A Survey on QoE-oriented Wireless Resources Scheduling

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Abstract—Future wireless systems are expected to provide a wide range of services to more and more users. Advanced scheduling strategies thus arise not only to perform efficient radio resource management, but also to provide fairness among the users. On the other hand, the users’ perceived quality, i.e., Quality of Experience (QoE), is becoming one of the main drivers within the schedulers design. In this context, this paper starts by providing a comprehension of what is QoE and an overview of the evolution of wireless scheduling techniques. Afterwards, a survey on the most recent QoE-based scheduling strategies for wireless systems is presented, highlighting the application/service of the different approaches reported in the literature, as well as the parameters that were taken into account for QoE optimization. Therefore, this paper aims at helping readers interested in learning the basic concepts of QoE-oriented wireless resources scheduling, as well as getting in touch with the present time research frontier.

Index Terms—Quality of Experience (QoE), Scheduling, Radio Resource Management, Wireless Networks.

I. INTRODUCTION

Wireless resources scheduling is the process of allocating physical radio resources among users and of determining the order for serving the users (also known as prioritizing). The goal is to fulfill some service requirements such as fairness (including avoiding greedy users, where one user consumes overmuch system resources) or congestion, along with other constraints like delay or packet loss rate.

Since a wireless channel has a time-varying behavior in comparison to wired networks, more complex scheduling schemes are required for the former case. However, since the scheduling process allows to save resources, wireless schedulers play an important role in efficient management of scarce radio resources.

In order to improve the service level, wireless systems have adopted in the past years schedulers that provide Quality of Service (QoS), i.e., the ability of the network to provide a service with an assured service level. Since QoS is usually measured in terms of delay, packet loss rate, jitter or throughput, it can be regarded as a network-centric characterization of the service quality.

Despite the popularity of QoS-oriented schedulers design, the final judge of the received service quality still remains the end-user, i.e. humans. In literature, some pioneering authors [1]–[4] showed that the application of a subjective-based approach may lead to significant improvements on user perceived quality, i.e., Quality of Experience (QoE), compared to network-centric approaches, such as throughput maximization. Hence, a shift from QoS- to QoE-oriented mechanisms design has been observed in recent years.

QoE is a concept that tries to cover everything that a user experiences when dealing with multimedia services and systems [5]; it is not only limited to the use of a multimedia system or service, but also takes into account the information content. Therefore, QoE can be regarded as a user-centric characterization of the service quality.

As the number of dimensions involved in the users’ subjective evaluation is immense, QoE-based techniques are becoming progressively more complex and sophisticated than the previous QoS-oriented algorithms. Schedulers that make use of QoE features consequently try to directly reflect the subjective experiences of the users, resulting that their resource allocation and prioritization techniques are more efficient in terms of satisfying the users than the schedulers that adopt conventional metrics. This efficiency can be achieved by avoiding wasting resources in situations where there is little or even no effect on the user experience. Therefore, QoE-oriented wireless resources schedulers are the ones that aim at fulfilling the mobile system users expectations: watch/listen what I want, when I want and where I want.

This survey paper provides a comprehensive overview of the key facets of QoE-oriented wireless resources scheduling. The first two sections that follow this introduction provide a contextualization regarding what is QoE and how traditional schedulers work: in Section II the factors that influence the QoE in multimedia services over communication systems are presented, along with some QoE estimation methods; Section III illustrates some scheduling algorithms, ranging from the simplest ones to QoS-aware approaches, followed by the introduction of QoS-QoE mapping strategies and utility-based optimization. Section IV provides the main contribution of this survey, namely the presentation of recent research directions regarding QoE-oriented wireless resources scheduling — state-of-the-art QoE-aware scheduling methods are discussed and classified based on the adjustments required at the end-user devices in order to implement the different scheduling strategies on wireless systems. Section V concludes the paper.

This survey serves as a reference for those who want to implement QoE-aware wireless resource schedulers and also aims to be a value contribution for those who want to perform research within this topic.

II. UNDERSTANDING QoE

According to the Qualinet white paper [5], QoE is defined as “the degree of delight or annoyance of the user of an appli-
cation or service. It results from the fulfillment of his or her expectations with respect to the utility and / or enjoyment of the application or service in the light of the user’s personality and current state”.

In the context of communication systems, QoE can then be influenced by factors such as service, content, network, device, application and context of use. For instance, the authors of [7] showed that if supplementary visual observation of the speaker’s facial and lip movements are also utilized in addition to the oral speech, humans can tolerate higher noise interference levels than if no visual factors were utilized. Hence, QoE assessment operations are performed in a broader domain when compared to QoS measurements — cf. Fig. 1.

The following subsections provide some details about the factors that influence the user experience, as well as some QoE estimation methods regarding multimedia services over communication systems.

A. Factors Influencing QoE

Any characteristic of a user, system, service, application, or context whose actual state or setting may have influence on the QoE, can be regarded as an influence factor [5]. Factors influencing QoE may be grouped in the following categories: human, system, and context factors.

1) Human factors: The characteristics of the users such as gender, age, and visual and auditory acuity are examples of human physical factors that may impact the users’ perceived quality. On the other hand, more variant factors such as motivation, attention level, or users’ mood, i.e., emotional factors, also play an important role when addressing the QoE influence factors. Moreover, even educational background, occupation, and nationality will affect the QoE. In short, human factors that influence the perceived quality are complex and strongly interrelated, and their assessment should also take into account the time-dynamic perception of the service (i.e., the memory effect), where previous experiences also have influence on the current QoE.

2) System factors: The technology employed for multimedia content transmission may introduce distortions or impairments in the content, which may affect the users’ QoE. First, and in order to transmit the multimedia content through a capacity-limited network, the original data need to be compressed. This encoding process, which incorporates many technical decisions such as the chosen bitrate (constant or variable), video frame rate or spatial resolution, may be lossless or lossy, meaning that the latter may lead to a quality degradation. In addition, the transmission network may greatly affect the multimedia quality, namely due to major factors like packet loss, delay, and jitter. Even with the adoption of a buffer at the receiver side, these network factors may cause the need for rebuffering, a state of streaming invoked when the playback buffer is emptied and that leads to a playout stall, which is usually very annoying for the users. Considering non-streaming services, the task completion (e.g., the non completion of a download) or the excessive time a service takes to upload or to download are QoE degrading situations, which are also caused by packet delay or reduction of the flow rate. Other system factors that have an influence on the perceived quality are the type of device used at the users’ side (e.g., the screen resolution, user interface capabilities, audio loudness, computation power, or battery lifetime) and some system specifications (e.g., interoperability, personalization, security, or privacy).

3) Context factors: Apart from the two aforementioned group of factors, there are external factors that influence the users’ QoE by affecting the surrounding environment. These context factors include temporal aspects, such as time of the day and day of the week (e.g., a better experience may be obtained when users are more relaxed, like during evenings or weekends), duration of the content and its popularity (e.g., users tend to be more tolerant of distortion when watching popular videos), and service type, i.e., if it is live streaming or not (where users may have different quality expectations). The economic context can be also incorporated in this category of factors influencing QoE, namely costs, subscription type, and brand of the service/system (including the availability of other networks than the one currently used).
B. QoE Estimation Methods

Measuring and ensuring good QoE of multimedia applications is very subjective in nature. Hence, one way to assess QoE is to perform subjective tests, which directly measure the perceived quality by asking human assessors to give their opinion for the quality of the multimedia content under test. The subjective test results can also be used as a ground truth for validating the performance of objective assessment, which is another quality assessment methodology.

The most commonly used subjective method for QoE measurement is the Mean Opinion Score (MOS), which is standardized in the ITU-T recommendations [8]. MOS is defined as a numeric value ranging from 1 to 5 (1-Bad, 2-Poor, 3-Fair, 4-Good, 5-Excellent) and it corresponds to the arithmetic mean of individual ratings in a panel of users. This approach has some drawbacks, namely its high cost, it is time consuming, cannot be used in real-time, and lacks repeatability. Moreover, some useful information may not be captured (e.g., if an impairment occurs at a certain moment but affects the overall QoE, this particular moment may not be determined).

