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Fog Computing Quality of Experience:
Review and Open Challenges

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ABSTRACT

Since its inception in 2012, fog computing has played a dominant role in addressing the quality of service (QoS). However, with the emergence of the internet of things and artificial intelligence technologies, which create a "smart world" where everything is automated, offering quality of service alone is no longer sufficient as it does not offer a satisfactory user experience. Quality of experience (QoE), which satisfies user experience and improves user performance, becomes vital and fog computing remains a key technology. To understand QoE, there was a need to distinguish it from QoS based on stance, scope, perspective, focus, and methods. A systematic literature review was done looking at works that use fog computing to maintain or improve QoE with the focus being on problems being addressed in a paper and how the results contributed to improving QoE. Critical analysis of the review showed that even though strides have been made to improve QoE, open research challenges still exist that require intervention to improve or maintain acceptable QoE in fog computing to satisfy user needs.

KEYWORDS

Fog Computing, Quality of Experience (QoE), Quality of Service (QoS), User Experience

INTRODUCTION

With the dawn of the Internet of Things (IoT) technology made up of distributed sensors and intelligent terminals that generate much data that traverse the internet to the cloud where it should be saved, several challenges have also risen (Laghari et al., 2021). These challenges include but are not limited to high latency, congestion of network, loss of reliability, poor Quality of Service (QoS) and Quality of Experience (QoE), among other challenges (Michaela et al., 2018). The challenges mentioned above are caused by the geographical distance between cloud computing servers and IoT devices. Fog computing was introduced to bridge the geo-graphical distance and address some of the aforementioned challenges (Michaela et al., 2018) . Ever since fog computing inception by Cisco in 2012, much research has been done in academics and industries. Fog computing has been implemented in different platforms and application areas such as smart homes, smart grids, smart vehicles, and

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health data management (Laghari et al., 2021) . Moreover, the survey findings by Laghari et al., (2021), Babu et al., (2018) and Vambe et al., (2019) showed that fog computing provides improved QoS in different application areas where it was implemented.

However, due to the ever increase of IoT devices' use, users' need to get a guaranteed user experience. Quality of Service alone is no longer good enough to meet end-user requirements. As such, there is a need to improve fog computing to offer improved QoE since end-users are the ones who are supposed to benefit much from IoT devices. Quality of Experience is not only good for end-users, but network operators can also benefit if and only if they can have the ability to measure it (Nobre, 2018). Network operators' ability to measure QoE will contribute to the overall user's satisfaction regarding reliability, availability, scalability, speed, accuracy, and efficiency (Dr. Jens Berger, 2019)(Krasula et al., 2020). Many networks and other researchers now focus on improving QoE in fog computing to ensure that the user's needs are satisfied with minimum network resources. Thus, guaranteeing QoE to end-users. Therefore, this survey paper seeks to establish the following:

1. What are the similarities and or differences between QoS and QoE in general?
2. What are the QoE application areas, factors, measurements and management techniques?
3. How fog computing has been used to improve QoE in existing systems/applications?
4. What has been done to maintain and improve QoE in fog computing?
5. What are the open research gaps that need attention in fog computing to maintain and or improve QoE?

This paper starts by highlighting the methodology adopted in section 2. Section 3 gives a clear distinction and or similarities, if any, between QoS and QoE to understand QoE. Moreover, a synopsis of QoE application areas and factors are discussed. Followed by a brief discussion of QoE measurements and management techniques, respectively. Section 4 will give an in-depth systematic scrutiny of literature, looking specifically at works whose motive was to improve QoE in fog computing. Open research challenges are pinpointed and discussed in section 5. These open research gaps will act as future research areas in fog computing that need to be addressed to guarantee satisfactory QoE for users. In section 6, the summary of the whole paper is then given as a conclusion.

METHODOLOGY

Systematic literature review methodology (Cruz-Benito, 2016),(Tikito and Souissi, 2019) was adopted for this work to establish how fog computing was used to bring about improved QoE in existing systems by collecting and critically analyzing multiple fog computing research articles through a systematic process. Moreover, we looked at work that showed progress to further maintain or improve QoE in fog computing. Briefly, we searched Scopus with the search key term *"quality of experience (QoE)"* in combination with *"fog computing"; "edge computing"*. All the article titles and abstracts that were mostly from 2012 to 2022 (within 10-year range) and relevant were reviewed. Specifically, articles which had solutions clearly tested either in a simulated environment, experimental or real-world setup with clear development protocol with the intention to maintain or improve QoE in fog computing were considered and reviewed in full.

