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Review Article

Using QoE Metric as a Decision Criterion in Multimedia Heterogeneous Network Optimization: Challenges and Research Perspectives

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This article explores the growing importance of the QoE (Quality of Experience) metric as a fundamental criterion in the optimization of heterogeneous multimedia networks. We explore the benefits of using QoE, such as improving user experience, efficient resource management, and adaptation to network conditions. However, this paradigm presents technical challenges, including accurately measuring QoE and managing the complexity of heterogeneous networks. To address these challenges, we highlight promising research prospects, such as the development of advanced algorithms, real-time measurement of QoE, and the integration of machine learning. Ultimately, the use of QoE in the optimization of heterogeneous multimedia networks contributes to a substantial improvement in the quality of multimedia services offered to end users.

1. Introduction

The exponential growth of global data traffic, propelled by the ever-increasing consumption of multimedia content, is placing considerable pressure on communications infrastructures. According to reports from the Federal Communications Commission (ComCom) [1], the global volume of data exchanged over mobile networks is expected to reach 90 exabytes per month by the end of 2022, and this trend is expected to quadruple by 2028. This development demonstrates the continued explosion in demand for various multimedia services such as streaming video, online gaming, and augmented reality. Faced with this challenge, heterogeneous networks [2] are emerging as a strategic response, offering a diversity of communication technologies, including 5G, WiFi, and other wireless networks. These heterogeneous networks are designed to optimize traffic distribution according to the specific needs of each service or application. 5G, for example, is being deployed to provide high speeds and low latency, ideal for bandwidth-intensive applications, while WiFi can be leveraged for high-speed connectivity in localized environments such as homes and businesses. This exponential growth in multimedia traffic and the meteoric emergence of heterogeneous networks raise significant challenges in terms of resource management, quality of service (QoS), and, above all, Quality of Experience (QoE) for end users.

QoE, as a subjective metric reflecting user satisfaction, becomes a critical element in the management and optimization of HetNets. It transcends as a key factor in the provision of multimedia services. Recently, some research has focused on the concept of QoE [1–4] and its management [5–7] in network and multimedia services. Although the concept of QoE remains vague at this stage, all proposed definitions focus on the end-user's perception. This involves the complex management of QoE in multimedia Hetnets.

Current research efforts focus on monitoring and using QoE [3, 4] as a unified metric in decision-making. Indeed, to provide high-quality personalized services and meet user needs in terms of performance, reliability, security, and usability, new network architectures must be self-managing [7]. For example, if the video quality is low, the system can automatically adjust the resolution, reduce the code rate, or replace the server. In this context, the use of QoE as a decision criterion in optimization becomes a key issue for future heterogeneous multimedia communication networks (HetNets). Service providers must be able to collect real-time QOE data, analyze performance issues, and make active optimization decisions to ensure the best quality of service for each user.

However, despite efforts to optimize network performance parameters, the traditional approach focused on technical metrics such as throughput, delay, and bandwidth proves limited. Traditional optimization methods, such as quality of service (QoS) tuning, while essential, do not fully capture the real user experience. These approaches focus on measurable technical aspects, often disconnected from subjective expectations and individual user preferences.

The limits of these methods become more evident in a context where the diversity of multimedia services offers a varied range of user experiences. Today's users are no longer satisfied with simple data transmission, but demand rich, interactive multimedia experiences.

By integrating QoE as a decision-making criterion in the optimization of heterogeneous multimedia networks, we overcome the limits of approaches focused solely on QoS. QoE takes into account subjective factors such as audio clarity, image sharpness, video smoothness, and other aspects that contribute significantly to the overall rating of the user experience. Indeed, user satisfaction depends not only on the technical performance of the network but also on how this performance is translated into a meaningful and rewarding experience. Additionally, optimization decisions should be informed by how users experience and interact with media services. This requires a deep understanding of individual preferences, media consumption patterns, and usage contexts, aspects often overlooked by traditional methods.

Thus, to meet users growing expectations for quality multimedia experiences, it becomes imperative to adopt a holistic approach that integrates QoE as a central decision metric in the optimization process of heterogeneous multimedia networks. This shift in perspective provides a significant opportunity to improve user satisfaction and ensure exceptional multimedia service delivery in increasingly complex network environments.

However, this integration raises several challenges, including the subjectivity of evaluations, the variability of user preferences, the complexity of prediction models, and the need to adapt to the rapid evolution of multimedia services. Understanding these challenges is imperative for developing effective strategies for optimizing heterogeneous networks.

The objective of this article is to highlight the importance of the QoE metric in the optimization of heterogeneous multimedia networks. We discuss the benefits of its use, the technical challenges it poses, and research prospects for overcoming these challenges. Our contribution lies in synthesizing current knowledge and identifying key research areas to improve user experience in heterogeneous networks.

The rest of the article is structured as shown in Figure 1. Section 2 presents the state of the art on Quality of Experience and heterogeneous networks (HetNets). Section 3 explores the importance and different aspects of the application of QoE as a key optimization metric in these networks as well as plausible integration methods. Section 4 focuses on the challenges of using QoE as a decision criterion in heterogeneous networks, including the heterogeneity and complexity of multimedia heterogeneous networks, real-time QoE data collection, and model complexity adaptive for QoE prediction. We will then discuss research perspectives and potential solutions in Section 5. Finally, we conclude by highlighting the continued importance of QoE-based optimization in heterogeneous networks.

2. State-of-the-Art

This section presents an in-depth exploration of current knowledge and trends in the area of Quality of Experience (QoE) within heterogeneous multimedia networks. Over the years, research has significantly expanded its understanding of QoE, evolving beyond purely technical measures to encompass the subjective dimensions of user experience. Heterogeneous multimedia networks, by integrating a diversity of services and technologies, have introduced new challenges and opportunities in terms of optimization. Through this state-of-the-art, we will begin by exploring heterogeneous multimedia networks with an emphasis on the fundamental concepts, motivations, and limits of so-called traditional optimization in these complex environments. Subsequently, we will look specifically at the theoretical foundations of QoE, highlighting traditional and emerging models that capture user perception in complex multimedia environments. Additionally, it discusses the innovative work that has propelled QoE to the forefront of heterogeneous network optimization research.

2.1. Heterogeneous Networks (HetNets). In recent years, the study of heterogeneous networks (HetNets) has become a hot research area. This section provides a more detailed understanding of these networks and their advantages and limitations.

2.1.1. Definition and Architecture of HetNets. Heterogeneous networks (HetNets) represent a strategic merger of various network types into an integrated system, aiming to optimize resource utilization and provide seamless connectivity for a variety of heterogeneous devices. This wireless communication transformation combines macrocells and small cells to form an overall network architecture, improving coverage and capacity. Macrocells act as the backbone of the HetNet by providing extensive coverage, suitable for high density of users over large

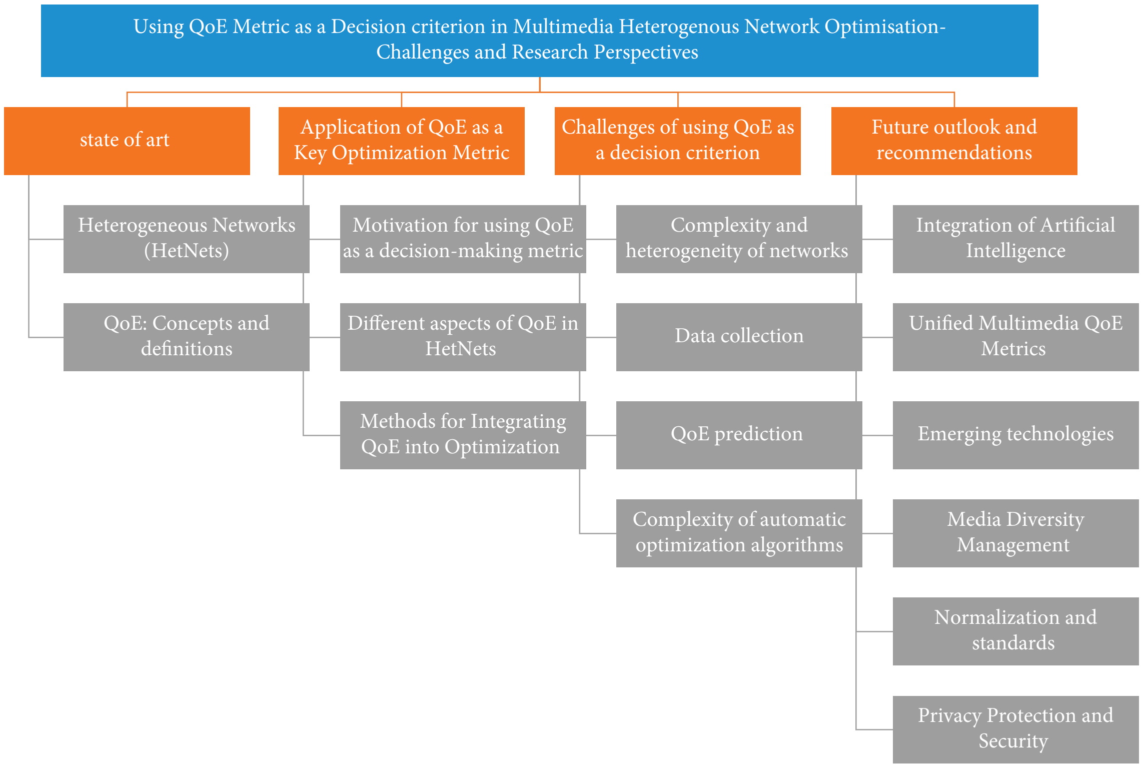

Figure 1: Organization of the article.