Objective quality methods have been developed in order to obtain a reliable QoE prediction while avoiding the need to perform subjective tests. The approach is based on mathematical techniques that generate a quantitative measure of the multimedia content quality. Within the objective methods, two types of approaches can be identified: parameter-based methods and signal-based methods. The former are based on network/application parameters, such as QoS parameters (Section III-B gives some examples of QoS-QoE mapping strategies), while the latter are based on the analysis of the signal; in signal-based intrusive methods, the analysis compares the received data with a reference, which can be the full original data (full reference methods) or some key features of it (reduced reference methods); non-intrusive methods, also known as no-reference methods, do not require access to the original multimedia content, relying only on the received signal to assess its quality. Nevertheless, some issues arise when performing objective assessment. Although intrusive methods are generally accurate, they are impracticable for monitoring live traffic due to the need of the original multimedia content. Also, objective assessment may not reflect the users’ perception of the delivered service; for instance, although some impairments may cause minor influence on the users’ QoE, and therefore they could be disregarded, the same impairments may be detected and emphasized by the objective methods.

C. Discussion

As can be inferred from what was presented so far, QoE cannot be easily modeled and assessed due to the fact that its influence factors are very diverse and they may interrelate, as well as different users have different quality expectations. Therefore, a combination of subjective and objective methods can be performed so as to obtain an optimized and more robust QoE evaluation [9]. Regarding mobile networks, some particular issues, like phone battery, phone overheat, or data connectivity costs, make QoE assessment more challenging when compared to fixed networks — the reader is suggested to refer to [10] for more examples and details on QoE modeling and measurement concerning mobile networks.

The growing consumer demand for mobile video services has also driven the research and development of new techniques to deliver multimedia services with enhanced QoE over wireless networks. One of the most recent examples is Dynamic Adaptive Streaming over HTTP (DASH), which was developed by the Motion Picture Experts Group (MPEG) [11]: this standard brings the possibility of adapting the data rate at the end-user device according to the network conditions or according to the user preferences. Due to its excellent potential to deal with the variability of wireless networks radio channels, DASH has been adopted by other standards bodies including the Third Generation Partnership Project (3GPP) and the Open IPTV Forum (OIFF) [12], [13].

Last but not least, QoE evolves over time in the same manner as technology itself does; for instance, although today a user may require Super High Definition (SHD) video content in order to say that he is experiencing a great QoE, some decades ago the same subjective perceived quality would be true for a TV transmission with standard definition. Consequently, a QoE assessment model that reflects today’s reality may not be the most appropriate one in the future, meaning that QoE evaluation will always attract the research community’s attention.

III. BACKGROUND ON SCHEDULING ALGORITHMS

Distributing the available wireless resources among the users, i.e., multi-user scheduling, is one of the most important tasks that must be implemented in any wireless communication system. Specifically, a scheduler decides how users share the wireless channel by allocating radio resources such as power, time slots, frequency channels, or a combination of these resources. For instance, Time Division Multiple Access (TDMA) systems are characterized by having time slots as the radio resources units that can be assigned to a user; on the other hand, a scheduler allocates frequency channels in Frequency Division Multiple Access (FDMA) systems; another example are the Orthogonal Frequency-Division Multiple Access (OFDMA) systems, where radio resources are scheduled into the time/frequency domain [14] — cf. Fig. 2.

Moreover, designing schedulers for wireless systems comprises many trade-offs among complexity, efficiency and fairness:

- **Complexity:** It is important to limit the processing time of scheduling algorithms, since they usually have to perform their job under very short periods of time (e.g., 1 ms is the time that Long Term Evolution (LTE) schedulers have for allocation decisions [15]). In addition, scheduling schemes should be scalable, meaning that low-complexity algorithms should be preferred over very complex and non-linear solutions, which could be prohibitive in terms of computational cost, time, and memory usage when applied to scenarios with a large number of users.
As previously mentioned, any scheduling strategy comprises many trade-offs among complexity, efficiency and fairness. In the case of schedulers that do not take QoE into account, these trade-offs also result from the significance that the different scheduling algorithms give to the communication channel characteristics and to QoS parameters.

1) Channel-unaware Strategies: The schedulers that implement these approaches assume that the transmission channel is error-free and time-invariant, which are unrealistic assumptions when dealing with wireless channels. Nevertheless, these strategies form the basis for more complex algorithms.

First In First Out (FIFO) can be regarded as the simplest scheduling scheme, in which users are served according to the order of their resource request. Even though this approach is very simple, it is inefficient and unfair.

The Round-Robin (RR) strategy tries to add some fairness to the FIFO approach, namely by allocating an equal share of resources to each user in a round-robin manner. Thus, this scheduling algorithm is fair regarding the amount of time in which the channel is occupied by each user. However, since channels conditions are not taken into account, this type of schedulers are not fair in terms of system throughput, nor they are efficient because the different requirements of the applications (e.g., bitrate) are also not considered.

2) Channel-aware/QoS-unaware Strategies: A wireless resource scheduler can take into account the channel state information that is usually fed back to the base stations, so as to enhance the efficiency of its scheduling algorithm. Maximum Throughput (MT) is an example of a policy that, in each scheduling period, prioritizes the resources to the user experiencing the best channel conditions. In this manner, these schedulers provide the highest system throughput, so that the best possible spectral efficiency is attained. Nevertheless, MT scheduling algorithms are very unfair to users with poor channel conditions (e.g., users further away from the base station) and can even make them suffer of starvation.

The concept adopted by Proportional Fair (PF) schedulers [16] provides a trade-off between fairness and spectral efficiency. Within this approach, past average throughput acts as a weighting factor in an MT-like strategy, i.e., if two users can achieve the same throughput (based on the experienced channel conditions), then the user that has been served with lower average throughput in the past is prioritized. This means that users with poor conditions will be surely served within a certain amount of time.

3) Channel-aware/QoS-aware Strategies: In order to attain a certain performance level, different applications have different requirements, which are typically mapped into QoS parameters. Accordingly, scheduling algorithms should also take into account these QoS parameters. For instance, some scheduling strategies try to guarantee a minimum data rate for the users, whereas others deal with delay constraints. This last approach is more common among QoS-aware schedulers, since many applications, such as real-time flows, video streaming or Voice over IP (VoIP) calls, require that their packets are delivered within a certain deadline.

The Modified Largest Weighted Delay First (M-LWDF) [17] algorithm and the Exponential/PF (EXP/PF) [18] scheme are two of the most popular QoS-aware scheduling strategies, as they provide a good trade-off among spectral efficiency, fairness and QoS provisioning. Besides taking service delay requirements into account, both algorithms support different services and treat differently real-time flows.

All the above mentioned scheduling strategies, either channel-unaware or channel-aware (with or without taking into account QoS requirements), are just an illustrative sample of
Application QoS
(rebuffering events, buffer level, …)

Network QoS
(packet loss rate, delay, …)

QoE

Fig. 3. Mapping between QoS levels and QoE.

B. QoS-QoE Mapping Strategies

QoS-QoE mapping strategies have been proposed to quantify QoE, thus making a transition from QoS- to QoE-oriented optimization. QoS-QoE mapping relies on various QoS parameters, which can be divided into two levels: network QoS parameters, such as packet loss rate or delay, and application QoS parameters, like rebuffering events or buffer level. Therefore, QoS-QoE mapping strategies try to find out the relationship between QoE and the two QoS levels, where the network QoS parameters are sometimes first mapped into application QoS parameters — cf. Fig. 3 Nevertheless, both types of QoS parameters can always be regarded as objective quality metrics, since their measurement is always well defined as they do not depend on any subjective judgment.