The reason for choosing works within the 10-year range is because, fog computing was officially implemented in 2012. Moreover, a lot would have changed in the field of technology if we looked for works that is more than 10 years, which makes it irrelevant to consider such works.

We excluded all articles that were not fully tested but being proposals and those that were older than 10 years.

QUALITY OF SERVICE AND QUALITY OF EXPERIENCE

Quality of Service (QoS) and Quality of Experience (QoE) are two terms that are constantly confused and used interchangeably in the literature (Ur et al., 2016) . In most literature, QoE is considered merely an extension of QoS, focusing on parameters that do not consider other important factors with human intentions and behavior. However, as Varela et al., (2014) highlighted, there is a clear, distinct difference between QoS and QoE even though intersections exist.

In a simplified way, QoS is regarded as a technologically centric approach, whereas QoE considers human-centric quality aspects (Ur et al., 2016). QoS can have several definitions depending on perspective. Authors Crawley et al., (1998) defined QoS as '*a set of service requirements to be met by the network while transporting a flow*', and International Telecommunication Union (2008) defined QoS as '*the totality of characteristics of a telecommunications service that bear on its ability to satisfy stated and implied needs of the user of the service.*' In Cisco 2014, as quoted by Vambe et al., (2019), QoS from a networking perspective can be achieved by "*any technology that manages data traffic to reduce packet loss, latency and jitter on the network*". Based on the definitions above, it can be concluded that QoS focuses on the system, and the users are not mainly considered.

Contrariwise, QoE considers user requirements, intentions, and perceptions regarding service in a particular context (Mahmud et al., 2019). As defined by the European Network on Quality of Experience in Multimedia Systems and Services, QoE is regarded as "*the degree of delight or annoyance of the user of an application or service. It results from the fulfilment of their expectations concerning the utility and or enjoyment of the application or service in the light of the user's personality and current state*" (Kjell et al, 2013). The International Telecommunication Union ITU-T also defined QoE as "*the overall acceptability of an application or service, as perceived subjectively by the end-user*"(Methods & Systems, 2016). Authors Vij & Bedi, (2016) and Laghari et al., (2018) summarised QoE as *"a measurement of user's satisfaction or user's performance depending on the objective or subjective measure of using any service or product"*. Researchers Nashaat et al., (2020) alleged that *"QoE considers technical parameters, like QoS, usage context variables, objective psychological measures that do not rely on the opinion of the user that is task completion time measured in seconds, and task accuracy measured in some errors"*. Moreover, subjective psychological measures based on the user's opinion, such as perceived quality of the medium and satisfaction with a service. Furthermore, QoE's definitions show that an assessment of human expectation, feelings, perceptions, cognition and satisfaction concerning a particular product, service or application are considered seriously in QoE assessment (Ur et al., 2016). In these definitions, the application refers to *"a software and or hardware that enables usage and interaction by a user for a given purpose"*, and service refers to *"an episode in which an entity takes the responsibility that something desirable happens on behalf of another entity"* (Kjell et al., 2013).

Authors Varela et al., (2014) summarized the main differences between QoS and QoE in Table 1 below based on the above definitions. As shown in Table 1 and explained by Kjell et al., (2013), QoS differs from QoE based on three factors: scope, focus, and methods. However, it should also be noted that QoE is inter-linked and depend more on QoS (Soundarabai & Chellaiah, 2018). In the networking context, network QoS impacts QoE, and QoE plays a pivotal role in understanding how the network performs (Muhammad-Sajid & Melllouk, 2017).

While there is a notion in the literature that QoE is an extension of the QoS concept based on QoS parameters (Ur et al., 2016), some mathematical models have been used to also prove how QoE is linked to QoS parameters based on consumer's perception and understanding the fundamental relationship of the two. Researchers Kim et al., (2008) used a correlation model in evaluating QoS parameters at the network layer. Whereas Reichl et al., (2010) used a logarithmic relationship to prove that QoE is a QoS reciprocal function. The work of Fiedler et al., (2010), which was based on the IQX hypothesis, found out that QoE has a general exponential dependency. It was concluded that the lesser the QoE, the greater the disturbances of loss, jitter and throughput, which are QoS parameters

Table 1. Difference and or similarities between QoS and QoE

	QoS	QoE (Callet et al.,2012)	QoE (Varela et al.,2014)
Stance	Utilitarian	Utilitarian or Hedonic	Utilitarian or Hedonic
Scope	Typically telecom services	Broader domain not necessarily network based	Broader domain not necessarily network based
Perspective	System's	User's	User's
Focus	Performance aspects of telecom systems; mechanism such as DiffServ	ICT services or application	ICT services, application or systems
Method	Technology oriented; empirical or simulated measurements	Multi-disciplinary and multi-methodological approach	Multi-disciplinary and multi-methodological approach

(Fiedler et al., 2010). Researchers Muhammad-Sajid & Melllouk, (2017) also proved that QoS is the main influencer in QoE since QoS parameters directly or indirectly impact the user's perceived QoS. Delay and packet loss rate of QoS parameters were used to determine and compute the user's QoE.

