the parameters J, the population size of the temporal multilayer quality network $\mathcal{M}'$, under network structures exhibiting a different level of heterogeneity, the scale-free (SF) network [81] and the small-world (SW) network [87], for both the intra-layer and the inter-layer interactions, which determine the co-adoption. SW networks are characterised by high clustering and modularity with an over-abundance of hubs which mediate the shortest path length, and, in terms of quality, co-adoption so distributed would entail high costs. SF networks, which are highly heterogeneous networks, are characterised by a high degree of correlation between nodes and degree distribution, which means that there are few hubs in the network. We find that the increase in the number of parameters J, whatever role they may play in the network $\mathcal{M}'$, has a greater impact on QoS_c if their co-adoption follows a small-world pattern, while it remains slightly invariant if we consider a scale-free one. The extra information on quality obtained from the complex structure is more variable as the number of high-degree nodes (hubs) is introduced, and the abundance of hub nodes results in more co-adoptions and, thus, higher computational costs. In Figure 5, we illustrate the variation in the infection rate β, characterizing the spreading dynamics of the user experience in the $\mathcal{M}$ temporal multilayer social network, as a function of the mean value of the participation coefficient $\overline{P}$, computed as in [61]. This trend is displayed against the number of attributes J of the $\mathcal{M}'$ temporal multilayer quality network, as in Figure 5a, while in Figure 5b, we show β vs $\overline{P}$ by fixing $J = 30$ and varying the network topology for co-adoption in $\mathcal{M}'$. We figure out how an increase in the average participation in the social network results in an increase in infection rate and whatever the number of attributes, the strong hierarchical difference in the scale-free hypothesis for co-adoption allows for the same growth trend. Differently, in Figure 5b, the introduction of the small-world hypothesis and with a fixed number of J, includes more co-adoptions between nodes than the scale-free case and with a less heterogeneous degree of distribution. This results in a faster rate of growth with lower participation values. Figure 6 shows the relationship between the MOS, %PoW, %GoB as used in the E-model [88]. It is a well-established practice to use the mean opinion square (MOS) to asses the perceived QoE, as with the usage of the percentage of poor-or-worse (%PoW) and good-or-better (%GoB) [89,90]. We compared these measures with the probability density function of the QoE_{social} distribution of values, as in Equation (5), referring to users not rating in terms of poor or worse as well as good or better or neutral, but as a result of the spreading dynamics of user experience in the $\mathcal{M}$ temporal multilayer social network. Around the mean value of the $QoS_{complex}$, computed for $J = 30$, the span of QoE_{social} is more flattened because it is the result of the spreading dynamics of the perceived experience in the social population, under the heterogeneous assumption of being scale-free, over time.

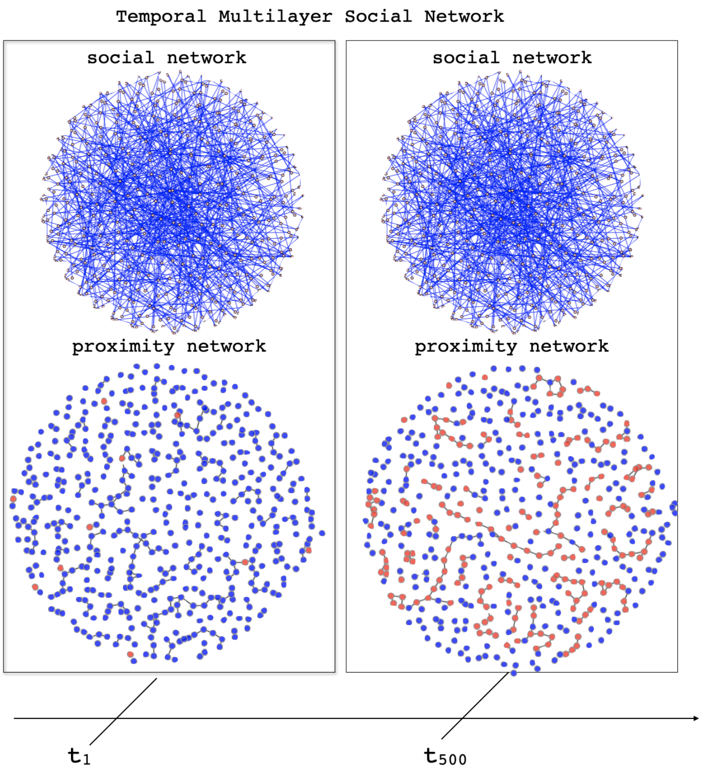

Figure 2. Spreading dynamics of user experience in the temporal multilayer social network. The plot displays the spreading of user experience within the network $\mathcal{M}$, showing the time steps t_1, t_{500} selected in T. The network $\mathcal{M}$ is composed of a virtual social network layer (the two graphs in the upper portion) and a proximity network layer (the two graphs on the lower side). The red circles represent the infected nodes, the blue circles the susceptible nodes.