Choosing a function that maps objective quality metrics into subjective score is not a straightforward task. If both objective and subjective scales were uniform, i.e., if equal perceived quality difference corresponded to equal numerical difference over the whole range, then a linear mapping function could be used [22]:

\[ QoE = a + b \cdot M, \]

where the parameters \(a\) and \(b\) are obtained by applying linear fit between objective quality metrics \(M\) and the respective measured subjective scores. However, the practical objective quality scores are rarely scaled uniformly, hence linear mapping may give too pessimistic view of the performance. To overcome this issue, nonlinear mapping functions have been adopted, discussed and compared [22], [23]. The most widely used nonlinear mapping functions are summarized as follows:

- **Cubic polynomial** [22], [24]–[26]:
  \[ QoE = a + b \cdot M + c \cdot M^2 + d \cdot M^3. \]

- **Logistic functions** [22], [27], [28]:
  \[ QoE = a + \frac{b}{1 + c(M + d)^e}, \]

  \[ QoE = a + \frac{b - a}{1 + \exp[-c(M + d)]}, \]

  \[ QoE = \frac{a}{1 + \exp[-b(M - c)]}, \]

  \[ QoE = a + \left[ \frac{M}{c} \right]^b e. \]

- **Exponential function** [22], [29]:
  \[ QoE = a \cdot \exp(-b \cdot M) + c \cdot \exp(-d \cdot M). \]

- **Power function** [22]:
  \[ QoE = a \cdot M^b + c. \]

- **Logarithmic function** [30]:
  \[ QoE = -a \cdot \log(M) + b. \]

In all cases, after computing the predicted QoE values, correlation analysis should be performed between these and actual scores, in order to evaluate the goodness of the mapping strategy. On the other hand, traditional QoS optimization techniques can be applied and assessed in QoE optimization scenarios by making use of QoS-QoE mapping strategies. For instance, in [31], the authors investigate and evaluate the performance of three downlink schedulers (PF, M-LWDF and EXP/PF) in terms of QoE metric for VoIP applications over LTE, making it possible to choose the most suitable one in terms of subjective experience.

C. Utility-based Optimization

The concept of utility functions emerged from microeconomics theory and formalizes the relationship between the service performance and the user perceived experience and satisfaction [32]. More specifically, the following utility function \(U : X \to \mathbb{R}\) relates the set \(X\) of all resources a user could possibly have to real numbers, such that \(U(x) < U(y)\) implies that the user prefers \(y\) over \(x\), with \(x, y \in X\).

The utility-based scheduling optimization may then be regarded as a maximization of the users’ aggregated sum of utilities through Network Utility Maximization (NUM) methods and mechanisms [33]. In mathematical terms, using NUM to allocate network resources (e.g., transmission power,
transmission rate, etc.) corresponds to perform the following maximization:

\[
\text{maximize } \sum_{i} U_i(x_i)
\]

subject to \( \sum_{i} x_i \leq X_{\text{max}} \),

(10)

where \( U_i \) corresponds to the utility function of the \( i^{th} \) user (therefore \( x_i \) stands for the resources allocated for this user) and \( X_{\text{max}} \) denotes the bounds of the available resources.

D. Discussion

Based on what was previously described, QoS-QoE mapping strategies combined with utility-based optimization can be regarded as the fundamental tools to perform the shift from QoS- to QoE-oriented scheduling algorithms design. Ideally, one should aim at obtaining mathematical formulas that relate application, transport, and physical layer parameters to subjective quality experienced by the users. With these it would become possible to know the impact of a certain resource allocation on the user QoE. For example, QoE metrics are proposed in [34] in order to capture the overall performance of radio resource management algorithms in terms of video quality perceived by the end users when considering video streaming over LTE. The authors measured average, geometric mean, and minimum QoE when scheduling algorithms like MT and PF are adopted. In [35], the QoE of adaptive video streaming is analyzed under several scheduling policies, like RR and MT, where the QoE is based on the mean video bit rate and the mean buffer surplus. The examination of the performance impact of the different scheduling schemes is then used to suggest the best strategy to be adopted in various mobility scenarios.

On the other hand, the QoE-based mathematical formulas also allow wireless systems design to be adjusted so as to enhance the quality perceived by the users. For instance, the authors of [36] provide a closed-form expression of the probability of timely delivery of video chunks for DASH video streaming over a wireless cell (such as LTE) as a function of the downlink wireless bandwidth level allocated to the user. As a consequence, and given a certain QoE requirement based on the probability of timely delivery and the received video stream quality level, the aforementioned expression allows to infer the number of users that can be accommodated in the wireless access system, as well as it can be used to design admission procedures, bandwidth pricing policies, and cell dimensioning. In [37], a general fairness metric is formulated for shared systems, which satisfies QoE-relevant properties, assuming that estimated QoE values are known. This QoE fairness metric may be adopted when comparing different resource management techniques in terms of their fairness across users and services, although it says nothing about how good the system is and thus needs to be considered together with the achieved (e.g. mean) QoE in system design.

IV. QoE-ORIENTED SCHEDULING ALGORITHMS

Numerous challenges may be identified related to the issue of performing QoE-oriented wireless resources scheduling. As seen in the previous sections, it is important to identify the QoE influence factors and their relationships to QoE metrics for a given type of service. Some more challenges arise after addressing the QoE modeling, namely identifying which parameters to collect (e.g., network performance, user requirements, context, application/service type, etc.), where, how, and when to collect them (e.g., the required parameters could be collected at the base stations or at the end-user devices, either before, during, or after service delivery). Finally, procedures have also to be defined in order to combine all these steps, i.e., it is necessary to design the methods that allow the collected data to perform QoE-aware scheduling.

In this section, state-of-art QoE-based scheduling strategies for wireless systems are reviewed, highlighting the parameters adopted for QoE optimization. To simplify the reading of the survey, the strategies that address the downlink scenario, with the goal of maximizing the aggregate experienced quality of all users within a cell of a single operator, have been classified into three categories — cf. Fig. 4: (i) passive end-user device; (ii) active end-user device/passive user; (iii) active end-user device/active user. This classification is based on the adjustments required at the end-user devices in order to implement the different scheduling strategies on wireless systems, specially over existing networks. Moreover, in each category, the solutions are grouped by application/service, such as video streaming, VoIP, and web browsing. The last part of this section provides a review of QoE-aware scheduling methods that can enhance the wireless resources management in other scenarios, namely the uplink direction, under heterogeneous, cognitive radio, relay and multi-user Multiple-Input Multiple-Output (MIMO) networks, as well as when dealing with energy-related issues.

A. Passive End-user Device Strategies

Scheduling techniques are easier to implement in a wireless network when the users, as well as their devices, do not perform any exclusive QoE tasks (e.g., monitoring, measuring and reporting relevant parameters), as the QoE assessment is based on measurements that can be carried out solely at the base station side. Since the required assessments can be performed by the scheduler on the network side, no extra information needs to be exchanged between the user’s device and the network. On the other hand, these approaches may not achieve the best possible QoE performance, since many relevant metrics, which could be collected at the end-user device (e.g., buffer status), either cannot be used or have to be estimated.

1) Video Streaming: The simplest QoE-based scheduling approaches consider only one relevant parameter within the the QoE optimization process; examples of these approaches can be found in [38–42]. The works described in [38], [39] deal with video delivery over LTE networks and make use of utility functions, which are based on the required transmission rate at the application-layer in order to achieve a certain level of QoE. In [38], the authors propose a framework that allows network operators to set their policy for providing service with a certain level of mean quality of all users, in order to save some
network resources, which could be used to serve more users in the cell or to support high-demand applications. The authors of [39] present a tuning mechanism that allows the network operator to dynamically adapt its network resource allocation between maximum perceived quality of all users (system efficiency) and the quality fairness among users. In [40], an LTE downlink radio resource allocation method is proposed to avoid playback interruptions, where the scheduling algorithm takes into account information provided at the DASH video server, namely the bitrate of the available versions, so as to optimize the wireless resources (time, frequency and spatial domain) of the LTE system. A QoE-aware real-time adaptive resource allocation algorithm is presented in [41] that also takes into account the user’s video required data rate. The goal is to provide a flexible tool within LTE systems to achieve a desired trade-off between fairness and efficiency among users. A QoE-oriented cross-layer optimization framework enabling efficient allocation of wireless resources in video delivery over LTE is described in [42], which takes into account the packet loss rate as the relevant input for the QoE-oriented scheduler (instead of the data rate, as adopted by the works mentioned previously).