Even though QoS is critical, as explained above, it is not adequate for gauging the total QoE. Therefore, considering QoS only as a symbolic component of QoE is likely to devalue certain non-technical aspects such as market factors, psychological factors and terminal characteristics (Muhammad-Sajid & Melllouk, 2017).

QOE APPLICATION DOMAIN AND INFLUENTIAL FACTORS

There exist several different application domains, as explained by Kjell et al., (2013), where QoE is important, which include but are not limited to web and cloud (Hoßfeld et al., 2012), multimedia learning (Mayer, 2009), sensory experience (Timmerer et al., 2012), haptic communication (Steinbach et al., 2012) and recently in IoT-Fog-Cloud architectures (Laghari et al., 2021). With these application domains, it should be noted that different requirements are also required as far as QoE terms are concerned. As such, QoE should be defined based on the context of its application area, considering the application area requirements. Several factors which influence application area requirements include system, human and contextual factors (Callet et al., 2012)(Reiter et al., 2014). Figure 1 taxonomy presents a summary of the QoE influential factors.

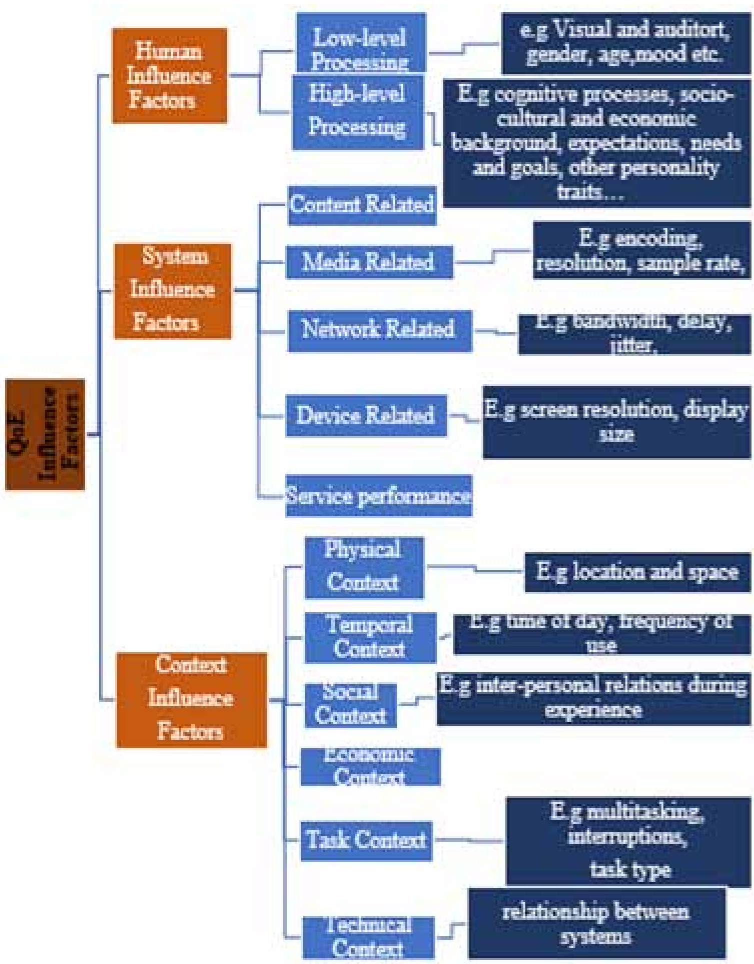
These influential factors contribute to a consumer's perceived QoE, which is subjective, be it in systems or services (Callet et al., 2012). Qualinet which is the European Network on QoE in Multimedia Systems and Services, defined QoE influential factors as: "any characteristic of a user, system, service, application, or context whose actual state or setting may have an influence on the QoE for the user" (Nashaat et al., 2020). These factors depend on the environment run context, application and user expectations.

Human and context factors sometimes determine which way and to what degree the system's settings can impact QoE. A user can have a different QoE perspective when watching the same video. Either watching it on a mobile phone whilst in a moving bus or television in the home. It should be noted that these influential factors are interlinked to one another (Aazam et al., 2019).