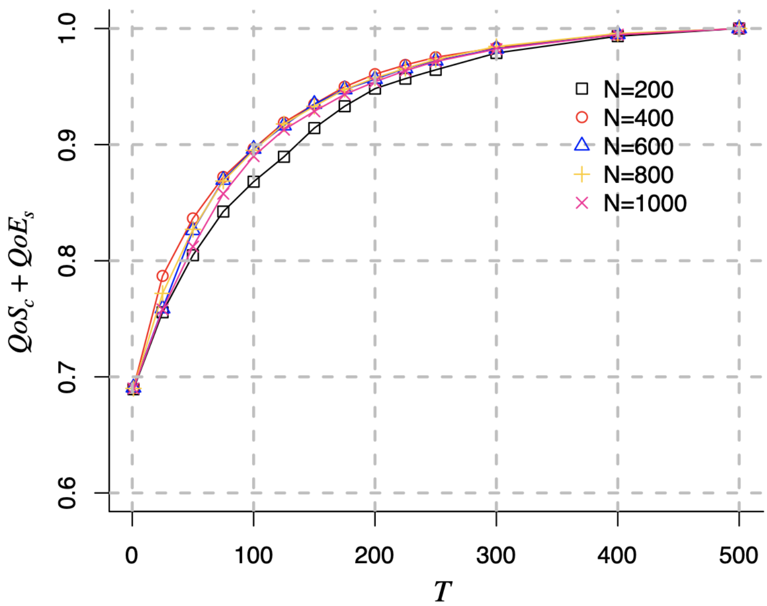

Figure 3. The overall complex QoS dynamics against the population of the temporal multilayer social network. We display the evolution of the overall complex quality measure in T temporal window, under the variation in N, and population of the $\mathcal{M}$ temporal multilayer social network. The overall measure is the sum of the complex $(QoS)_{complex}$ and the QoE_{social}. Its variation was computed considering $J = 30$.

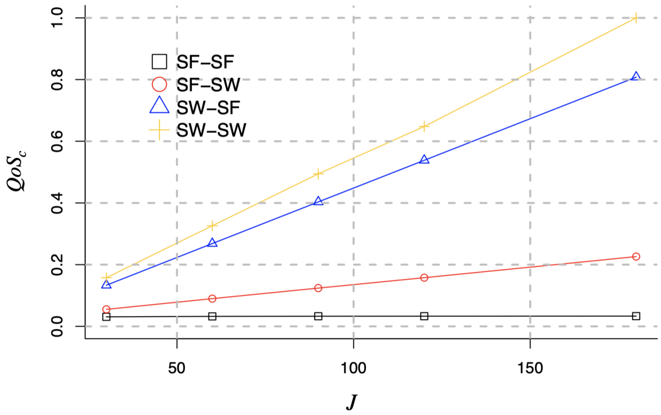

Figure 4. Complex QoS in function of population size and network-topology hypothesis of the temporal multilayer quality network. We shed light on the complex QoS in function of the J numbers of parameters, and population of $\mathcal{M}'$. We took into consideration different network topology hypotheses for the co-adoption in $\mathcal{M}'$. We explore four cases, choosing scale-free (SF) or small-world networks (SW). In each case, the first topology indicates the intra-layer scheme, while the second one indicates the inter-layer scheme.