territories. Femtocells, picocells, and microcells are integrated to optimize indoor and outdoor coverage, meeting the specific needs of small or large environments. WiFi integration further strengthens HetNets by providing high-speed connectivity in areas of high demand, while reducing congestion and improving network efficiency. This approach also enables efficient resource management, preserving the capacity of cellular systems and improving the overall user experience, especially in densely populated urban areas. An example of HetNet architecture is shown in Figure 2.

2.1.2. Heterogeneous Networks (HetNets): Advantages and Reasons for Integration. The increasing integration of heterogeneous networks (HetNets) arises from various imperatives. The rapid proliferation of smart devices and data-intensive applications has driven exponential demand for connectivity, requiring an adaptable and scalable solution. Figure 3 presents the expectations of heterogeneous networks.

To meet these expectations, HetNets orchestrate a dynamic combination of macro cells and small cells, ensuring extensive coverage and increased capacity. Their operational agility is manifested by dynamic adaptation to fluctuations in demand, optimizing the distribution of resources in real-time. The judicious integration of WiFi into HetNets presents itself as a clever response to the high demand for data in specific areas, thus offloading the conventional cellular network.

HetNets offer a plethora of significant benefits as shown in Figure 4, helping to improve network efficiency and optimize user experience. Among these benefits, we can cite the improvement of Quality of Service (QoS), efficient management of network capacity, improved mobility, deployment flexibility, and enriched user experience, seamless integration of various technologies, reduction of operating costs, adaptation to applications and users, as well as efficient use of the radio spectrum.

2.1.3. Challenges Inherent to Heterogeneous Networks. Management in HetNets becomes more complex due to the integration of various cells and technologies, requiring sophisticated coordination solutions. The coexistence of macrocells and small cells generates interference, requiring specific strategies to manage it. Managing different technologies and radio spectrum frequencies, the need for advanced security mechanisms, managing energy consumption, as well as intelligent coordination between cells and technologies present notable challenges as summarized in Figure 5.

In this context, the implementation decision based on Quality of Experience (QoE) becomes of crucial importance to overcome these challenges and fully realize the benefits of HetNets.

QoE, as a subjective metric reflecting user satisfaction, is positioned as an essential compass. It ensures that technical benefits translate into an exceptional user experience, defining the path for the future of wireless communications.

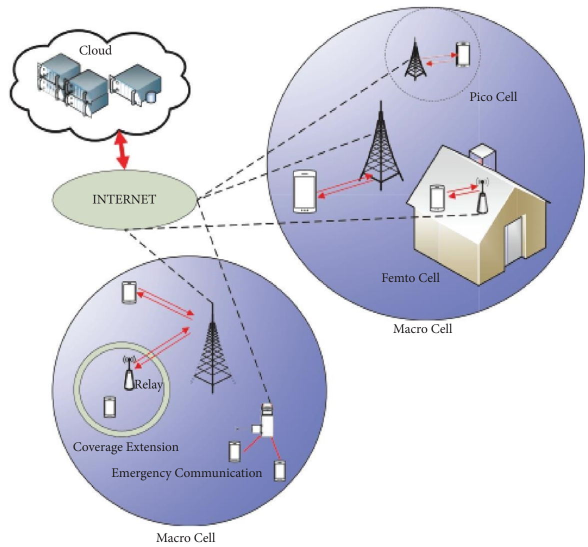

Figure 2: Architecture of a HetNet [2].

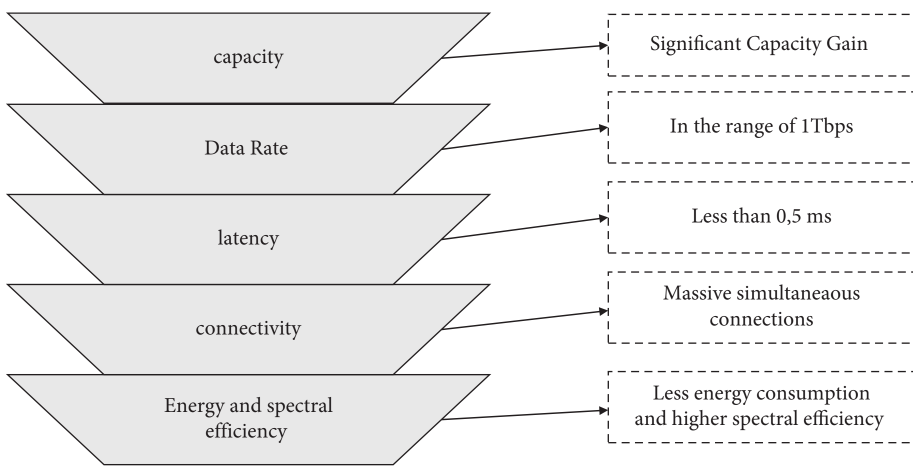

Figure 3: HetNets expectations.

It is essential to emphasize that although traditional methods are crucial, they have apparent limitations. These approaches, often focused on technical metrics, do not fully capture the real user experience.

HetNets, by integrating QoE as a decision criterion, goes beyond these limits, considering subjective factors such as audio clarity, image sharpness, and video fluidity, to guarantee optimization aligned with user satisfaction.

2.2. Quality of Experience: Definition and Key Concepts. QoE, a multidisciplinary concept, remains complex and multifaceted as illustrated in Figure 6.

Despite various definitions, it generally converges around the user's satisfaction or dissatisfaction with an application or service.

Currently lacking a standardized definition, QoE is approached from various perspectives, notably that of [2], describing it as the user's feeling of pleasure or annoyance concerning an application or service. As for Qualinet [3], it is defined as the degree of satisfaction or dissatisfaction of the user, while ETSI [4] considers it as a performance measure based on both objective and subjective. From the perspective of OEMs such as Nokia, QoE refers to how the user perceives the usability of a specific service and their satisfaction. Although the concept remains nebulous, all definitions converge towards the importance of the final user perception, thus leading to complex management of QoE within multimedia environments.

Today, QoE is becoming an essential indicator for evaluating and improving user satisfaction, particularly in heterogeneous environments such as heterogeneous networks (HetNets). As a decision-making metric, QoE enables network operators and communications system managers to optimize performance and user satisfaction. This optimization is achieved through strategic actions, such as rerouting traffic to the most suitable network, more efficient allocation of resources, and targeted improvement of quality