QoE Measurements

Several methods have been used over the years to measure QoE based on end-to-end performance. Among them, there is Mean Opinion Score (MOS), which is regarded as a subjective measurement and objective evaluation and is further categorized into two, that is "one which is based on the technical QoS data and the other is based on the physiological test such as MRI and EEG" (Krasula

Figure 1. QoE influential factors (Callet et al., 2012) (Reiter et al., 2014)



et al., 2020). In MOS, the service quality is rated by users using a scale of one to five (1-5), where one (1) represents the worst quality and five (5) represent the best quality. After realizing that MOS only denotes discredit values, an extended discrete value that adds a zero (0) was proposed, known as the opinion score and regarded as a new QoE measurement (Krasula et al., 2020). Based on this new QoE measurement opinion score scale, bad, poor, fair, good and excellent quality is now classified as [0-1],[1-2],[2-3],3-4],[4-5] respectively (Laghari, He, Zardari, et al., 2017).

Even though the usefulness of MOS is debated, according to Hoßfeld et al., (2016), it is widely used specifically for audio and speech communication. Moreover, in assessing multimedia sig-nals such as internet video, television, and web browsing (Winkler, 2009)(Egger et al., 2012). The subjective quality evaluation is regarded as a time-consuming method since it uses a lot of human resources. Contrariwise, objective evaluation is faster as they use computing methods. Even though objective evaluation is faster, human ratings regard their QoE prediction accuracy as low when compared to MOS.

QoE Management

In order to have and keep high QoE where users are adequately gratified, QoE fairness has to be managed carefully in a network (Muhammad-Sajid & Melllouk, 2017). From the QoE perspective, the internet itself affects pure QoE-centric management because the internet protocols and architecture were not originally designed for today's complex and highly demanding multimedia services (Accedian, 2021). Therefore, it is important to provide QoE management by allocating sufficient resources to maintain a specific user satisfaction level to minimize storage and network resources (Krämer et al., 2013). Moreover, there is a need to have better tools with new insights to manage network communication to improve QoE. It is possible to have effective QoE management with the use of analytics and automation (Nobre, 2018)

Role of Fog Computing in QoS and QoE

As articulated in NIST special publication, traditional cloud computing can no longer be able to offer QoS and QoE to the ever-increasing IoT devices. Cloud computing is challenged with high latency, heterogeneity and large scale owing to their geographical location (Michaela et al.,2018). Overall user's satisfaction regarding reliability, availability, scalability, speed, accuracy, and efficiency is now more important than ever for both users and network providers especially with the coming in of IoT (Dr. Jens Berger, 2019)(Krasula et al., 2020). As such, fog computing has been proved to be a better solution to offer better QoS (Vambe et al, 2019) and QoE due to its aware application management policies (Skarlat et al., 2021). Moreover, fog computing essential characteristics as discussed by Michaela et al., (2018), plays a pivotal role in offering improved QoS and QoE in different applications and systems as proved in literature review below.

RELATED WORK

Several interesting architectures such as mobile edge computing (MEC), information-centric networking (ICN) and fog computing have been used for managing and controlling QoE in different systems and or application areas (Barakabitze et al., 2019). As highlighted by Ullah et al., (2018), fog computing has a competitive advantage compared to MEC and ICN technologies. One such advantage of fog computing is that it brings about acceptable QoE in systems/applications. As articulated by Michaela et al., (2018) in NIST special publication, this is attributed to the adoption of fog computing in many application areas.

As a result of the advantages brought by fog computing characteristics as defined by Michaela et al., (2018), many researchers have implemented fog computing in existing systems to bring about acceptable QoE in existing systems. The surveys by Opeyemi et al., (2017) and Barakabitze et al., (2019) proved that fog computing had been used to improve QoE in existing systems. This is evidenced by how several researchers have applied fog comping.

For example, researchers Choy et al., (2014) introduced a hybrid edge-cloud architecture (fog computing) to reduce on-demand gaming latency. Also, Zhu et al., (2015) introduced fog computing to process, transmit video applications to enhance QoE in the real-time video surveillance cameras and promote their interactive nature. This helped reduce delay, which is detrimental to the QoE of time-sensitive traffic, especially real-time videos.

The works of Opeyemi et al., (2017) supported that fog computing has a greater potential to enhance improved QoE in existing systems that support real-time applications. Based on their findings, the authors concluded that QoE can be enhanced by fog computing within a predefined timeframe. Fog computing was also used by Iotti et al., (2017) to improve QoE in future wireless access. Based on the experimental results, the authors concluded that the fog-based approach helps optimize bandwidth usage, reduce latency, enhance QoE, and manage download data significantly.