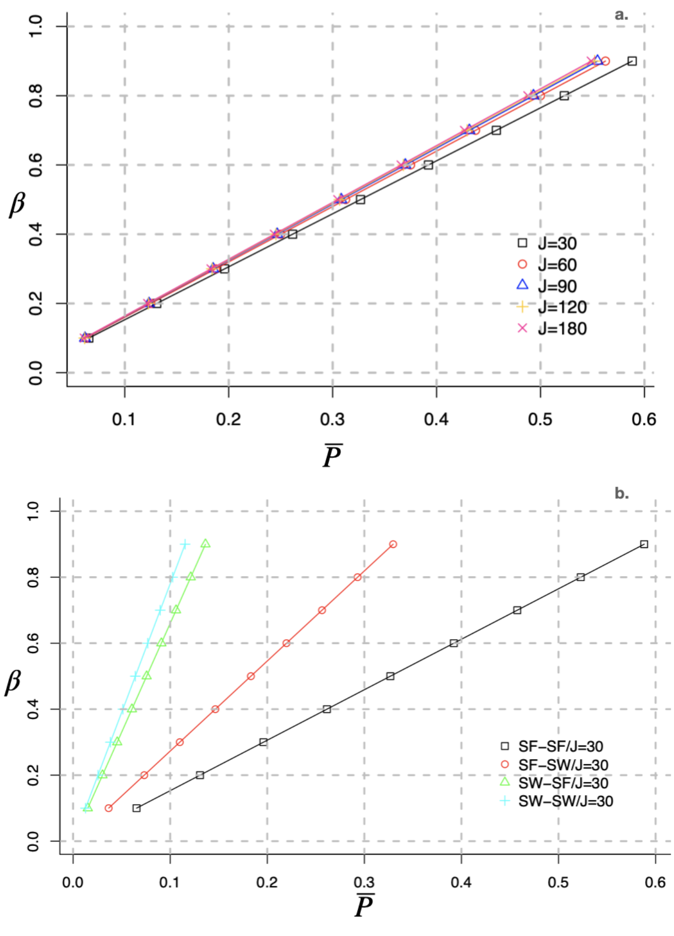

Figure 5. Participation coefficient vs. infection rate, under the number of quality parameters. We show in (**a**) the infection rate as function of the mean value of the participation coefficient in $\mathcal{M}$, against the J parameters in $\mathcal{M}'$, taking into consideration a network topology hypothesis for the co-adoption that follows the scheme SF-SF. In (**b**), by fixing the $J = 30$, we vary the network hypothesis, by including also the small-world network.

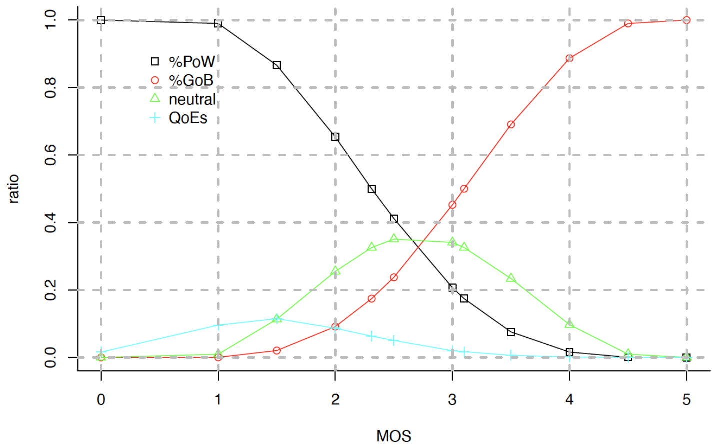

Figure 6. Relationship between MOS, $\%PoW$, $\%GoB$, and QoE_s. We compare the relationship between the MOS, %PoW, %GoB as used in the E-model, with the probability density function of the QoE mined from the spreading dynamics of user experience in $\mathcal{M}$ during T temporal window.

6. Conclusions and Future Works

Quality is the result of a combination of many factors, some derived from objective evaluations, others from subjective or mixed ones. In the 6G era, where the network will be more pervasive, ubiquitous, persuasive and cognitive, quality can benefit from further evaluations, taking into account social and dynamical aspects, assessed through a complex networks approach. Our proposal is based on a complex representation and analysis of both a social network and a quality network. The social network, which is a socio-technical system of users and devices, is modeled as a temporal multilayer social network, composed of a proximity and a virtual layer. The quality network is modeled as a temporal multilayer quality network and it is populated by nodes, which represent heterogeneous measurable quality parameters. This allows us to equally treat both quality parameters and social nodes, in complex structures, giving us the opportunity to investigate information that we otherwise overlook. The overall complex system of QoS is the sum of a measure mined from the structure of the temporal multilayer quality network and the social QoE. The first value depends on the co-adoption of parameters, while the second one from the spreading dynamics of user experience in the temporal multilayer social network. Our outcomes show how the proposed complex framework adds new insights to assess QoS. This is relevant for the quality of a microservice where its granularity and the dynamic context necessitate more in-depth evaluation. To determine the overall complex QoS, we jointly consider the social QoE as a result of the spreading dynamics of user experience in the temporal multilayer social network. The social QoE, as a perceived and collective dynamical measure, is a sort of social marker of the network, able to forecast the trend of QoS in time. In future works, the application of our mathematical approach and algorithm with data-driven and real cases could represent a task or resource at the edge of the network to drive and improve caching, training, inference, offloading and, more broadly, edge intelligence. Furthermore, encompassing aspects of social dynamics, the application of community detection methods may be crucial for unveiling polarizing effects and echo chambers emerging from the network and changing in time, based on interests, homophily, or urgency. Such effects, studied at the level of communities, taken from a multilayer structure, can have a marked influence on the perceived quality and, thus, on user experience. This approach would allow, through distributed and dynamic computation, to synchronize socio-technical systems with social collective evolution. The social network becomes a useful source domain for the estimation of users' preferences or interests, and a marker of how the networks can evolve.

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