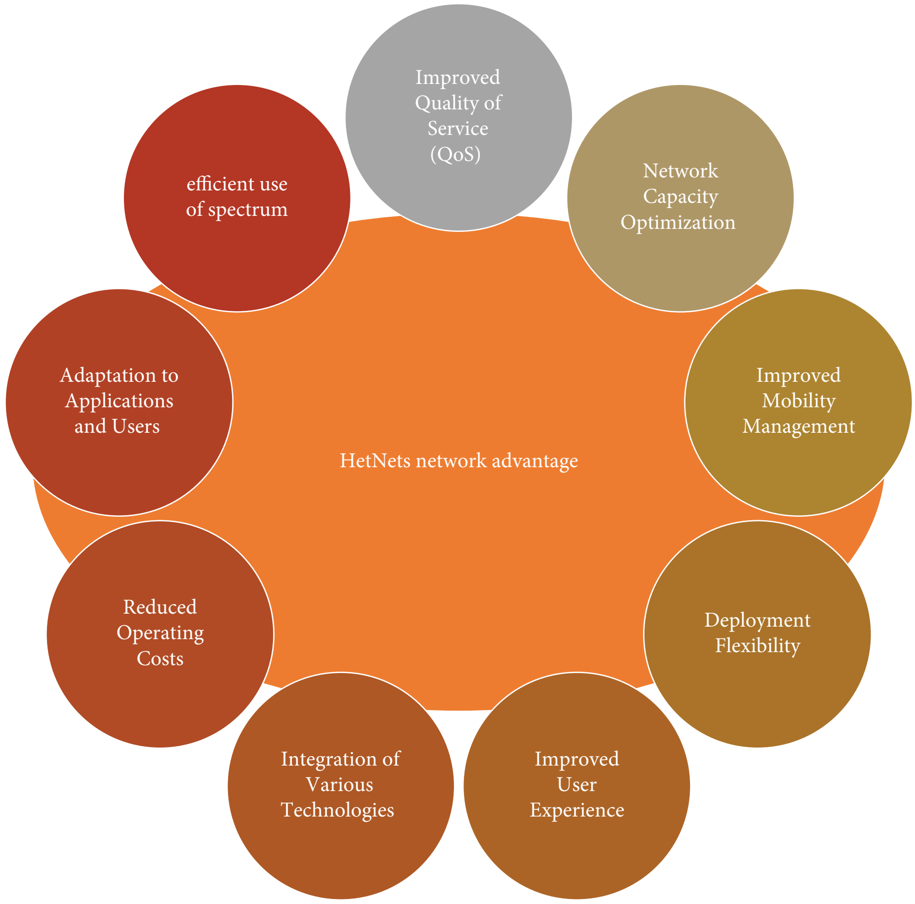

FIGURE 4: Advantages of HetNets.

Management Complexity	• The coexistence of microcells and small cells can lead to interference, requiring interference management strategies to avoid disruptions in the network.
Management Complexity	• The integration of various cells and technologies increases the complexity of network management. Operators must implement advanced coordination and control solutions to ensure optimal performance.
Need for Advanced Security Mechanisms	• Het Nets require enhanced security mechanisms to protect communications between different cells, thereby minimizing the risks of vulnerabilities and cyberattacks.
Need for Intelligent Coordination	• To optimize the performance of Het Nets, intelligent coordination between different cells and technologies is essential. This can be complex to implement.
Coexistence of Technologies and Frequencies	• Managing different technologies and radio spectrum frequencies is complex, requiring intelligent coordination to avoid conflicts and disruptions.
Energy Consumption Management	• Optimizing energy efficiency and reducing the environmental footprint requires constant efforts to minimize equipment energy consumption.

FIGURE 5: HetNets challenges.

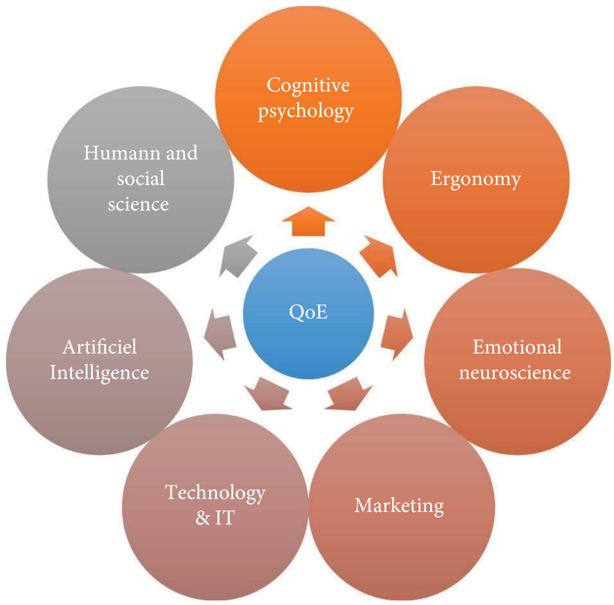

Figure 6: Multidomain QoE.

of service (QoS) in specific areas. Thus, QoE emerges as a crucial tool to guide operational decisions for an optimal user experience.

2.2.1. Influencing Factors and QoE Metrics. The influencing factors of Quality of Experience (QoE) refer to all the technical, ergonomic, and contextual parameters that affect how users perceive and evaluate their experience when using a service or digital application.

For the European community of the Qualinet network [5], the influencing factors of QoE are any characteristic of a user, a system, a service, an application, or a context whose state or real setting can influence the quality of the user's experience. At the same time, Qualinet [5] proposed a classification of factors influencing QoE into three different categories, namely, Human IF, System IF, and Context IF. A perfect illustration is given in [6] as shown in Figure 7.

2.2.2. Relationship between QoS/QoE and Model. QoS (Quality of Service) appeared in the 1990s to designate a set of techniques for ensuring the routing of sensitive network traffic such as voice or applications. Since then, the acronym QoS has been used to refer to the performance improvement achieved by hardware and/or software. But with the market for video streaming growing rapidly year over year, Quality of Service (QoS) metrics such as bandwidth, delay, jitter, and loss rate that are typically used to guarantee services, fail to measure the subjectivity associated with human perception. Network operators tend to move towards policies based on a global approach to end-to-end quality, such as Quality of Experience (QoE).

Quality of Experience (QoE) and Quality of Service (QoS) are interconnected. While QoS measures the technical performance of the network, QoE evaluates how this performance translates into the user experience. High QoS can contribute to positive QoE, but discrepancies may arise due to subjective factors. Based on the existing literature, several QoS/QoE correlation methods are identified in [8] (see Figure 8).

2.2.3. QoE Management in Multimedia HetNet Networks. QoE management brings together all the activities and processes put in place to ensure, measure, monitor, optimize, and improve user satisfaction when using a product or service. It is broken down into three stages [9]: QoE modeling, QoE monitoring and measurements, and QoE optimization and control as illustrated in Figure 9.

(1) Modelization. Karan et al. [10] defined modeling as a process of creating mathematical or statistical models that make it possible to represent and quantify user satisfaction when using a product or service. These models aim to capture the different dimensions of QoE, such as subjective satisfaction, technical performance, perceptual characteristics, or even user expectations. QoE modeling [10] aims to transform objective technical data into a mathematical or computational representation of subjective user satisfaction, thereby enabling better understanding and optimization of the user experience.

The goal of QoE modeling is to quantify and predict how technical parameters impact and how users perceive and evaluate their experience. These models can be used for various applications, such as optimizing QoS, recommending configurations, predicting QoE under different conditions, and many more.

QoE modeling uses a variety of methods, including statistical models [10], machine learning techniques [11, 12], neural networks [13], models based on user experience data [12], or even QoS to QoE models. The choice of method will depend on the specific characteristics of the data and the objectives of the evaluation. Each of these QoE modeling methods has its advantages and limitations, and the choice of method will depend on the specific objectives of the QoE assessment, the resources available, and the nature of the data collected.

In [14], the author in his doctoral thesis reviewed the works that attempted to formulate a mathematical expression of QoE. We present some explicit formulas derived from his thesis and analyze the factors considered in each model to calculate QoE. It begins by first describing the correlation model between QoE and QoS and then the method of evaluating QoE using QoS parameters. These parameters are jitter, delay, error rate, loss rate, signal success rate, and bandwidth. The expression for the correlation between QoE and QoS is calculated as follows:

$$\mathrm{QoE}(\mathrm{QoS}) = k\left(\frac{e^{\mathrm{QoS}-\alpha} + e^{-\mathrm{QoS}+\alpha}}{e^{\mathrm{QoS}-\alpha} + e^{-\mathrm{QoS}+\alpha} + \beta} + 1\right), \quad (1)$$

with α QoS quality class of the network level.

The measured QoE value is mapped to an existing mean opinion score (MOS) with a five-point scale. The parameter β is calculated based on the class of service. K is a constant

