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Resilience in Edge Computing: Challenges and Concepts

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Resilience in Edge Computing: Challenges and Concepts

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ABSTRACT

Edge computing has evolved significantly from early research ideas to modern 5G mobile and multi-access edge computing (MEC). In many 6G-related projects, we see a clear trend toward virtualizing computing resources at the edge. Motivated by the cloud-edge-continuum that is the basis for next-generation metaverse applications, and the need for low-latency solutions, distributed computing is now receiving even more attention. A final hurdle for the wide use of (virtualized) edge computing for mission-critical applications is resilience. In this context, resilience is the ability of modern communication and computation systems to deal with unknown and unforeseen events, both from internal and external sources. Thus, making MEC resilient to outages (e.g., system failures or energy outages due to natural disasters), security incidents (e.g., the use of intelligent jamming or malicious users), and overall challenging conditions (e.g., high mobility or impaired connectivity) is of the highest importance. In this monograph, we review the current

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state-of-the-art of resilience in mobile edge computing. We explore MEC-specific challenges and resilience objectives, and discuss selected resilience measures. We trust that this monograph will be an invaluable resource for beginners and experts in the field as a compound resource on resilience in MEC.

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1

Introduction

Computing paradigms have continuously evolved to address the growing demands of modern applications. Initially, cloud computing emerged as a transformative approach, enabling the offloading of computationally intensive tasks to centralized and virtualized infrastructures. These infrastructures provide resource scalability and flexibility, and thus can adapt to the diverse applications with varying requirements. However, the centralized nature of cloud computing resources induce additional communication delay and cause network overhead. This is especially problematic for time-sensitive and mission-critical applications. Eventually, edge computing is introduced as a complementary paradigm, bringing computational resources closer to end-users and devices [42]. This proximity benefits time-critical applications by reducing delays and improving responsiveness. It also offers better privacy by processing sensitive data locally on devices or nearby servers, reducing the risk of exposure during transmission to centralized cloud systems.

As a natural progression, multi-access edge computing (MEC) has emerged to address the unique requirements of highly dynamic environments. Unlike traditional edge computing, MEC is tailored to the mobility and connectivity constraints of devices that cannot rely on

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consistent connection with centralized entities [76]. For instance, modern connected vehicles must process vast amounts of sensory data for tasks like obstacle detection, navigation, and collision avoidance. MEC can offload these computationally intensive tasks to nearby edge servers, reducing the processing burden on individual vehicles and enabling faster response times [21], [54]. Moreover, internet of things (IoT) applications in smart cities, healthcare, and industrial automation, all orchestrated with mobile sensors, require real-time monitoring and analysis, and thus necessitate MEC solutions close to the data sources [43], [47], [58], [84]. Immersive applications like the Metaverse, using virtual and extended reality (VR/XR) technologies, take place in large-scale events, training simulations, digital twins, and collaborative mobile environments [48], [100], [102]. These applications generate massive amounts of data, requiring artificial intelligence (AI)-empowered processing at the edge due to the limited computational capacity of user devices. These diverse application requirements make it challenging to provision computational resources dynamically, and they remain a persistent hurdle for MEC systems.

Apart from the variety of MEC applications, the heterogeneity of MEC resources is also rapidly increasing, adding further complexity to MEC ecosystems. Initially, these resources were dedicated virtualized servers managed centrally by edge or cloud controllers. However, advancements such as 5G-enabled computation at the network edge have pushed these resources closer to applications, making them an integral part of the communication infrastructure, such as 5G base stations [98]. The evolution has also introduced mobile entities, like connected vehicles, which can act as both consumers and providers of computational resources. This dual role introduces additional layers of complexity, as computing resources are now not only heterogeneous but also mobile. Emerging concepts like virtual edge computing (V-Edge) are further decentralizing computation by enabling ad-hoc resource aggregation from diverse nodes like modern cars with advanced computational capabilities [20]. Ensuring interoperability across this heterogeneous landscape is an ongoing challenge.

In the light of this complexity, resilience has become a critical concern for MEC systems [7], [83]. It can be defined as *"the ability*

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(of the network) to provide and maintain an acceptable level of service in the face of various faults and challenges to normal operation" [85]. As an example, for critical applications, computational results must be reliable and accurate despite potential failures in virtualized edge resources, e.g., as a result of system overloads, operational errors, or connectivity loss. Since the MEC ecosystem becomes more diverse, a multitude of security threats can be found at different MEC actors and components, such as (malicious) end hosts, (compromised) virtualized environments, and communication infrastructure and protocols. Privacy is another concern, particularly for offloaded tasks that involve sensitive user or application data [15], [88]. As a result, *resilience objectives* such as availability, reliability, security, and privacy must be carefully considered in the design of MEC systems.

Given the inherent complexity of MEC systems and their diverse resilience objectives, it is crucial to develop effective resilience measures. These must address potential faults and attack vectors while also overcoming the unique challenges to which MEC systems are exposed. Accordingly, this monograph provides a systematic analysis of potential resilience measures designed to fulfill the selected resilience objectives. Our contributions can be summarized as follows:

- We first present an overview of a heterogeneous MEC system model, analyzing key characteristics of different components within the MEC ecosystem. We also associate this model with an existing reference MEC architecture to align our analysis with the literature and standardization efforts.

- Second, we identify the primary challenges that limit and also necessitate the development of resilience measures. We also present the main resilience objectives (dependability and trustworthiness) and techniques (proactive and reactive) that are aimed at and employed in common by several resilience measures.

- We introduce advanced resilience concepts, linking them to MEC components and addressing identified challenges. This analysis is based on a literature review, each article providing essential building blocks for implementing comprehensive resilience measures.

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Following these contributions, the methodological overview of our analysis is also shown in Figure 1.1. The rest of the work is organized as follows: Section 2 reviews related work that addresses resilience in the context of MEC. Section 3 introduces a system model for a comprehensive MEC ecosystem, encompassing various types of resources, users, and interfaces. Section 4 discusses the challenges specific to MEC that influence the design of resilient systems and highlights key resilience objectives considered in our analysis. Section 5 categorizes our resilience concepts by analyzing several selected studies from the literature and underlining their relevance with the presented resilience challenges and objectives. Section 6 outlines potential future directions, and Section 7 concludes the monograph.

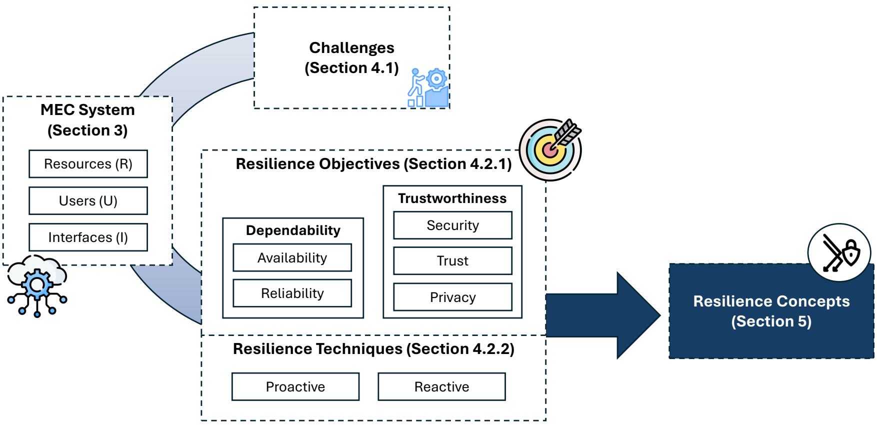

Figure 1.1: Overview of our analysis of challenges, objectives, and concepts of resilience in MEC.

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