Researchers Rosário et al., (2018) introduced SDN-based multi-tier fog computing architecture in cloud computing based existing systems. The approach helped run video services with improved QoE as the traffic on the core network was now being sent to fog nodes instead of cloud servers. The authors observed that fog computing introduction helped ensure low delay, less network overhead, and improved QoE support, which improved users' experience.

The works of Soundarabai & Chellaiah, (2018) introduced Fog Radio Access Network (FRAN) framework in the radio access network to enhance better QoE. The model used four transmission modes, namely global (centralized) mode, local distributed coordination mode, device-to-device relay mode and Macro Remote Radio Heads (MRRH) modes. Their works concluded that FRAN can enhance better QoE.

In 2019, Kharel & Shin, (2019) introduced fog computing to address unstable connections, internet connection speed, bandwidth issues that affect QoS and QoE for multimedia streaming in vehicular networks. Their simulation results based on performance evaluation proved that introducing fog computing can enhance QoS and bring better QoE to users.

As evidenced by the above literature, indeed, fog computing can enhance improved QoE. However, with the ever increase of IoT devices, the onus now is to find different approaches that can be implemented in fog computing itself. This is of paramount importance if the user experience is to be guaranteed. Guaranteeing user experience is only possible by maintaining or improving QoE in fog computing that is being compromised by the ever increase of real-time applications brought up by IoT devices. It is important to note that QoE can be automatically improved if influential factors highlighted in Figure 1 above are improved.

Though it is still in its embryonic stage, several approaches and research have been done to come up with ways to maintain or improve QoE in fog computing.

Improving QoE in Fog Computing

A lightweight system named CloudFog was introduced by Lin & Shen, (2015) in a Massively Multiplayer Online Game (MMOG) to improve QoE. This approach introduced fog nodes that reduced latency and significantly reduced traffic and bandwidth consumption when sending game videos and streaming to the cloud. Furthermore, the researchers introduced the receiver-driven encoding rate adaptation strategy in fog nodes that helped to further enhance QoE as it increased the playback continuity, which promoted segments of the game to reach players within their response time. This was verified from the experimental results obtained from the PeerSim Simulator and PlanetLab real-world testbed. It was concluded that the CloudFog effectively reduced response latency, thereby offering acceptable QoE to users. Their future work highlighted the need to study rendering and transmitting game videos to further reduce response latency and address security matters.

MEdia FOg Resource Estimation (MeFoRE) policy was introduced by Aazam et al., (2016), which was a QoE resource estimation in fog computing, basing on Relinquish Rate (RR), a service give up ratio. The approach used previous QoE, and Net Promoter Score (NPS) records to improve resource estimation and QoE. Their experimental results obtained from implemented real IoT traces and Amazon EC2 Service showed that the approach helped in minimizing resource underutilization and enhanced QoS.

Furthermore, to address the major concern of attaining QoS in multimedia services, Aazam & Harras, (2019) used the Net Promoter Score (NPS) to implement a QoE-based resource estimation to calculate the ratio of resources needed. A mathematical model that used overall QoE and specific customers' QoE to determine the ratio was implemented and tested using Java in CloudSim Simulator. Their research findings showed how a QoE based resource estimation could be useful in offering desirable service quality in multimedia services such as Tacticle Internet applications. They concluded that their system would minimize the underutilization of resources whilst offering better QoE, enhancing overall QoE. Which in turn, will lead to the fulfilment of customers' QoE expectations and maintain QoS.

A novel offload forwarding strategy that decides where the workload is to be processed, either in fog nodes or cloud, was proposed by Xiao & Krunz, (2017) to address the workload offloading problem, which affected end users' QoE. Moreover, to approach the global workload allocation that maximizes users' QoE under a given power efficiency of fog nodes, an alternating direction method of multipliers (ADMM) distributed optimization algorithm was proposed and implemented. A wireless network supported fog computing system was used as a case study whilst using response time to check the effectiveness of the proposed model. Numerical results proved that the proposed approach further improved the QoE of users and maximized users' QoE

A QoE-aware placement application policy that used fuzzy logic models in mapping applications to compatible instances by calculating applications Rating of Expectations and Capacity class store was introduced by Mahmud et al., (2019) in fog computing. Its main function was to prioritize different application placement requests considering user expectations of fog instances current status. The motive was to facilitate placements of applications to suitable fog instances in a fog computing environment to maximize QoE in respect to utility access, service delivery, and resource consumption. The system was implemented and evaluated in an iFogSim simulation environment. Results obtained from the policy indicate that it significantly improves data processing time, resource affordability, service quality, and network congestion, which maximized the QoE. The authors proposed that the system has to be tested in a real fog environment in the future to draw concrete conclusions.