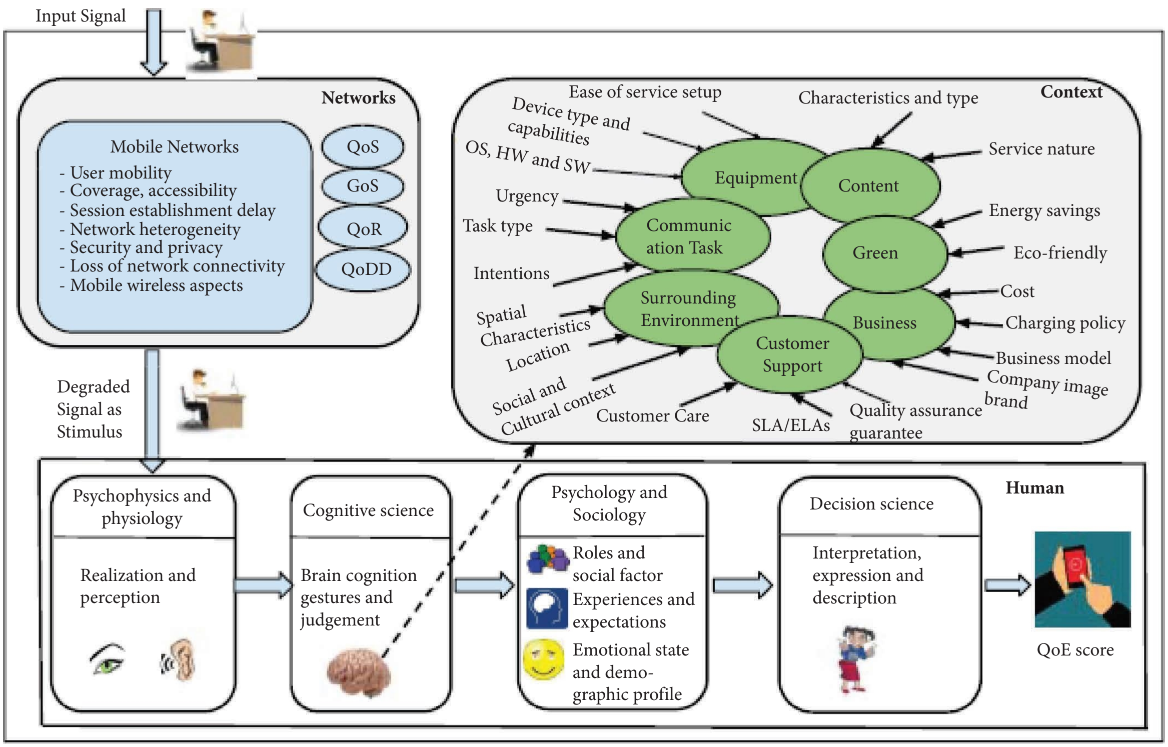

Figure 7: QoE influencing factor [6].

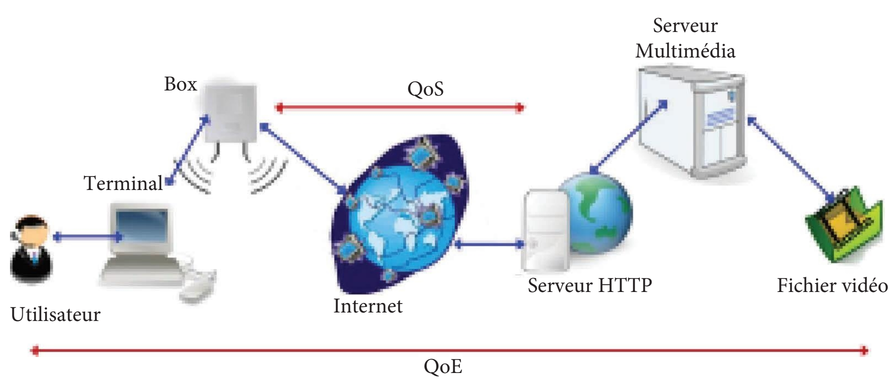

Figure 8: QoS/QoE relationship [7].

vector mapping user satisfaction with the service used. Finally, the author explains how to use the measured QoS information (i.e., jitter, delay, error rate, loss rate, signal success rate, and bandwidth) to extract the objective QoE using their model in equation (1).

Then, it describes a model to measure QoE based on five factors which are retention, usability, completeness, availability, and immediacy. To measure QoE, the following formula is proposed:

$$\frac{1}{2}\sin(\lambda)\,(ab + bc + cd + de + ca), \tag{2}$$

with (i) λ a constant equal to an angle of 72 degrees. (ii) Conceivability: service interruption rate rated b. (iii) Usability: usability of a service noted d. (iv) Completeness: packet loss, jitter, and delay noted a. (v) Availability: the success rate for accessing a service rated c. (vi) Immediacy: the response time to access a service rated e.

In another approach, the author tends to better evaluate QoE using the correlation between QoE and QoS. It proposes an adaptive learning model divided into three submodels:

(i) User model: encompasses user characteristics, namely, location, device preferences, and learning objective

(ii) Domain model: the concept of data mapping, semantic networks, or conceptual graphs

(iii) Adaptation model: this component links the two models mentioned above using adaptive rules

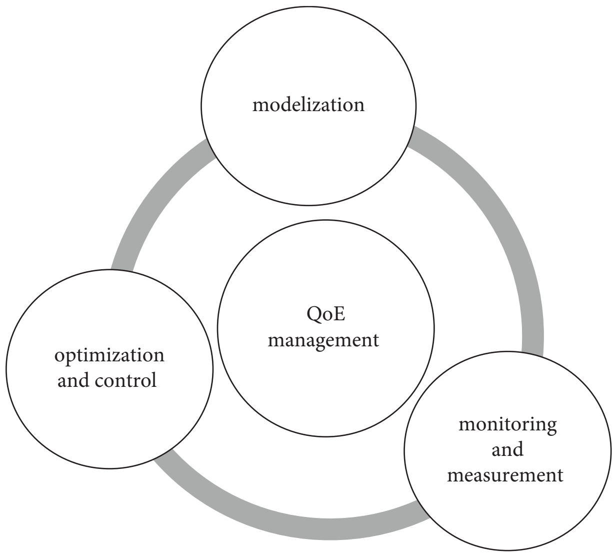

Figure 9: Different aspects of QoE management.

QoE is expressed as follows:

$$\text{QoE} = f(\text{QoL}(\text{QoS}), \text{QoF}(\text{QoS})). \tag{3}$$

with (i) QoL the Quality of Learning (i.e., learning strategy, feedback). (ii) QoF the quality of the flow (i.e., the interaction, the technology used, and the emotions).

However, current research focuses on neural network models. A description of this model is given in [15]. A random neuron is characterized by its internal state called potential. The potential is noted as $\text{kj}(t)$ for neuron j at time t. The value of $\text{kj}(t)$ is as follows:

(i) Increases by one unit, if the neuron receives an excitatory signal
(ii) Decreases by one unit, if the neuron receives an inhibitory signal
(iii) Decreases by one unit, if the neuron emits a signal

The behavior of the output neuron depends on its potential:

(i) If $\text{kj}(t) > 0$, the neuron is then excited. It therefore emits signals with a frequency rj
(ii) Otherwise, it emits no signal (neuron not excited)

Calculations in an RNN are carried out in terms of the probability of neuron excitation.

We note $\text{qj}(t)$ the probability that neuron j is excited at time t.

$$\text{qj}(t) = P[\text{kj}(t) > 0]. \tag{4}$$

The neuron transforms the input frequencies into a quantity kj. The stationary probability distributions associated with this model are as follows:

$$\text{qj} = \lim_{t \longrightarrow \infty} \text{qj}(t). \tag{5}$$

A representation of the RNN neuron is shown in Figure 10.

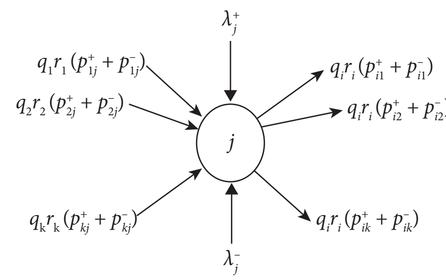

Figure 10: Neural network model [7].

(2) QoE Assessment. Evaluation (IUT-T recommendation P.10/G.100) is a process of measuring or estimating the QoE for a set of users of an application or service with a dedicated procedure and taking into account the influencing factors (possibly controlled, measured, or simply collected and reported). Based on the literature, several evaluation methods exist as shown in Figure 11.

Subjective assessment methods are defined in [16] as measurements taken from customers. Users rate their experience by answering questionnaires, surveys, or providing feedback [17]. The parameters evaluated include overall satisfaction, perceived audio/video quality, and ease of use. The most frequently used measure is the mean opinion score (MOS), recommended by the International Telecommunication Union (ITU). This model is based on an evaluation of various voice samples, taken from different means of transmission [12]. Table 1 presents the different levels which reflect users' judgment regarding the quality of a service.

This method has the advantage of providing direct information on user satisfaction that corresponds well to the actual user experience. However, it is limited by the cost of time and resources and the variability of tests from one user to another.

Objective metrics use technical data [17, 18] to evaluate performance, such as latency, MOS, and bandwidth. It refers to the techniques and/or internal to the network [16]. This method provides precise quantitative measurements and can be automated for continuous monitoring but does not capture the subjective user experience. Technical results do not always reflect satisfaction. In the literature, several simple models exist to evaluate QoE.