Solutions that consider more than one relevant parameter have also been proposed for the QoE optimization process in video streaming services. A QoE-aware scheduling algorithm that allocates radio resources in a High-Speed Downlink Packet Access (HSDPA) network is proposed in [43], where the users’ MOS requirements are derived from metrics like average data rate and packet loss rate, while the mapping between these parameters and QoE scores was generated based on a trained random neural network. Considering the use of similar metrics (amount of lost packets and source rate of the video signal), the authors of [44] propose a MOS-driven energy efficient power allocation algorithm over OFDMA based wireless networks, which enables the design of a scheduling scheme that jointly optimizes MOS and the system power consumption. In order to improve the system QoE level while guaranteeing the fairness for users, a cross-layer resource allocation problem is modeled and formulated in [45]. This scheduling algorithm considers the transmission bitrate as well as the video quality fluctuation that affects the system QoE.

Other passive end-user device scheduling schemes follow an approach where video QoE is assessed through metrics that need to be estimated at the network side because, although they are available on the end-user device, these metrics are not reported to the base station (otherwise the end-user device would be regarded as active, which falls under the category of the works that will be presented in Section IV-B). The authors of [46] propose a QoE-aware scheduling solution for HTTP progressive video downloading in OFDMA systems, where the amount of video data stored in the player buffer is estimated at the base station and adopted as the main criterion for resource allocation. The scheduler then works by reducing the resources assigned to users with enough buffered data and by transferring these to users with a low buffer level, in order to diminish the number of playback interruptions. In [47], and in order to try to avoid rebuffering, a QoE-aware scheduling algorithm is presented for video delivery over wireless LTE networks, where the state of the users’ buffer is also estimated at the base station from the periodic Medium Access Control (MAC) layer acknowledgments received from each user. Online scheduling policies to optimize QoE for video-on-demand applications are proposed in [48], where the QoE of each flow is measured by the duration of video playback interruptions and the playback buffer status is estimated at the wireless access point. The authors studied, in particular, the heavy-traffic regime in order to address not only the long-term average performance, but also short-term QoE performance. In [49], a lower bound for the rebuffering percentage (percentage of the total streaming time spent on rebuffering) is presented for the transmission of video content over cellular networks. This analytic approach is followed by a scheduling strategy based on the same QoE parameter (estimated at the base station), which is more suitable to use only in the congestion cell state as, in this conditions, it increases the average user’s throughput and cell capacity with an insignificant decrease of the fairness.

Another QoE-based scheduling policy that can be adopted,
specially when dealing with scalable video streaming, is based on priority marking of video flows. The main goals are to avoid the need of video content processing capabilities at the base station and to minimize delay bound violations under congestion for the most important priority classes. This approach has been adopted in [50] for the scheduling of multiple medical video streams in wireless networks, whereas the authors of [51] focus on scalable video streaming over LTE systems. A similar scheduling policy is proposed in [52] for video delivery over IEEE 802.11n/ac networks, where a low-complexity QoE scheduling scheme prioritizes packets taking into account how important they are in enhancing the video quality.

2) Voice over IP: VoIP can also benefit from QoE-oriented scheduling. Considering LTE networks, the authors of [53] designed an algorithm to meet the tight delay requirements of VoIP and to solve, at the same time, the problem of radio resource scarcity, where the maximum delay of a client with a certain average transmitting rate is determined theoretically by a mathematical model also proposed by them. The work described in [54] also presents a QoE-driven LTE scheduling for VoIP application where, by taking into account the delay and the packet loss rate obtained at the scheduler itself, the resource allocation is prioritized according to the QoE requirements of the users, while enabling the maximization of the number of users per cell. In [55], a QoE model for mobile VoIP services is proposed, which is based on the amount of user effort to continue a conversation. This human effort is estimated from the user’s conversations (through the processing of the semantic information in the audio streams) and it is also used to formulate a QoE-oriented resource allocation scheme as a non-cooperative game between the provider and the VoIP user experiencing a deteriorating QoE.

3) Web Browsing & Instant Messaging: In addition to video delivery and VoIP, the user experience in some other wireless applications can also be enhanced by the use of QoE-aware scheduling methods. In [56], the authors address web browsing applications and estimate the service response time as a function of the user data rate, so as to derive a mapping function from these QoS metrics to subjective quality satisfaction, having as final goal the incorporation of this knowledge into the radio resource allocation algorithm for OFDMA systems. A scheduling algorithm to provide fair QoE to instant messaging service over cellular networks is proposed in [57], where the subservice that a user is currently focusing on is defined as the representative service and the respective QoE is based on the experienced delay; more specifically, the scheduling scheme first finds the user with the worst QoE and then performs resource allocation taking into account the respective representative service.

4) Unspecified Applications: Some authors have also proposed QoE-oriented wireless resources scheduling solutions without addressing any particular application. In order to carry out QoE-aware power allocation in multi-user Orthogonal Frequency-Division Multiplexing (OFDM) systems, a scheme that maps data rate into MOS values is described in [58]; the authors claim that, even with limited amount of power, the proposed algorithm can lead to enhanced user experiences. In [59], a QoE-driven resource allocation technique is presented for downlink multi-user multi-service OFDM systems. The QoE estimation models consider the required data rate of the different services in order to minimize the total consumed power with lower computational complexity when scheduling subcarriers and allocating transmission power. Also considering OFDM systems and by taking into account the required data rate of several multimedia applications, the authors of [60] presented a scheduling algorithm that tries to maximize the overall total QoE, while guaranteeing all the users can perceive a relatively good QoE level and an acceptable fairness in the system. In [61], a QoE-oriented resource allocation problem is formulated among BSs as a local cooperation game, where BSs are encouraged to cooperate with their adjacent cells in user scheduling. The goal is to mitigate intercell interference in the OFDMA-based cellular networks, where the performance metric jointly considers spectrum efficiency, user fairness and service satisfaction, being the latter based on a mapping between data rate and MOS. The authors of [62] also addressed the inter-cell interference coordination by proposing a QoE-aware PF resource allocation strategy for multi-cell OFDMA networks, where a new relationship between data rate and MOS, followed by a new utility function, are introduced in order to achieve QoE maximization as well as fairness among users for heterogeneous service requirements.

The works referred in the previous paragraph take into account only the data rate as a relevant parameter for QoE optimization. Nevertheless, other approaches have also been considered. In [63], a QoE-based carrier scheduling scheme is proposed for multi-service LTE-Advanced networks; by taking into account packet delay and the data rate required by each service, the component carriers are dynamically scheduled so as to improve QoE and fairness for the users. Two QoE-aware joint subcarrier and power radio resource allocation algorithms are presented in [64] for the downlink of an heterogeneous OFDMA system, where resource allocation is based on the QoE (delay, data rate and packet loss rate) of each heterogeneous service flow: the first algorithm tries to assure the same level of QoE to all users, whereas the second scheme performs a trade-off between the users’ QoE and the spectral efficiency of the system. The authors of [65] propose a radio resource allocation control scheme, which aims at minimizing the global drop out rate of users in cellular networks; the impatience caused by the network (e.g., if a download time is too long) is first modeled, in order to subsequently estimate the drop out probability. In [66], an application-aware resource block and power allocation for LTE is proposed, which tries to increase the overall QoE by giving priority to users with real-time applications over delay-tolerant ones. Another QoE management solution for LTE systems is proposed in [67], which autonomously monitors the traffic and dynamically derives QoE targets (e.g., download time for web pages, data rate for videos) for individual application sessions based on their characteristics (content and traffic pattern). These QoE targets are then converted to per session bandwidth targets and enforced by a flexible self-programming scheduler, in order to maximize the QoE without significantly degrading the overall resource allocation and throughput efficiency. In [68],
IEEE JOURNAL 9