A Multi-Dimensional QoE (MD-QoE) model was proposed in 2020 by Nashaat et al., (2020) to address the placement problem in the fog computing environment, which was now affecting QoE. IoT application placement request was prioritized based on environmental runtime context, application usage, and user expectation, which are influential factors that consider QoS violation as feedback. The approach was evaluated in iFog-Sim, which is a simulation environment. It was found out that the proposed algorithm significantly improved the QoE in respect of application placement time, application delay, network usage, and power consumption. The researchers highlighted that it was important to evaluate the algorithm in different IoT applications and model more influential factors for QoE to have a concrete conclusion for future work. Moreover, testing the algorithms in a real fog environment.

A FollowMe Cache approach was implemented again by Abar et al., (2020) on the Internet of Vehicle (IoV) application area to improve catching nodes decisions based on nodes' characteristics to enhance the QoE of users. The approach focused on the geo-graphic position of nodes around the zone of interest. It was evaluated in a simulation environment that used OMNeT++ Discrete-Event Simulator (*OMNeT++ Discrete Event Simulator*, 2019) and INET Framework (*INET Framework*, 2019). The FollowMe Cache approach managed to obtain maximum QoE. It reduced end to end delay to 1.02E-03ms, improved network performance, and obtained the highest throughput from 0.3 to 0.41 compared to the previously proposed Greedy algorithm approach by Han et al., (2010) and Cache on the Move approach by Chandrasekaran et al., (2015) .

In order to balance the unbalanced data processing requirement caused by the uneven distribution of vehicles in time and space, which limits the service capability of IoV, which requires low latency, Ye et al., (2020) proposed a hybrid architecture which was made up with fog computing radio access network (F-RAN) and Vehicular Fog Computing (VFC) named VF-based FRAN. Furthermore, they introduced a heuristic algorithm enhanced by deep learning to optimize the computation offloading in this VF-based FRAN, which helped in resource allocation. This approach was implemented in a simulation environment that portrays the Internet of Vehicle application area. The VF-based FRAN was compared with the other three computation offloading strategies. From the results obtained, the VF-based FRAN approach effectively improved the data processing efficiency and balanced the QoE. The researchers further noted that the QoE of this network could be improved by rebalancing the data processing burden of eRRHs. The researchers highlighted a need to check the VF-based F-RAN architecture's computation, communication, and energy resources for future works.

After the realization that QoE aware placement of application in fog computing is a challenge, Baranwal, (2020) proposed a lightweight QoE aware application placement policy in fog computing. Their approach used a Modified Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) that prioritized the applications and fog instances based on their expectation and computational capability respectively for the placement. The Modified TOPSIS inherited all the features of the classical TOPSIS, with the only difference that the modified one removed the rank reversal problem faced in classical TOPSIS. This approach was implemented and tested in a simulation environment designed using MatLab. The experimental results showed that the model reduced network congestion, gave desired resource utilization, reduced application placement time and improved QoE when compared to the one proposed by Mahmud et al., (2019), which used fuzzy logic approach as explained earlier on. The author's future work proposed developing placement policies that would incorporate exchange and price-based policies.

QoE-Aware Rendering Service Allocation (QoERSA) was proposed by Tsipis et al., (2020) to address the facility location problem's optimization problem. QoERSA used purely local network information to reallocate rendering services inside the Fog computing network towards optimal delay-sensitive placement due to the QoE gaming limits and the requirement to reduce capital expenditure. To verify the efficiency of the approach, the online game application was tested in a simulation environment. Three things, namely: a) Overall Latency Cost Ct, (b) Number of Renderers jFts j, and (c) Overall QoE Qt, as a function of t, were used to evaluate the approach. From the research findings, it was noted that it is feasible to achieve significant overall service access cost reduction for game clients, considerably cutting down on game providers' capital expenses by over-all deployment cost reduction and meet the provided QoE constraints

Nashaat et al., (2020) suggested an IoT application placement technique in a fog computing environment based on the Multi-Dimensional QoE (MD-QoE) model. There were two primary steps to the algorithm: differentiation and optimization. The initial step involved prioritizing distinct IoT application placement requests based on three key domains: a) environment runtime context, b) application use, and c) user expectations, with QoS violation as feedback. The request was then mapped and routed to the appropriate fog node instance based on its location, computational capabilities, and predicted response time. The model was evaluated in an iFogSim simulation environment. According to research findings, MD-QoE considerably increases QoE in application placement time, application latency, network utilization, and power consumption.