Recently, data analysis is recognized as a measurement approach [18–27] to overcome the challenges of traditional methods. This approach is made plausible through the use of machine learning and metadata produced by networks [13]. In [15], Lamine proposed a new QoE calculation model based on neural network methods in QoE-aware variable bitrate (ABR) video streaming. It aims to estimate the QoE of users using data collected during subjective tests. To do this, they use a set of factors as input and calculate predicted MOS scores using either statistical regression methods or machine learning methods. For the authors of [19], their proposed Quality of Experience (QoE) evaluation method is based on the use of a deep learning approach called "Deep Learning" (DL) for adaptive video streaming (VAS). In [20], the authors proposed a QoE evaluation approach based on data

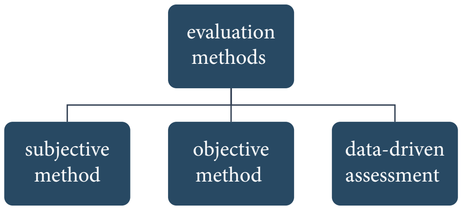

Figure 11: Overview of QoE assessment methods.

Table 1: MOS table [12].

Quality	Score MOS
Excellent	5
Good	4
Fair	3
Poor	2
Bad	1

analysis and ML. Their approach presented in Figure 12 has 5 phases: (1) data collection, (2) data processing, (3) parameter selection, (4) modeling and prediction, and (5) model validation.

(3) QoE Control and Optimization. Optimization is defined in [21] as a complex process that aims to improve the end-user experience in communication networks. In future heterogeneous multimedia communication networks, QoE-based optimization plays a vital role, especially in maximizing the efficiency of communication networks by dynamically adjusting parameters and configurations to meet the changing needs of users and applications. This helps maintain high QoE even under varying network conditions. From a mobile network operator (MNO) perspective, the goal is to retain satisfied end users in a way that reduces churn, while efficiently allocating available radio and network resources [11]. Based on the research work [6, 10, 13], QoE optimization and control is a difficult task due to many issues, including the heterogeneity of multimedia-enabled user devices. As discussed in [22], the main challenges in QoE optimization and control can be summarized in the answers to the following four questions: (1) Which key quality parameters to optimize and control? (2) Where to control (e.g., client side, server side, and network side)? (3) When to perform QoE optimization and control (e.g., during service, i.e., online or offline control)? (4) How often to monitor and optimize QoE? Different studies have been carried out in the literature to answer the questions above and are treated in [21]. Furthermore, they have illustrated the difficulty of control and optimization by proposing the multimedia broadcast chain presented in Figure 13.

Thus, several key aspects of optimization in QoE management are considered. For example, auto-configuration: Communication networks can automatically configure their parameters optimally based on network conditions and application requirements. For example, resource allocation [23], data routing, and scheduling [28] of transmissions can be dynamically adapted to maximize network efficiency.

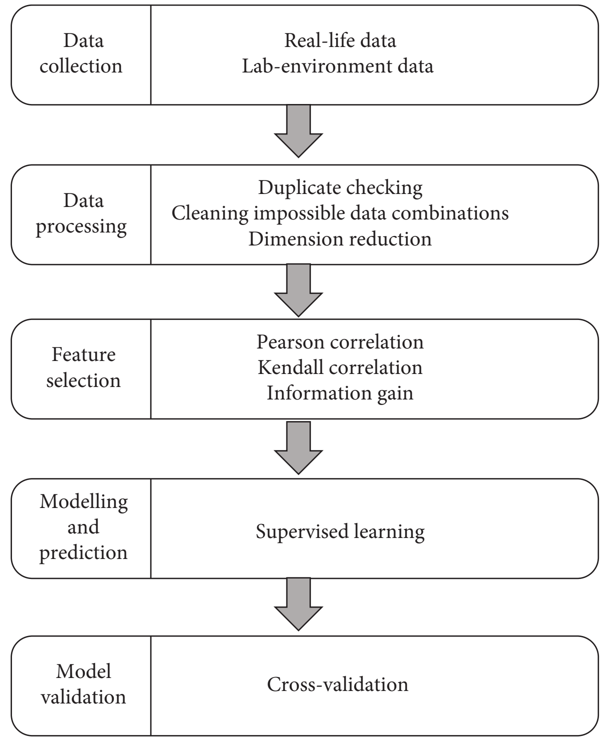

Figure 12: Data-driven QoE assessment method.

Self-organization [29, 30]: Networks can organize themselves automatically to optimize their performance. This may include self-load balancing mechanisms to efficiently distribute traffic, cell reconfiguration mechanisms in mobile networks [24], or beamforming mechanisms in wireless networks [25] to improve coverage and signal quality. Self-diagnosis [21–35]: Networks can automatically detect and diagnose performance problems or outages [26]. This enables early problem detection and rapid repair, minimizing service interruptions, and QoE disruptions. Real-time self-optimization [27]: Networks can dynamically adjust their parameters in real-time to respond to variations in traffic and network conditions. This may include mechanisms for bandwidth adaptation, video quality management, and congestion management.

The authors in [6] explained that QoE management in multimedia networks involves continuous optimization and dynamic control of relevant mechanisms, from content generation to content consumption, throughout the service delivery chain. They also identify challenges related to QoE optimization and control, including the heterogeneity of multimedia-enabled user devices.

In [31], the authors presented a QoE visualization and prediction model, which is one of the components of QoE-centric operation. They also demonstrated how the concept of cocreated quality allows all actors in a network to contribute to improving QoE by providing service providers or users with visualized information that is the output of this model. Thus, to improve QoE, the authors developed an operating cycle that includes quantification and

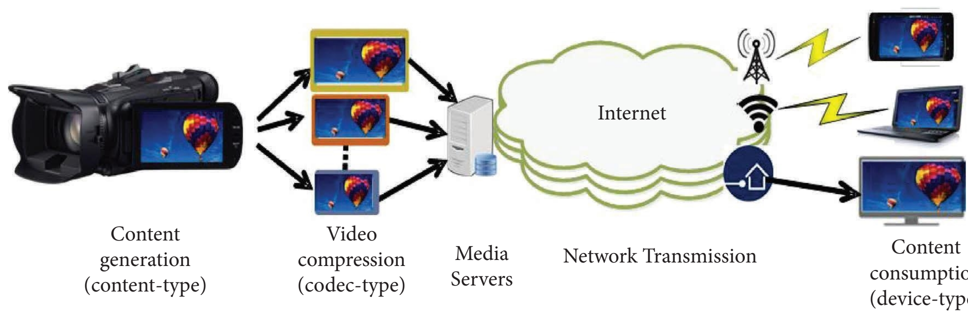

Figure 13: Media streaming channel [21].

optimization of QoE based on information relating to QoE (information about the network, the terminal, or the user which affects the QoE) obtained from in-service monitoring. Similarly, their proposed visualization model is based on the use of a map and allows network operators to visually detect degraded areas based on QoE and identify preferential areas to focus on to optimize QoE when resources are limited.

As for the authors of the benchmark [32], they designed a QoE-oriented network selection mechanism to dynamically select the best network for each application based on current network conditions and the desired user experience.

A QoE-oriented network selection mechanism to dynamically select the best network for each application based on current network conditions and desired user experience is presented in [32]. To do this, they first proposed a QoE prediction model based on data from heterogeneous wireless networks. Then, using simulations with MATLAB, they validated the effectiveness of the proposed mechanism. Their methodology is based on the collection of performance data from heterogeneous wireless networks, the modeling of the relationship between network performance measurements and the QoE perceived by users using a QoE prediction model, the design of a QoE-oriented network selection mechanism that uses the QoE prediction model to dynamically select the best network for each application based on current network conditions and user experience, and finally simulation to validate the effectiveness of the proposed mechanism. The authors in [29] proposed a multidimensional QoE prioritization model for IoT applications, as well as an assignment algorithm that uses this model to place IoT applications on available fog computing nodes efficiently. Table 2 presents a summary of Quality of Experience (QoE) management references in various application domains, highlighting the challenges and research opportunities associated with each domain. We thus highlight the diversity of QoE application areas and the specific challenges they face. We also show that many research opportunities exist, particularly in the use of machine learning (ML) and other emerging technologies such as SDN and NVF, to improve QoE management. Challenges related to data collection, modeling, QoE prediction, and automatic optimization remain key areas of research. The diversity of factors influencing QoE requires a multidisciplinary approach to optimize the user experience in these different contexts.

3. Application of QoE as a Key Optimization Metric in HetNets

In a landscape where the rapid evolution of heterogeneous networks, characterized by the coexistence of technologies, and the variety of multimedia services offered, constant optimization to meet the growing expectations of users is necessary. At the heart of this optimization, Quality of Experience (QoE) emerges as an essential metric, directly linked to user satisfaction. The application of this metric becomes a crucial issue because it captures the real perception of the end user. Beyond the technical measures of Quality of Service (QoS), it reflects the experience lived by the user, integrating subjective aspects such as satisfaction, usability, and engagement.