TABLE I
PASSIVE END-USER DEVICE STRATEGIES.

| Ref. | Application       | QoE optimization based on | Technology |
|------|-------------------|----------------------------|------------|
|      |                   | Data rate | Packet loss rate | Delay | Other |         |
| [38] | Video streaming   | X         |                     |       |       | LTE     |
| [39] | Video streaming   | X         |                     |       |       | LTE     |
| [40] | Video streaming   | X         |                     |       |       | LTE     |
| [41] | Video streaming   | X         |                     |       |       | LTE     |
| [42] | Video streaming   | X         |                     |       |       | LTE     |
| [43] | Video streaming   | X         |                     |       |       | HSDPA   |
| [44] | Video streaming   | X         |                     |       |       | OFDMA   |
| [45] | Video streaming   | X         | Video quality       | —     |       | —       |
| [46] | Video streaming   | X         | Estimated buffer status | OFDMA |
| [47] | Video streaming   | X         | Estimated buffer status | LTE  |
| [48] | Video streaming   | X         | Estimated buffer status | —    |
| [49] | Video streaming   | X         | Estimated buffer status | —    |
| [50] | Video streaming   | X         | Marked priority flows | —    |
| [51] | Video streaming   | X         | Marked priority flows | LTE  |
| [52] | Video streaming   | X         | Marked priority flows | —    |
| [53] | VoIP              | X         |                     |       |       | LTE     |
| [54] | VoIP              | X         |                     |       |       | LTE     |
| [55] | VoIP              | X         |                     |       |       | LTE     |
| [56] | Web browsing      | X         |                     |       |       | OFDMA   |
| [57] | Instant messaging | X         |                     |       |       | —       |
| [58] | Unspecified       | X         |                     |       |       | OFDM    |
| [59] | Unspecified       | X         |                     |       |       | OFDM    |
| [60] | Unspecified       | X         |                     |       |       | OFDM    |
| [61] | Unspecified       | X         |                     |       |       | OFDM    |
| [62] | Unspecified       | X         |                     |       |       | OFDM    |
| [63] | Unspecified       | X         |                     |       |       | LTE     |
| [64] | Unspecified       | X         |                     |       |       | LTE     |
| [65] | Unspecified       | X         | Estimated drop out rate | —    |
| [66] | Unspecified       | X         | Real-time applications | LTE  |
| [67] | Unspecified       | X         | Application characteristics | LTE |
| [68] | Unspecified       | X         | Application characteristics | LTE |
| [69] | Unspecified       | X         | Throughput fluctuations | —    |

A two-step radio resource allocation algorithm is presented for an LTE network, which provides a trade-off between QoE and spectral efficiency: in the first step, it allocates resources according to which application the user equipment is using, so that a minimum QoE is guaranteed for each user; in the second step, the algorithm’s goal is to improve the system throughput by allocating the remaining resources to the users with the best channel conditions. The authors of [69] propose a fluctuations-aware scheduler, which takes into account the evolution of the achieved throughput over time (per user) and the impact of this evolution on the end-user QoE. More specifically, the scheduler tries to provide the best possible combinations of resources that maintain the past average throughput values per user, in order to avoid throughput fluctuations and, thus, providing better QoE.

A summary of the aforementioned passive end-user device strategies is given in Table I. This table also enables to point out that data rate is a parameter that plays a central role when performing QoE-oriented scheduling using this type of strategies for video streaming as well as for unspecified applications. On the other hand, delay is of prime importance compared to other parameters for applications such as VoIP, web browsing, and instant messaging.

B. Active End-user Device / Passive User Strategies

One way to enhance the subjective quality perception of a service is to perform QoE assessment as close as possible to the end-user and to report this information to the base station. In this way, there is a higher degree of confidence regarding the influence of the scheduler adjustments versus the QoE improvement, since more accurate QoE metrics can be used. On the other hand, this type of scheduling algorithms require feedback channels for QoE measurements. Recent standards, like DASH, already incorporate specifications about how relevant QoE parameters can be reported to the server.

In the scheduling strategies described in this subsection, the end-users devices are regarded as clients that are able to measure and to report to the base stations the QoE metrics...
that will be be taken into account by the scheduler, while the user itself does not perform any action.

1) Video Streaming: In [70], a QoE cross-layer design for video service is formulated where the scheduler allocates resources taking into account the video distortion caused by the radio channel, which is estimated and reported by the end-user devices according to channel quality and packet loss rate. A radio resource management with tunable parameters is proposed in [71], which works in conjunction with adaptive streaming of video delivery in order to maximize the number of satisfied customers within LTE systems. Besides introducing the notion of unsatisfying outage capacity for evaluating the capacity of downlink LTE air interface for buffered video services, the buffering percentage (the percentage of the total video streaming time spent rebuffering) is adopted as a QoE metric that the clients feedback, enabling to design a QoE-aware prioritization engine and a playback buffer aware downlink scheduler.

The buffer status of a video client can also play an important role when performing QoE-based scheduling. The authors of [72] describe and evaluate a QoE-oriented scheduling for YouTube videos in OFDMA networks, where a client-based feedback is used to directly forward the buffered playtime of each video, so as to optimize the user perceived quality by allocating resources according to the current state of the respective end-user application. In [73], a cross-layer media-buffer aware optimization framework is proposed for wireless resource allocation that constrains rebuffering probability for adaptive video streaming over LTE. The scheduling algorithm is based on periodic feedback of the buffer status of video clients, where priorities are given not only taking into account the absolute values of client media buffer levels, but also considering the rate of change of these buffer levels. The work described in [74] presents a framework to fairly allocate wireless transmission slots to multiple video streams from a base station to mobile clients, where the authors propose that clients communicate their buffered data in order to suggest a scheduling scheme that attempts to prevent stalls by equitably maximizing the buffer level among all receivers. The authors of [75] propose an optimization process to adapt the mobile video in LTE by considering the radio conditions and playout buffer levels of the clients. More specifically, a proxy-based method is adopted to match the streaming rate of each user to the QoE optimization result, as well as a resource allocation based on the buffer demands of the users. In [76], a QoE-based interworking call admission, handoff, and scheduling system is proposed to provide a seamless multimedia streaming services over LTE networks. QoE metrics are defined based on the amount of stored video frames at the video decoder buffer, which are then used to try to guarantee the QoE satisfaction levels of already admitted UEs, to provide smooth multimedia streaming services to as many UEs as possible and to keep a balance of the QoE satisfaction levels among adjacent cells. An application-aware scheduler for video delivery over LTE is proposed in [77] where, by taking into account the buffered playtime sent by the users, the scheduler prioritizes the video flows that are in a critical state.

More elaborate techniques have also been proposed, which combine other QoE relevant parameters with information related to either the rebuffering events or the buffer level. The authors of [78] presented a dynamic priority assignment algorithm that enables a wireless scheduler to prioritize DASH video, so as to guarantee a minimum QoE, which is defined by the authors as a weighted sum of video bitrate, jitter and smoothness of playback. This algorithm works in conjunction with a rate adaptive HTTP video streaming proxy for wireless broadband access networks, so that when the selected video rate is below a certain threshold, it can be interpreted that the DASH user’s channel condition is not good enough, meaning that the respective flow should be prioritized by the scheduler. In [79], the authors propose a resource scheduling scheme to improve the performance of HTTP video streaming service in LTE systems. First, by analyzing the time-dimension of QoE, namely frame freezing, and by considering not only instantaneous service quality, but also past service quality deterioration, an algorithm to measure the ‘jerkiness’ at each end device is presented. Afterwards, the proposed base station scheduling algorithm prioritizes the traffic flow accordingly to the ‘jerkiness’ reported by each device: the end users who experience the maximum ‘jerkiness’ are scheduled with the highest priority. A DASH-based scheduling scheme is developed in [80] for the streaming of scalable videos over HTTP in OFDMA systems, which is cross-layer and QoE-aware. The proposed algorithm dynamically allocates wireless subchannels and power based on the currently played segment and following requested segment (both reported by the clients), so as to avoid playback interruption due to buffer underflow and to improve the decoded video quality of all users.