OPEN CHALLENGES

As evidenced from the above literature review, a lot of work was done to try and maintain or improve QoE in fog computing as to fulfil users' expectations. However, much more still needs to be done to capture positive, accurate QoE and then maintain or improve some of the QoE aspects in fog computing as highlighted in most future works of researchers. This is a difficult task due to the ever-changing technologies and growing complexities that create a quandary for service providers, companies, and users. This was also triggered by the coming in of Covid 19 pandemic where everyone adopted the use of technology leading to high demand of QoE.

Moreover, traffic generated by these technologies requires different approaches in fulfilling QoE needs as they vary and behave differently. This is another problem that service providers need to deal with to allow applications to run smoothly whilst fulfilling QoE to make their customers happy. As can be observed, traditional network and service performance management solutions are no longer sufficient in the present environment. As such, service providers and researchers should provide and propose better tools that come with new insight.

To enhance the work in this field the following aspects need to be tackled well in networking and fog computing to address QoE needs based on the reviewed literature. These claims are also supported by the work of Laghari et al., (2019) and other researchers as highlighted in their future work.

QoE Essentials and QoE Domains

Institutes such as the ITU and QUALINET have established QoE standards and processes for assessment, yet objective QoE evaluation methodologies remain a mystery. Thus, qualitative research methodologies, physiological assessment techniques and applications, sensory evaluation, behavioral assessment, statistical methodologies, and experimental validity must be investigated further to define

QoE based on domains. Moreover, to enhance services based on user demands, the QoE domain is important in some application areas, such as those articulated by Laghari et al., (2019), as shown in Table 2 below.

As seen in literature, every field has its own technical specifications, such as video bitrate, frame rate, and video codecs. For example, VoIP employs audio codecs, but fog/cloud computing employs a variety of technological characteristics for service delivery, including packet latency, packet loss, user distance from the fog or cloud, and storage and data retrieval. The CPU allocates resources in accordance with the SLA. For example, the footage is delivered in either HD or lower resolution in games, and user input responsiveness varies between fast and slow games.

Table 2 below shows QoE requirements for different areas that need future considerations.

In addition, the time it takes for content to load on a web page with picture and video quality varies in web technologies. In the several application areas highlighted in Table 2 below, as discussed by Laghari et al., (2019) in their study, these technological characteristics have policy consequences. If QoE is benchmarked, for instance, sellers might charge for high QoE. However, if the user does not obtain the QoE, they can request a refund and reimbursement for their services. As a result, if QoE is benchmarked, the rise in multimedia traffic across various application areas may lead to the formulation of new rules.

Image, Video QoE Analysis and Social Media Contents

The rapid expansion of social media networks especially during the last five years and the competition for money among service providers encourage QoS provision to end-users. Image and video sharing are prominent social media networks, but high-quality photographs and videos demand more storage and maintenance. Thus, future work should include quality, compression, and content analysis of photos, videos, and audios. Furthermore, people from various groups and geographical places do not want to view everything on social media networks, which are open platforms for users worldwide to contribute their views in the form of images, videos, text, and audio. As a result, the primary variables for QoE assessment and future research areas include QoE to content and filter for social media, QoE in communities, and social televisions.

Fog/Cloud, Network and Service Management

For service providers to deliver QoE to end-users, fog/cloud and network management are critical since it allows them to assess their services based on subjective input from users, which can occasionally contain erroneous and unfavorable replies. As a result, precise and positive QoE is necessary for appropriate management, necessitating additional labor in QoE monitoring and administration. This includes analyzing subjective and objective QoE for accuracy and service provision according to SLA for specific services or applications. As well as the network environment

Table 2. QoE requirements for different areas (Laghari et al., 2019)

Applications	QoE Parameters	Future Considerations
Multimedia Services	AQoS such as codec, frame rate	NQoS (bitrate) client devices monitoring, algorithm design for accurate analysis of QoE and network policy change
Network Services	NQoS such as packet loss and reorder	SLAs, automatic network monitoring, dynamic policy
VoIP	NQoS such as delay and AQoS such as audio codec	QoE performance parameters per service type
Web Development	NQoS such as loading time	New protocols such as Multi-media Transmission Control Protocol (MPTCP)
Games	NQoS, AQoS, PSNR and VGA	Speculation based technologies

(fixed or wireless), network conditions (available bandwidth, packet loss, terminal capabilities, CPU power, resolutions, codec, and SLA with network or service operator), subjective and objective QoE for accuracy and service provision according to SLA for specific services or applications. The development of fog/cloud and network-based frameworks for regulating and optimizing QoE in the runtime environment is critical.