3.1. Motivation for Using QoE as a Decision-Making Metric. The application of QoE as a key optimization metric in HetNets represents a fundamental pivot towards proactive and user-centric management. Indeed, the coexistence of heterogeneous technologies, the diversity of services, and the specific requirements of each application introduce significant complexity to the management and optimization of multimedia HetNets. In addition, traditional optimization faces several limitations such as the lack of contextualization of the user experience, the disconnection with the diversity of multimedia services, the negligence of dynamic changes, the variation of mobility in the network environment, or even the absence of real-time evaluation of user satisfaction when applied to heterogeneous multimedia networks (HetNets). These limitations highlight the need for a transition to a more user experience-centric approach for comprehensive optimization. This approach offers a promising avenue to address the dynamic challenges of heterogeneous multimedia networks such as coordination between different technologies, managing user mobility, and minimizing interference, ensuring an optimal user experience in an ever-changing technological landscape.

3.2. Different Aspects of QoE in HetNets. Heterogeneous networks (HetNets) are complex environments composed of different communication technologies, such as macrocells, microcells, and pico cells, as well as various frequencies and access technologies such as 4G and 5G. The optimization of

Table 2: Summary of challenges and research opportunities associated with the use of QoE in network management.

References	Domain	Application considered	Challenges	Research opportunity
[30]	QoE management	Multimedia services	Subjective measurement of QoE, management (QoS) and real-time QoE, diversity of users and devices, and environmental factors	SDN, NVF, ML, mega data
[20]	QoE assessment	Multimedia services	Data collection and processing and the complexity of ML techniques	Data-driven approaches
[34]	QoE estimation	Streaming video, voice-over IP, and online gaming	Commonly used parameters are MOS and OS (opinion score), but the challenge is the need for accurate reference data and model parameters	N/A
	Modeling, measurement, and prediction	Multimedia services	Various factors (QoS) (UX), environmental factors, and user characteristics	The use of ML, hybrid models, and new approaches to measuring QoE
[10]	QoE management	N/A	Bandwidth management, quality of service (QoS) management, and network resource management	
[9]	QoE management	Streaming video services	Lack of large-scale datasets and benchmarks	Using ML for QoE management
[33]	QoE management	Network services, streaming	Bandwidth management, quality of service (QoS) management, and network resource management	Modeling technique and prediction
[35]	QoE measurement	Multimedia communication	Measure and optimize QoE in wireless communications	QoE management in wireless networks
[36]	QOE measurement	Multimedia	Data collection, modeling, and prediction, design of a complete, efficient, reliable, and accurate open big data analysis and processing prototype system	N/A
[37]	QoE monitoring	ISP	Optimization of user QoE Encryption and privacy aspects	N/A
[19]	Load balancing	N/A	The growth of big data implementation of millimeter wave (mm-wave) security and privacy	SDN/network functions virtualization (NVF) deep learning transfer learning (tl)
[11]	QoE prediction	N/A	Domination of ML over DL Adaptive deep learning for enhanced video delivery Computational cost and interoperability Self-healing networks and failure recovery	N/A
[21]	QoE management	Multimedia	(1) Which key quality parameters to optimize and control? (2) Where to control (e.g., client side, server side, and network side)? (3) When to perform QoE optimization and control (e.g., during service, i.e., online or offline control)? (4) How often to monitor and optimize QoE?	N/A

these networks to guarantee an optimal user experience requires a holistic approach that integrates Quality of Experience (QoE) as a central decision criterion. Two essential aspects of this integration are the management of capacities and resources, as well as the dynamic adjustment of parameters in a heterogeneous network.

3.2.1. Dynamic Parameter Adjustment in a QoE-Based Heterogeneous Network. Dynamic parameter adjustment in a heterogeneous network involves the ability of the network to adapt in real-time to variations in demand and network conditions. For example, in situations with high user density, the network can dynamically adjust transmission power, frequency scheduling, and other parameters to avoid congestion and ensure optimal performance. Incorporating QoE as a decision criterion means that these adjustments are not only based on technical metrics but also on how these adjustments will affect the end-user experience. In the literature, several articles address different aspects of this approach, notably the dynamic management of [25] transmission resources, interference management, mobility management, and even technology selection.

(1) Dynamic Management of Transmission Resources. The dynamic management of transmission resources, based on Quality of Experience (QoE), constitutes an innovative strategy in heterogeneous networks (Het Nets) to optimize transmission efficiency while preserving user satisfaction. The main objective of this approach is to ensure optimal user experience by dynamically adjusting transmission resources based on variations in network demand and environmental conditions. When QoE degrades due to increased interference, network congestion, or other performance-robbing factors, dynamic resource management is enabled. Sophisticated bandwidth allocation, power control, and frequency management algorithms come into play to restore an optimal balance. For example, for adjusting the transmission power.

$$\mathrm{Pajuste} = \mathrm{Pinitial} \times \frac{\mathrm{QoEcible}}{\mathrm{QoEmesurée}}, \tag{6}$$

with (i) Pajuste, the adjusted transmission power, (ii) Pinitial the initial transmission power, and (iii) QoE Target, the QoE target value.

(2) Dynamic Management of Interference. Dynamic interference management in heterogeneous networks (HetNets) refers to an innovative strategy aimed at optimizing and minimizing interference between different technologies and frequencies within these complex networks. By relying on QoE as a decision-making metric, we can mitigate the negative effects on the user experience. When interference levels exceed pre-established thresholds, thereby degrading QoE, interference management mechanisms are activated to maintain optimal network performance. An equation integrating QoE with interference-related parameters such as interference level (I), network capacity (C), and *QoS*-specific factors could be formulated as follows:

$$\mathrm{QoE} = \mathrm{wI}\,.\,\mathrm{fl}(I) + \mathrm{wC}\,.\,\mathrm{fC}(C) + \mathrm{wQoS}\,.\,\mathrm{fQoS}(\mathrm{QoS}). \tag{7}$$

Activation of dynamic interference management would be triggered when QoE falls below a critical threshold, indicating significant degradation. Interference management algorithms could then dynamically adjust transmission power, cell scheduling, and other parameters to minimize the impact of interference on QoE.

(3) Mobility Management. Mobility management is an essential aspect in heterogeneous networks focused on quality of user experience (QoE). For example, when users move across different network types, such as cellular and WiFi networks [38], major challenges arise regarding continuity of connectivity and ensuring optimal QoE. Table 3 presents a description of the challenges related to mobility management in these complex environments:

(4) Dynamic Technology Selection. Dynamic technology selection in heterogeneous networks (HetNets) relies on Quality of Experience (QoE) as the main criterion for making informed decisions on the preferred access technology. The fundamental objective is to optimize QoE by adapting access technology according to the specific needs of each user and network conditions. A mathematical formulation could integrate QoE with parameters such as transmission speed (V), bit error rate (BER), and latency (L) associated with each technology.

$$\mathrm{QoE} = \mathrm{wV} * f(V) + \mathrm{wBER} * f(\mathrm{BER}) + \mathrm{wL} * f(L), \tag{8}$$

with w being the weight associated with each technology and

$$f(v) = \frac{1}{1 + e^{-\mathrm{aV}(V - \mathrm{bV})}}. \tag{9}$$

This sigmoid function models the relationship between transmission speed and perceived QoE. The aV and bV parameters adjust the slope and position of the sigmoid curve based on the speed sensitivity of the QoE. Dynamic technology selection would then be triggered when the current QoE is below a critical threshold, indicating potential user dissatisfaction. Technology selection algorithms could automatically adjust the connection between different access technologies such as 4G and 5G based on network conditions and QoE requirements. Challenges include defining relevant thresholds for the transition between technologies, coordination between cells of different technologies, and implementing intelligent algorithms capable of making rapid and accurate decisions. Using QoE as a guide, dynamic technology selection seeks to deliver optimal connectivity for each user, maximizing user satisfaction, and ensuring a superior user experience in heterogeneous environments.

3.2.2. Capacity and Resource Management in a HetNet Based on QoE. Managing capacities and resources in a HetNet network based on QoE (Quality of Experience) involves taking into account several aspects to ensure optimal user satisfaction.

Table 3: Description of the major challenges linked to mobility.