The integration of not only both rebuffering events and buffer level informations, but also other metrics for the development of QoE-oriented scheduling methods, has been also addressed by some authors. In [81], an approach for joint transmission scheduling (capacity allocation) and video quality selection is presented, in order to design an efficient system that supports a high number of unicast HTTP adaptive video streaming sessions in a dense wireless access network. The authors use QoE-related performance metrics such as total rebuffering time, start-up delay, average media bitrate, media bitrate fluctuations and media bitrate fairness (computed by users and communicated to the network as part of the download request), so as to not only maintain a desired video quality, but also to allocate the remaining capacity, if available, in a fair manner in order to provide high network utilization and to eventually enable users to switch to a higher video quality. A simple asymptotically optimal online algorithm to jointly optimize HTTP video delivery quality adaptation and wireless network resource allocation is presented in [82]. The authors propose that minimal signaling is used from the clients to the network controller in order to enhance the scheduling task and to fairly maximize video clients’ QoE, taking into account trade-offs among the average quality, temporal variability in quality, rebuffering time (including startup delay), and cost of video delivery.

2) VoIP, Web Browsing & Unspecified Applications: Turning the attention to applications other than video streaming, the authors of [83] proposed a downlink scheduling method...
for LTE networks, which is evaluated for VoIP traffic. More specifically, the users’ devices compute and feedback to the base station a QoE metric based on the overall effect of delay and packet loss rate, so that the scheduler is able to allocate the radio resources in a fairly and efficient way. In [84], a collaborative QoE-aware resource redistribution mechanism is proposed for web browsing where, taking into account the web page load time, a method is investigated that takes capacity from users during QoE insensitive periods and redistributes the respective network resources among users who can utilize this capacity to increase their QoE. Regarding multi-service applications, a QoE-oriented strategy is introduced in [85] for OFDMA radio resource allocation based on game theory, in which users cooperate with each other in a practical way to jointly maximize QoE. In particular, the authors consider a utility function that aims at the maximization of the minimum MOS experienced by the users, which is based on date rate and packet-error-probability, in order to optimize the fairness in terms of MOS of heterogeneous users’ requirements (voice, video, and data).

A summary of the aforementioned active end-user device / passive user strategies is given in Table II. As can be seen, information related to the rebuffering events and the buffer level are commonly adopted as QoE metrics for these type of scheduling approaches when dealing with video streaming. On the other hand, delay still plays an important role for VoIP and web browsing applications, whereas buffer-aware scheduling is also not adopted for the case where the application is not specified, since it might not make sense to use this information when dealing with generic approaches (i.e., where the application or its buffer characteristics are not known in advance).

C. Active End-user Device / Active User Strategies

As mentioned in the Introduction, the final judge of the received service quality still remains the end-user, i.e. humans. Therefore, scheduling strategies that exploit direct inputs of the users have the advantage of knowing their preferences and if they are satisfied with the service. On the other hand, these approaches require that the end-user devices are capable of receiving the necessary user inputs. The strategies described next and summarized in Table III adopt this active user approach.

In [86], the authors propose a QoE provisioning framework that enables users to dynamically and asynchronously express their preference with respect to the instantaneous experience of their service performance. To attain this goal, a Graphical User Interface (GUI) displays and captures the users’ options (increase/decrease quality), the feasibility and the consequences of their action (cost). Upon a user’s preference declaration, an online dynamic alteration of the utility functions attributes is performed, in order to exploit the NUM theory by allowing the seamless integration of users’ subjectivity in the resource allocation process. A QoE-aware scheduling framework is proposed in [87] to maximize the average number of satisfied users, where it is assumed that users can feedback a single bit to indicate their satisfaction levels. Since users are in the control loop of the QoE maximization, non-trivial fairness constraints are also added so as to prevent starvation.

D. Other QoE-oriented Scheduling Methods

All the previous scheduling algorithms addressed the downlink scenario, with the goal of maximizing the aggregate experienced quality of all users within a cell of a single operator. Nonetheless, QoE-aware scheduling methods can enhance the wireless resources management in other scenarios, such as the uplink direction, under heterogeneous, cognitive...

| Ref. | Application | QoE optimization based on | Technology |
|------|-------------|---------------------------|------------|
| [70] | Video streaming | Packet loss rate; channel quality | — |
| [71] | Video streaming | X | LTE |
| [72] | Video streaming | X | OFDMA |
| [73] | Video streaming | X | LTE |
| [74] | Video streaming | X | — |
| [75] | Video streaming | X | LTE |
| [76] | Video streaming | X | LTE |
| [77] | Video streaming | X | LTE |
| [78] | Video streaming | X | Data rate | — |
| [79] | Video streaming | X | Past experience | LTE |
| [80] | Video streaming | X | Video quality | OFDMA |
| [81] | Video streaming | X | Data rate | — |
| [82] | Video streaming | X | Video quality; cost of delivery | — |
| [83] | VoIP | Delay; packet loss rate | LTE |
| [84] | Web browsing | Delay | — |
| [85] | Unspecified | Data rate; packet loss rate | OFDMA |
radio, relay and MIMO networks, as well as when dealing with energy-related issues.

1) Uplink: A resource allocation algorithm for live video uplinking is proposed in [88], which assigns more resources for popular contents while maintaining a minimum guaranteed QoE (based on the data rate) for the less popular ones. The authors of [89] presented a QoE-driven scheduler for uplink unicast video delivery (intended for surveillance systems), in which the required data rate and delay are the main factors taken into account by the resource allocation scheme. In [90], a QoE-aware joint resource allocation algorithm is proposed for uplink LTE-based systems that make use of carrier aggregation, where the evaluation of the users’ QoE satisfaction level is performed by a link reward, resource cost and a link utility function designed by the authors.

2) Heterogeneous, Cognitive Radio, Relay & Multi-user MIMO Networks: Only single operators have been considered so far, but some research has already been done regarding heterogeneous wireless networks, where users want to be associated to the best available networks according to their preferences and application specific requirements. For instance, the authors of [91] adopt a game-theoretic approach as a framework for user satisfaction based resource allocation with several operators, several types of users and different classes of services. Regarding mobile traffic offloading, a solution for video streaming services, with the optimization of QoE distribution across the network through the interworking between LTE base station and WiFi hotspots, is proposed in [92], where the subjective quality assessment is based on video playback discontinuities. In [93], a QoE-aware scheduling scheme is proposed for video streaming through Device-to-Device (D2D) communications, where the target of radio resource allocation is to maximize the time-averaged quality of video streams transmitted over D2D communications, while constraining the number of stall events for each stream.

QoE provisioning schemes can also be used when addressing other wireless resources scheduling problems, such as in cognitive radio networks. In [94], the authors develop a channel allocation scheme for multimedia content transmission over cognitive radio networks, where the base station allocates available channels to secondary users based on their QoE requirements (delay and multimedia content quality). A jointly design of spectrum sensing and access policies for QoE-aware multi-user video streaming within cognitive radio networks is presented in [95], in which the goal is to achieve fairness among the users while maximizing the overall QoE (which is based on the data rate). The authors of [96] addressed networks where different types of base stations are deployed to exploit a heterogeneous spectrum pool, consisting of licensed and harvested spectrum, in order to propose a game-theoretic approach that solves the problem of maximizing the users’ satisfaction across the network (based on their transmission rate requirement) by jointly optimizing spectrum sharing, user scheduling, and power allocation in a decentralized manner. Regarding wireless relaying in cognitive radio networks, and by considering QoE indicators (relay buffer status) rather than traditional QoS indicators, the authors of [97] showed that better user experience can be achieved with sub-optimum system capacity. The work presented in [98] also considers multi-hop wireless networks and introduces a scheduling algorithm that jointly optimizes the delivery of multiple video, audio and data flows according to certain QoE metrics. In [99], a system is proposed for efficient delivery of video content over a wireless network formed by a number of densely deployed wireless helper nodes with multi-user MIMO capabilities, where QoE metrics like video quality and rebuffering percentage are used to optimize the transmission scheduling of users at each base station. Another example of QoE-based scheduling is given in [100], where a user selection procedure based on transmitted rate and delay is proposed in order to maximize the average satisfaction degree of multi-user MIMO systems.