Challenges Faced by Service Providers

Some of the challenges mainly to be faced by service providers to fulfil the ever-growing demand for quality by users (QoE) as pinpointed in some future works in the reviewed literature above include:

- *Lack of end-to-end visibility isn't sustainable*

Traditional management tools are usually distributed, probe-centric architectures that use SNMP and CLI protocols to monitor network components such as routers, firewalls, switches, and load balancers, as well as protocols like NetFlow, sFlow, jFlow, and IP FIX to monitor and analyze bandwidth (traffic) performance and utilization. However, these old protocols do not give a comprehensive index for determining what matters most: the QoE and how well the service performs for the end-user. SNMP, for example, uses periodically acquired data to estimate the performance of specific devices only (not end-to-end). Therefore, there is a need to manage the QoE across these discontinuous domains; end-to-end visibility and a consistent monitoring layer in fog computing are required.

- *Best-effort QoE assurance is no longer enough*

While every attempt is made, the established norm for online applications and services has been QoE assurance, but that is fast evolving in response to the quality needs of today's knowledgeable digital customers. Customers are no longer willing to accept "good" rather than "great" service. Even a lousy Netflix or YouTube experience might influence customers' perceptions of network quality and contribute to turnover. Therefore, there is a need to come up with QoE assurance in fog computing.

- *Quality management for the on-demand virtualized network is the future*

The transition from conventional to virtualized networks has a big influence on how operators maintain QoE. Because traditional networking was mostly static, determining the impact of Layer 2 and 3 faults on QoE was quite simple. On the other hand, virtualized networks are dynamic, requiring big data analytics and machine learning to drive QoE optimization in real-time. This still remains a challenge in fog computing, which calls for further research.

- *Understanding the relationship between QoS and QoE is critical*

As a carryover from conventional phone performance monitoring, operators are still more comfortable monitoring QoS than QoE. The issue is that customer happiness is mostly determined by QoE rather than QoS. Operators' business models are jeopardized if they are unable to monitor QoE. As customers become increasingly reliant on mobile connections as a way of life, QoE is quickly becoming a competitive differentiation that needs to be handled well in fog computing platforms.

The above claims were also supported by Accedian, (2021)

CONCLUSION

With the coming in of IoT devices which seeks to support the dream of “smart world, it is no longer enough to have only quality of service as it does not satisfy the user experience. As such, quality of experience has now become key to get user’s satisfaction regarding reliability, availability, scalability, speed, accuracy, and efficiency. Fog computing has played a role in offering improved QoE in existing systems/applications. Recently, a lot of researchers have started at looking at ways of maintaining and or improving QoE in fog computing.

To understand this phenomenon, this paper started by distinguishing QoE from QoS. Furthermore, an analysis of how researchers have used fog computing to improve QoE in existing systems was done. Research works that tried to maintain and or improve QoE in fog computing in various applications to increase customer happiness (as their needs will be satisfied) were articulated.

Our findings exhibited that even though preliminary work has been done to improve QoE in fog computing, there is quite a lot of work to be done as there are still several open gaps (research challenges) that need more attention to keep up with the ever-increasing and changing technologies. This also helps in catering for user traffic which increased due to people working from home due to Covid 19 pandemic. The researchers of this work noted that QoE-aware application placement in fog computing must be done carefully. Thus, determining which application is most suited for improving consumer QoE while also improving system QoS in areas like throughput, packet loss, packet loss ratio, lower latency, and fulfilling deadlines set by an authorized user. While mapping applications to Fog instances is beneficial in every aspect, the task of mapping should not take up too much time or processing resources since this might constitute a system overhead. Furthermore, service providers still need to quickly detect and isolate issues with the QoS and QoE; find out about unanticipated key performance indicators (KPI) patterns and linkages; correlate measurements to determine the core cause of performance difficulties, such as “ghosts in the network” and uncover these ‘invisible’ QoE impairments. This is important because network performance and assurance are paramount to enterprises to ensure optimal application performance and user experience, thereby satisfying users.

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CONFLICT OF INTEREST

The authors declare no conflict of interest. The funders had no role in the study’s design, in the collection, analyses, or interpretation of data, in the writing of the manuscript, or in the decision to publish the results.

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