Major challenges	Description
Handover Transparent	Ensure smooth and seamless transitions when moving from one network to another to avoid service interruptions and QoE disruptions
Handover decisions	Make handover decisions based on factors such as signal quality, network load, and user preferences while minimizing QoE impacts
Internetwork handover	Effectively manage handovers between different technologies and network types, such as switching from WiFi to cellular networks, while maintaining optimal QoE
Latency management	Reduce latency during handover transitions to avoid any user-perceivable delay
Energy optimization	Perform handovers in a way that minimizes the power consumption of mobile devices while maintaining satisfactory QoE

(1) Dynamic Resource Allocation. Heterogeneous communication networks offer a variety of technologies to meet the diverse needs of applications and users. Efficient allocation of resources in these networks is essential to ensure an optimal user experience. Recently, several studies have addressed this question. For example, the authors [39] proposed a novel QoE-aware SDN-based MPTCP approach for 5G networks, which dynamically controls the number of side flows and efficiently utilizes available network resources by transmitting network traffic through multiple disjoint paths. In [40], a novel QoE-based resource allocation mechanism is proposed to dynamically assign tasks to virtual network nodes to achieve optimized end-to-end quality. In [41], the authors addressed the problem of QoE-based multilayer optimization for uplink video transmission focusing on throughput maximization. A multilayer optimization framework based on QoE was proposed in [42] to efficiently allocate network resources for a video streaming service.

(2) Routing Optimization. Routing optimization in heterogeneous networks based on the quality of user experience (QoE) represents the set of strategies, algorithms, and mechanisms designed to efficiently direct the flow of data across various types of networks. The goal is to maximize end-user satisfaction and positive perception in terms of performance, latency, throughput, and other experience aspects. This optimization takes into account performance differences between heterogeneous networks, user preferences, specific application requirements, and other relevant factors to ensure smooth connectivity, low latency, and superior user experience while taking into account the challenges associated with internetwork coordination, security, and variability of network conditions. Routing optimization plays a crucial role in heterogeneous networks focused on the quality of user experience (QoE). By efficiently directing traffic across different network types, routing can significantly influence user-perceived performance.

(3) Smart Scheduling. Intelligent scheduling in heterogeneous networks based on quality of user experience (QoE) refers to the implementation of sophisticated strategies and algorithms aimed at optimizing the distribution of network resources, such as bandwidth, transmission times, and processing capabilities, to ensure a superior user experience. The objective is to take into account the diverse characteristics of users, applications, and network conditions, to maximize overall user satisfaction while respecting specific constraints and needs. This involves balancing priorities, effectively managing resource conflicts, and dynamically adapting scheduling to maintain optimal performance and high QoE in complex heterogeneous environments.

(4) Load Balancing. Load balancing in heterogeneous networks refers to the set of techniques and strategies implemented to optimally distribute traffic flows, resources, and workloads between the different components of the network, such as nodes, servers, access points, and communication links. The goal of load balancing is to ensure fair and efficient use of available resources while optimizing network performance and ensuring high-quality user experience (QoE). This approach aims to minimize congestion, reduce latency, increase overall capacity, and avoid overloading network elements, helping to provide a smooth and optimal user experience, regardless of load variations or network conditions. Load balancing is the uniform distribution of cell loads between adjacent cells, or the transfer of traffic from congested cells to more available cells so that the use of radio resources remains highly optimized.

3.3. Methods for Integrating QoE into Optimization.

Integrating QoE into HetNets involves several key steps as illustrated in Figure 14.

(i) QoE data collection: This step aims to collect, generate, and prepare QoS information from the HetNets network and the Mos collect users. At the end of this step, the essential data for training and validating the proposed machine-learning model will be ready.

   (a) Collection of the real-time QoS data set (PKI) of the HetNet network: In this step, the QoS data set appropriate for the network should be collected. This data can be signal quality, power level, throughput, latency, packet loss rate, technology used, cell type, as well as geographic coordinates.

   (b) Collection of MOS: This step consists of conducting user surveys to collect their opinions regarding the use of the network or a particular

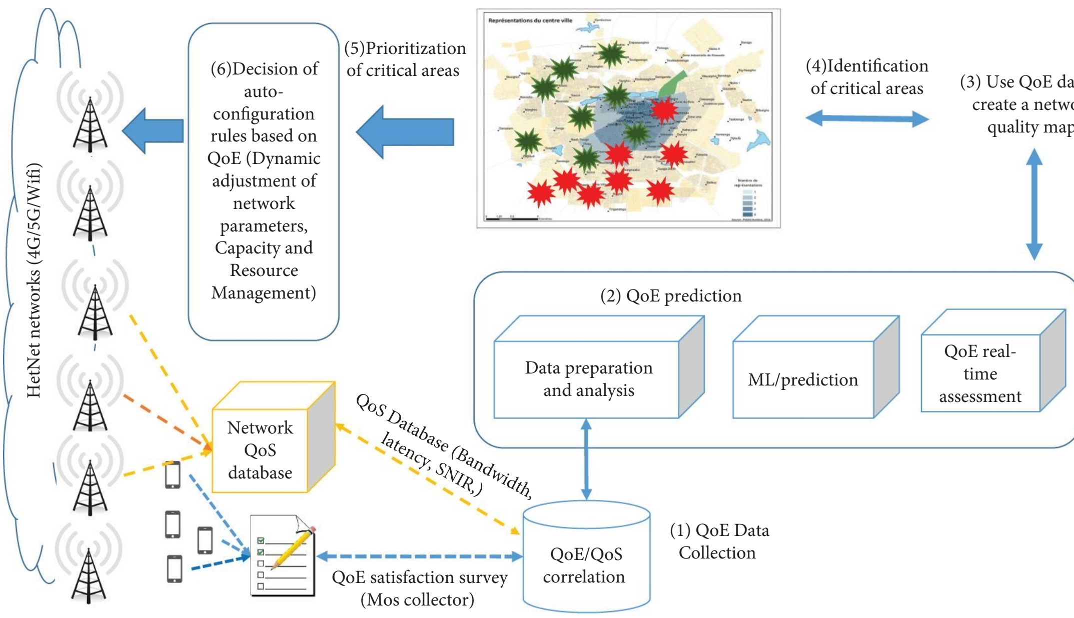

Figure 14: Implementation of an optimization method based on the QoE metric.

service. The database may contain the user's personal information, geographic coordinates, type of service and technologies, as well as the MOS score assigned by the user.

(c) The correlation with the technical parameters of the QoS: this last phase consists of the deployment of a dynamic database that can contain all the QoS and MOS data collected. The geographic location information of BSs and users in terms of latitude and longitude coordinates must exist in this database.

(ii) QoE prediction: at this stage, we prepare, analyze the data, and then train an ML model for QoE prediction.

(iii) Quality mapping on the network: we use the predicted QoE data to create a map, and then we identify the critical areas (degraded QoE).

(iv) Dynamic adjustment of network parameters in real-time based on QoE data: this last step consists of the application of dynamic algorithms for self-optimization.

4. Challenges of Using QoE as a Decision Criterion

This section presents the challenges related to the use of QoE as a decision-making criterion in the optimization of heterogeneous multimedia networks. The inherent challenges linked to the QoE metric concern in particular the complexity and heterogeneity of future multimedia networks, real-time collection in these types of networks, adaptive prediction, and the integration of automatic optimization algorithms that adapt to conditions of variability of the network, services, and users. Figure 15 provides an overview of these different challenges for the effective use of QoE as a decision-making metric in heterogeneous multimedia networks.

4.1. Complexity and Heterogeneity of Networks. As wireless communications continue to play a central role in our daily lives, HetNets has emerged as the essential answer to the challenges of modern connectivity. They are now deployed on a large scale, whether in densely populated urban environments, remote rural areas, bustling commercial establishments, or thriving businesses. The inherent complexity of HetNets is evident, characterized by the superposition of different layers of cells, from macro cells to femtocells, each offering a specific range of capacities, range, and transmission power. The heterogeneity and complexity inherent in Heterogeneous Networks (HetNets) represent a major challenge for their deployment and optimization. HetNets integrates various communication technologies, such as small cells, macro cells, and IoT devices, creating a heterogeneous ecosystem. The work in [43] highlights the impact of this heterogeneity on resource planning, interference management, and quality of service. Integrating various technologies into a HetNet, such as Massive MIMO antennas, femtocells, and IoT devices, intensifies the complexity of resource management. Models recommend adaptive approaches to optimize the efficiency and coherence of the network despite this diversity. HetNets suffer from multifrequency and multilevel interference problems. The challenges associated with managing this interference require sophisticated algorithms to balance wireless performance in an environment characterized by frequent variations. Operational complexity emerges from the need to coordinate and optimize various network components. 's