3) Energy-related Issues: The “green” networks is also a domain where QoE-based wireless resources management can have an important role. For instance, an approach to power-cycle base stations and to control the playback of video streams is presented in [101], where the goal is to reduce the overall energy consumption of the base stations while maintaining a high QoE for the users. A framework to reduce the energy consumption of small cell networks subject to QoE constraints has been proposed in [102], where an analytical investigation is performed regarding the trade-off between switching off loaded base stations and the performance degradation experienced by the users. In [103], a framework is presented that reduces the energy consumption of wireless mobile devices during streaming video content over Wireless Local Area Networks (WLANs), in which a QoE-based algorithm estimates the user level video quality and adjusts the sleep intervals of the wireless adapter to maintain video quality while maximizing power efficiency. The authors of [104] proposed a novel approach for energy conservation in mobile terminals regarding VoIP flows over WLANs, namely by controlling the sleep periods based on the requested quality in term of the user QoE. An adaptive discontinuous reception method for LTE systems has been proposed in [105], which can provide battery saving for the terminals without degrading the QoE of the services, namely the delay perceived by a user. In [106], a scheduling policy is proposed to save energy of mobile devices via optimal transmission scheduling of mobile-to-cloud task offloading, which considers several QoE domains in order to capture the energy-latency trade-off. An energy

| Ref. | Application | QoE optimization based on | Technology |
|------|-------------|---------------------------|-------------|
| 86   | Unspecified | Users’ quality preference indication | —            |
| 87   | Unspecified | Users’ satisfaction feedback | —            |
efficient resource on-off switching framework for a cellular network comprising a femtocell at the cell edge of a macrocell is investigated in [107], where the goal is to minimize the energy consumption of the cellular network while satisfying a desired level of QoE, which is defined as buffer starvation probability of a mobile device. In [108], an “energy-source” aware asynchronous content delivery mechanism is presented, which adapts delivery of bulk delay-tolerant content in periods of availability of renewable energy, i.e., balances the operator’s energy cost and the QoE (namely the delay) experienced by users.

Table IV contains a summary of the QoE-oriented scheduling methods presented in this subsection.

### Table IV

| Ref. | Scope | Application |
|------|-------|-------------|
| 88   | Uplink | Live video  |
| 89   | Uplink | Unicast video |
| 90   | Uplink | Unspecified (within LTE systems) |
| 91   | Heterogeneous networks | Unspecified |
| 92   | Heterogeneous networks | Video streaming offloading between LTE and WiFi |
| 93   | Heterogeneous networks | Video streaming over D2D |
| 94   | Cognitive radio networks | Multimedia content transmission |
| 95   | Cognitive radio networks | Video streaming |
| 96   | Cognitive radio networks | Unspecified |
| 97   | Cognitive radio & relay networks | Multimedia content transmission |
| 98   | Relay networks | Multimedia content transmission |
| 99   | Relay & multi-user MIMO networks | Video streaming |
| 100  | Multi-user MIMO networks | Multimedia content transmission |
| 101  | Base stations energy consumption | Video streaming |
| 102  | Base stations energy consumption | Unspecified |
| 103  | Terminals energy consumption | Video streaming over WLANs |
| 104  | Terminals energy consumption | VoIP over WLANs |
| 105  | Terminals energy consumption | Unspecified (within LTE systems) |
| 106  | Terminals energy consumption | Mobile-to-cloud offloading |
| 107  | Cellular network (macro-femto) energy consumption | Multimedia content transmission |
| 108  | Renewable energy aware | Unspecified |

### E. Discussion

All the scheduling methods referred above perform resource allocation and/or prioritization at the wireless MAC/physical layer level, which is the scope of this work. Nevertheless, there are also QoE-aware algorithms that permit to retain a fully standard and application-layer unaware MAC/physical operation while still taking into account the wireless channel specificities (e.g., [109]–[117]).

Taking into account the scheduling strategies previously mentioned, video streaming is clearly the application that can benefit more from QoE-aware schedulers. In addition, this will keep being an important topic of research, since not only video streaming is now the most popular application on the Internet, having accounted for 55% of total mobile data traffic in 2015, but also three-fourths of the world’s mobile data traffic will be video by 2020 [118]. It is also foreseen that in the future, with the help of various biometric sensors embedded in smartphones (some of them already available nowadays), QoE assessment will be performed directly from live human biometric data such as galvanic skin response and pupil dynamics [119], body gestures [120], and facial expressions [121]. This approach will enhance the wireless systems capability of gathering more accurate QoE data for better serving a user at any instance.

### V. Conclusions

Wireless resources scheduling is evolving from system-centric QoS-oriented to user-centric QoE-oriented. Thus, the network operators, as well as the service providers, aspire to have reliable models that can assess, predict and even control QoE, specially for multimedia content transmissions. This paper provided an extensive survey about this research topic: first, QoE was explained, namely the factors that influence the user experience, as well as some QoE estimation methods regarding multimedia services over communication systems; next, the evolution of wireless scheduling techniques was presented, including QoS-QoE mapping strategies and utility-based optimization; finally, state-of-art QoE-based scheduling strategies for wireless systems were described, highlighting the application/service of each solution, as well as the parameters adopted for QoE optimization. Since there are still many issues to be explored and resolved, it is foreseen that a lot of research activity will surely be performed in the future, in order to expand the research frontier of wireless resources schedulers.

### REFERENCES

[1] S. Khan, S. Duhovnikov, E. Steinbach, and W. Kellere, “MOS-based Multiuser Multiapplication Cross-layer Optimization for Mobile Mul-
tion,” IEEE Communications Letters, vol. 15, no. 5, pp. 494–496, May 2011.

[86] G. Aristomenopolous, T. Kastrinogiannis, V. Kaldanis, G. Karantonis, and S. Papavassiliou, “A Novel Framework for Dynamic Utility-Based QoE Provisioning in Wireless Networks,” in 53rd IEEE Global Telecommunications Conference (GLOBECOM 2010), December 2010.

[87] G. Lee, H. Kim, Y. Cho, and S. H. Lee, “QoE-Aware Scheduling for Sigmoid Optimization in Wireless Networks,” IEEE Communications Letters, vol. 18, no. 11, pp. 1995–1998, November 2014.

[88] A. E. Essaili, E. Steinbach, D. Munaretto, S. Thakolrsi, and W. Kellerer, “QoE-driven resource optimization for user generated video content in next generation mobile networks,” in 18th IEEE International Conference on Image Processing, September 2011, pp. 913–916.

[89] P. H. Wu, J. N. Hwang, J. Y. Pyun, K. M. Lan, and J. R. Chen, “QoE-aware resource allocation for integrated surveillance system over 4G mobile networks,” in 2012 IEEE International Symposium on Circuits and Systems (ISCAS 2012), May 2012, pp. 1103–1106.

[90] Y. Song, Y. Han, and Y. Choi, “A QoE-aware joint resource allocation algorithm for uplink carrier aggregation in LTE-Advanced systems,” in 2014 IEEE International Conference on Communications (ICC 2014), June 2014.

[91] U. Toseef, M. A. Khan, C. Görg, and A. Timm-Giel, “User Satisfaction Based Resource Allocation in Future Heterogeneous Wireless Networks,” in 9th Annual Communication Networks and Services Research Conference (CNSR 2011), May 2011, pp. 217–223.