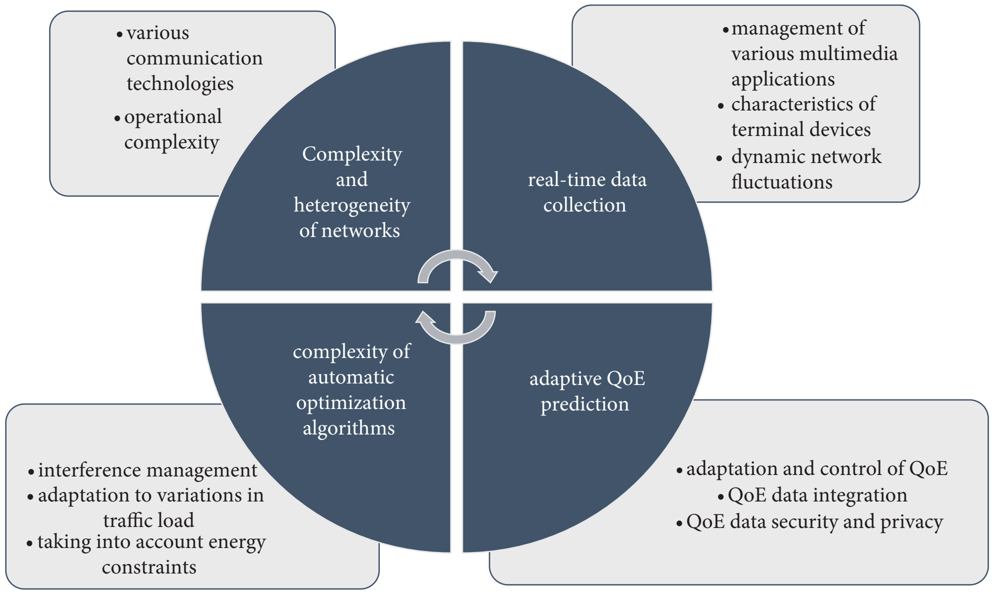

Figure 15: Challenge in HetNets.

research [44] which highlights the efforts required to integrate intelligent management algorithms that simplify operations while improving reliability and QoS.

4.2. Data Collection. Real-time data collection is a continuous and instantaneous process of acquiring, recording, and processing information as it is generated, thus allowing constant updating of databases or data systems. This approach aims to provide current and relevant data, often with minimal latency between the actual event and its recording. Thus, the convergence of heterogeneous multimedia networks raises significant questions regarding the collection of QoE data in real time. The challenges inherent in this crucial task are multiple and complex, involving managing various multimedia applications, taking into account the characteristics of end devices, and responding to dynamic network fluctuations. The first difficulty lies in the diversity of multimedia services, including streaming, virtual reality, and online gaming. Each service has specific requirements for bandwidth, latency, and video/audio quality. QoE data collection must therefore be adaptive and scalable to ensure an accurate assessment of user experience. Next, the plurality of end devices used to access media services adds a layer of complexity to QoE data collection. Factors such as screen resolution, processing power, and storage capacities vary greatly between smartphones, tablets, laptops, and other gadgets. Implementing data collection mechanisms adapted to this diversity is essential. Finally, heterogeneous multimedia networks are subject to dynamic variations in load, congestion, and Quality of Service. QoE data collection must incorporate robust mechanisms to adapt to these fluctuations, ensuring measurement reliability even under changing network conditions.

4.3. QoE Prediction. Adaptive QoE prediction in heterogeneous multimedia networks is a constantly evolving research area. The challenges related to adaptive QoE prediction in heterogeneous multimedia networks are numerous and complex. The main challenges are related to QoE data collection, QoE adaptation and control, QoE data integration in heterogeneous networks, and QoE data security and privacy. QoE adaptation and control are challenges related to the need to adapt to variations in network conditions and user requirements while ensuring an optimal user experience. Heterogeneous multimedia networks are characterized by high complexity, with many different components and technologies, making it difficult to coordinate and optimize network resources. For the authors, the integration of QoE data in heterogeneous multimedia networks requires coordination between different network components, such as network infrastructures, operating systems, and applications, which can be complex due to differences in protocols and technologies. QoE data must be integrated into multimedia heterogeneous networks to enable effective QoE optimization. Referring to the article [45], QoE security and data privacy are also important challenges in multimedia heterogeneous networks. QoE data can contain sensitive information about users and network activities, raising security and privacy concerns. QoE data must be protected against malicious attacks and privacy violations. In short, predicting the quality of user experience (QoE) in heterogeneous networks requires machine learning and machine learning algorithms to analyze historical data and predict future trends, which can be difficult due to fluctuations, constant network conditions, and user behaviors. Adaptive QoE prediction algorithms should be able to predict QoE for different types of multimedia services.

Table 4: Perspectives, recommendations, and progress in the optimization of heterogeneous multimedia networks.

Future outlook	Description	Suggestions for future research	Recommendations for network operators	Recommendations for researchers	Anticipated developments and potential advancements
Integration of artificial intelligence	Used AI to improve QoE in real-time	Develop AI methods to predict QoE and optimize networks	Invest in AI solutions for QoE optimization	Collaborate with AI experts to develop optimization solutions	AI will be widely used for real-time optimization, including self-optimization of networks based on user needs
Unified multimedia QoE metrics	Unify QoE metrics for accurate assessment	Develop unified QoE metrics for various media formats	Implement unified QoE metrics to evaluate QoE consistently	Promote standards for unified QoE metrics	Standardization of QoE metrics will facilitate interoperability between networks and assessment of QoE for various types of media content
Emerging technologies	Seize the opportunities offered by 5 G and emerging technologies	Explore QoE applications in 6 G and beyond	Invest in 5 G infrastructure and prepare for the transition to future technologies	Anticipate QoE needs for emerging technologies	Technological advancements such as 6 G will open up new opportunities for cutting-edge multimedia services
Media diversity management	Effectively manage media diversity in networks	Develop algorithms for managing media diversity	Implement media management strategies for different types of content	Investigating the implications of media diversity on QoE	Managing media diversity requires flexible methods to optimize QoE across content types
Normalization and standards	Establish standards for QoE metrics and protocols	Promote the standardization of QoE metrics and measurement protocols	Follow emerging QoE standards and protocols for interoperability	Collaborate with standards organizations to promote the adoption of standards	QoE standards will drive interoperability and widespread adoption of QoE as an optimization metric
Education and awareness	Raise awareness among users, operators, and decision-makers of the importance of QoE	Organize awareness campaigns to educate users and decision-makers	Educate users about QoE and provide transparent information	Raise awareness among stakeholders of the importance of QoE	Awareness of QoE is essential for understanding and informed decision-making
Privacy protection and security	Protect user privacy and ensure system security	Establish privacy and data security frameworks	Implement privacy and data security policies	Consider the ethical implications of collecting QoE data	Privacy protection is essential to gain user trust in QoE data collection
Interdisciplinary collaboration	Collaborate with experts from other fields for an interdisciplinary approach	Promote interdisciplinary research by collaborating with experts in psychology, economics, etc	Encourage collaboration between experts in networking and other related fields	Promote interdisciplinary collaboration for comprehensive QoE assessment	Interdisciplinary collaboration promotes a holistic approach to QoE optimization
Adaptation to local needs	Adapt optimization strategies to local user needs	Customize optimization strategies based on the specific needs of each region	Adapt services to local needs taking into account QoE requirements	Anticipate local needs to personalize services	A personalized approach ensures a better match to local QoE expectations

4.4. Complexity of Automatic Optimization Algorithms. Designing algorithms to automate optimization in heterogeneous networks poses significant challenges. Current research, in particular [46, 47], highlights the complexity of this task, particularly in the face of the diversity of technologies, equipment, and service requirements. The main challenges include managing interference, adapting to variations in traffic load, and taking into account energy constraints. The complex interaction between the various layers of the network generates interference, impacting the quality of service. Sophisticated resource allocation mechanisms [46] are required to minimize this interference and improve spectrum efficiency. Research [25] shows the importance of dynamic adaptation to ensure optimal performance taking into account changes in user demand and variability. In addition, energy efficiency [48] becomes crucial in this context of evolution towards more sustainable networks. Automatic algorithms must integrate energy optimization strategies taking into account the variability of energy sources and associated costs.

5. Future Outlook and Recommendations

This section presents future possibilities in the field of HetNets optimization using the QoE metric as a decision criterion. We summarize in Table 4, with emphasis on future perspectives, recommendations for network operators, researchers, and suggestions for future research, as well as anticipated developments and potential advances in this ever-growing field. Considering these perspectives and recommendations will help ensure a high-quality user experience in the ever-changing media networking landscape.

6. Conclusion

This article has highlighted the growing importance of the QoE (Quality of Experience) metric as a fundamental criterion in the optimization of heterogeneous multimedia networks. Using QoE provides many benefits, including improving user experience, managing resources efficiently, and adapting to network conditions. However, this paradigm is not without its technical challenges, such as accurately measuring QoE and managing the complexity of heterogeneous networks.

To address these challenges, we explored promising research prospects, such as the development of advanced algorithms, real-time measurement of QoE, and the integration of machine learning. These approaches pave the way for innovative solutions to ensure high-quality QoE in an ever-changing network environment.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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