[92] M. Seyedebrahimi and X. H. Peng, “Optimising QoE Distribution for Video Applications through LTE-WiFi Interworking,” in 9th International Conference on Next Generation Mobile Applications, Services and Technologies, September 2015, pp. 335–340.

[93] H. Zhu, Y. Cao, W. Wang, B. Liu, and T. Jiang, “QoE-aware resource allocation for adaptive device-to-device video streaming,” IEEE Network, vol. 29, no. 6, pp. 6–12, November 2015.

[94] T. Jiang, H. Wang, and A. V. Vasilakos, “QoE-Driven Channel Allocation Schemes for Multimedia Transmission of Priority-Based Secondary Users over Cognitive Radio Networks,” IEEE Journal on Selected Areas in Communications, vol. 30, no. 7, pp. 1215–1224, August 2012.

[95] Z. He, S. Mao, and S. Kompella, “Quality of Experience Driven Multi-User Video Streaming in Cellular Cognitive Radio Networks With Single Channel Access,” IEEE Transactions on Multimedia, vol. 18, no. 7, pp. 1401–1413, July 2016.

[96] N. Zhang, S. Zhang, J. Zheng, X. Fang, J. W. Mark, and X. Shen, “Qoe driven decentralized spectrum sharing in 5g networks: Potential game approach,” IEEE Transactions on Vehicular Technology, vol. PP, no. 99, pp. 1–11, March 2017.

[97] K. Wu, L. Guo, H. Chen, Y. Li, and J. Lin, “Queuing based optimal scheduling mechanism for QoE provisioning in cognitive radio relaying network,” in 16th International Symposium on Wireless Personal Multimedia Communications (WPoMC 2013), June 2013.

[98] A. B. Reis, J. Chakareski, A. Kassler, and S. Sargento, “Quality of experience optimized scheduling in multi-service wireless mesh networks,” in 17th IEEE International Conference on Image Processing (ICIP 2010), September 2010, pp. 3233–3236.

[99] D. Bethanabhotla, G. Caire, and M. J. Neely, “WiFlix: Adaptive Video Streaming in Massive MU-MIMO Wireless Networks,” IEEE Transactions on Wireless Communications, vol. 15, no. 6, pp. 4088–4103, June 2016.

[100] H. Cao, P. Wang, L. Chen, F. Liu, X. Wang, Y. Zhu, and H. Pang, “User Satisfaction Based ZFPF Scheduling Algorithm in Multi-user MIMO System,” in 11th IEEE International Conference on Trust, Security and Privacy in Computing and Communications (TrustCom 2012), June 2012, pp. 1486–1490.

[101] M. Draxler, P. Dreimann, and H. Karl, “Anticipatory power cycling of mobile network equipment for high demand multimedia traffic,” in 4th IEEE Online Conference on Green Communications (OnlineGreenComm 2014), November 2014.

[102] N. Sapountzis, S. Sarantidis, T. Spyropoulos, N. Nikaein, and U. Salim, “Reducing the energy consumption of small cell networks subject to QoE constraints,” in 2014 IEEE Global Communications Conference (GLOBECOM 2014), December 2014, pp. 2485–2491.

[103] M. Csernai and A. Gulyas, “Wireless Adapter Sleep Scheduling Based on Video QoE: How to Improve Battery Life When Watching Streaming Video?” in 20th International Conference on Computer Communications and Networks (ICCCN 2011), July 2011.

[104] A. Ksentini and Y. Hadjadj-Aoul, “QoE-based energy conservation for VoIP over WLAN,” in 2012 IEEE Wireless Communications & Networking Conference (WCNC 2012), April 2012, pp. 1692–1697.

[105] G. Szabó, G. Pongrácz, I. Góbor, R. Cöster, and M. Sintorn, “Service aware adaptive DRX scheme,” in 2014 IEEE GLOBECOM Workshops, December 2014, pp. 1132–1138.

[106] S. T. Hong and H. Kim, “QoE-Aware Computation Offloading Scheduling to Capture Energy-Latency Tradeoff in Mobile Clouds,” in 13th IEEE International Conference on Sensing, Communication, and Networking (SECON 2016), June 2016.

[107] A. Farrokhii and O. Ercetin, “QoE Based Random Sleep-Awake Scheduling in Heterogeneous Cellular Networks,” in 2016 IEEE Wireless Communications & Networking Conference (WCNC 2016), April 2016.

[108] V. Gabale and A. P. Subramanian, “GreenSlic: Enabling renewable energy powered cellular base stations using asynchronous delivery,” in 6th International Conference on Communication Systems and Networks (COMSNETS 2014), January 2014.

[109] G. Bianchi, A. Detti, P. Loret, C. Pisa, S. Thakolrsi, W. Kellerer, and J. Widmer, “Cross-layer H.264 scalable video downstream delivery over WLANs,” in 11th IEEE International Symposium on a World of Wireless Mobile and Multimedia Networks (WoWMoM 2010), June 2010.

[110] V. Ramanurthi, O. Oyman, and J. Foerster, “Video-QoE aware resource management at network core,” in 2014 IEEE Global Communications Conference (GLOBECOM 2014), December 2014, pp. 1418–1423.

[111] X. Chen, J. N. Hwang, C. J. Wu, S. R. Yang, and C. N. Lee, “A QoE-based APP layer scheduling scheme for scalable video transmissions over multi-RAT systems,” in 2015 IEEE International Conference on Communications (ICC 2015), June 2015, pp. 6779–6784.

[112] N. Radics, P. Sžilgyd, and C. Vulkán, “Insight based dynamic QoE management in LTE,” in 26th IEEE Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC 2015), August 2015, pp. 1746–1751.

[113] N. Eswara, S. Channappaya, A. Kumar, and K. Kuchi, “eTVSQ based Video Rate Adaptation in Cellular Networks with α-Fair Resource Allocation,” in 2016 IEEE Wireless Communications & Networking Conference (WCNC 2016), April 2016.

[114] I. Triki, M. Haddad, R. El-Azouzi, A. Feki, and M. Gachoaoui, “Context-Aware Mobility Resource Allocation for QoE-Driven Streaming Services,” in 2016 IEEE Wireless Communications & Networking Conference (WCNC 2016), April 2016.

[115] M. Borkowski, O. Skarlat, S. Schulte, and S. Dustdar, “Prediction-based prefetch scheduling in mobile service applications,” in 2016 IEEE International Conference on Mobile Services (MS 2016), June 2016, pp. 41–48.

[116] T. Tajima and Y. Okabe, “Optimizing Packet Transmission Scheduling for Enhanced Web QoE in Wireless LAN,” in 40th IEEE Annual Computer Software and Applications Conference (COMPSAC 2016), vol. 2, June 2016, pp. 312–318.

[117] S. Kumar, S. Sriram, A. Sarkar, and A. Sur, “A Three Level Adaptive Video Streaming Framework Over LTE,” in 2016 IEEE International Conference on Systems, Man, and Cybernetics (SMC 2016), October 2016, pp. 2442–2447.

[118] CISCO, “Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2015–2020 White Paper,” CISCO White Papers, February 2016.

[119] A. Shye, Y. Pan, B. Scholbrock, J. S. Miller, G. Menlik, P. A. Dinda, and R. P. Dick, “Power to the people: Leveraging human physiological traits to control microprocessor frequency,” in 41st IEEE/ACM International Symposium on Microarchitecture, November 2008, pp. 188–199.

[120] G. Castellano, S. D. Villalba, and A. Camurri, “Recognising human emotions from body movement and gesture dynamics,” in 2nd International Conference on Affective Computing and Intelligent Interaction (ACII 2007), September 2007, pp. 71–82.

[121] J. Whitehill, M. Bartlett, and J. Movellan, “Measuring the perceived difficulty of a lecture using automatic facial expression recognition,” in 9th International Conference on Intelligent Tutoring Systems (ITS 2008), June 2008, pp. 668–670.