Resource Management in Wireless Access Networks: A layer-based classification - Version 1.0

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Resource Management in Wireless Access Networks: A layer-based classification - Version 1.0

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Abstract: In recent years, wireless access networks have recently experienced significant breakthrough that strongly impacted the way of managing network resources. We can observe considerable emergence of heterogeneous wireless networks where different types of wireless technologies coexist in the same region. Beside widespread deployment of heterogeneous wireless networks, the progress of electronic devices enables implementation of multiple radio interfaces on a single mobile device. Consequently it requires new resource management approaches to exploit diversity gain. Moreover, the dramatic increase in traffic leads to a necessity of efficient resource management. As a result, numerous studies have been conducted to address various issues in resource management. In this report, a survey of recent resource management solutions is presented. It is a layer-based classification survey that can be helpful for any researcher that wants to know the state of the art on existing resource management schemes as well as for technical experts who wants to apply them to real devices.

Key-words: Wireless Access Networks, Resource Management, Layer-based Classification, Heterogeneous Environment, Quality of Experience (QoE) , Quality of Service (QoS)

Gestion de ressources dans les réseaux d'accès sans-fils : Une classification par couches - Version 1.0

Résumé : *La percée fulgurante des réseaux d'accès sans-fil au cours de ces dernières années ont eu un impact sur la manière de gérer les ressources dans les réseaux. On peut observer l'émergence des réseaux sans-fil hétérogènes où co-existent differents types de technologies sans-fil. Parallèlement au déploiement généralisé des réseaux sans-fil hétérogènes, l'évolution des appareils électroniques fait que l'on peut avoir plusieurs interfaces radios sur n'importe quel terminal mobile. De nouvelles approches de gestion de ressources sont donc nécessaires pour exploiter cette diversité. Par ailleurs, l'augmentation du trafic oblige à une gestion efficace des ressources des réseaux sans-fil. Ce rapport propose un état de l'art des travaux qui ont été menés pour traiter les différents problèmes de gestion de ressource. C'est une classification en couches qui peut servir à tout chercheur souhaitant connaître l'état de l'art en matière de gestion de ressources dans les réseaux sans-fil ainsi qu'à des experts techniques qui veulent les implémenter.*

Mots clés : *Réseau sans-fil, Gestion de ressources, Classification par couche, Environnement hétérogène, Qualité d'Experience (QoE), Qualité de Service (QoS)*

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1 Introduction

The rapid progress on wireless technologies has changed the field of communications and the convergence of wireless technology contributes significantly in enhancing the overall experience of users. On one hand, the wireless wide area networks (WWANs) such as third generation (3G), Long Term Evolution (LTE), and Worldwide Interoperability for Microwave Access (WiMAX) supply users with a large coverage and mobility support. On the other hand, the wireless local area networks (WLANs) provide high-speed wireless connections in a local area but do not support mobility. Besides, wireless personal area networks (WPANs) offer short-range and energy efficient communications. The overlapping deployment of all aforementioned wireless technology constitutes the context of *heterogeneous wireless networks (HWNs).*

Because more and more HWNs are deployed, mobile terminal with multiple radio interfaces are expected to keep users always best connected. The modern devices can be equipped with multiple radio interfaces. For example, a laptop can have connections to WLAN, Bluetooth, and even WiMAX or LTE. These devices can be categorized into two main types depending on their ability to support or not IP mobility or multi-homing. The multi-mode terminals can only select and use one interface for a given session at a time. Conversely, the multi-homing terminals can use multiple connections simultaneously to share load for a communication session. Consequently, the connection will be seamless during mobility or link break.

The traffic load in wireless networks is increasing significantly. Therefore, the shared medium in wireless networks becomes a critical resource that requires effective control and management mechanisms. There are different ways to control the resources in the wireless networks. Most of existing resource management schemes took technical metrics to evaluate the performance of services. They are also called quality of services (QoS) based schemes. However, technical metrics are not completely correlated with user's satisfaction. Consequently, quality of experience (QoE) was proposed to address the evaluation true feelings of users. Recently, more and more QoE-based resource management solutions are proposed in the literature.

This report provides a survey of major existing QoS-based and QoE-based resource management solutions in wireless access networks. For sake of clarity, we choose to classify them according to layers where they can be applied. This layer-based classification will consider three main categories: Upper layers solutions (corresponding to transport and application layer), Lower layers solutions (corresponding to physical, data-link, and network layers), and Cross-layer solutions (corresponding to combination of upper and lower layers). For each category, the main resource management problems to be resolved are described. For each of these problems, existing solutions for major wireless technologies are presented.

The report is composed of four main sections. In the Section 2, we first describe the major wireless technologies. Then, main resources to be managed in each of the three categories of layers are described. The notion of quality of experience (QoE) and how it can be evaluated and used for resource management is presented in detail. Section 3 contains the layer-based survey on resource management schemes. The Section 3.1 summarizes the few exisiting schemes that have been proposed for Upper layers. As much more solutions exist for Lower layers, the Section 3.2 provides details on resource management solutions for physical, data-link and network layers. The Cross-Layer resource management schemes are presented in 3.3. This survey ends in Section 4 by synthesizing main solutions and by presenting open research issues in resource management in wireless networks.

2 Overviews

In this section, we provide a brief discussion of existing wireless technologies and their practical applications. Resource management plays an important role in wireless networks because it can enhance users' experience and utilization. Hundreds of researches on resource management that have been conducted. Although different existing classifications have been proposed, we believe that our layer-based classification of resource management can bring benefits to engineers and researchers. Furthermore, QoE has been proved that it is an appropriate method to assess the networks performance beside of existing QoS-based methods. Consequently, an overview of QoE-based assessment is also discussed in this section.

2.1 Major wireless technologies

In recent years, wireless technologies have had significant developments. With the increase of users and high-definition multimedia services, more wireless resources and stricter QoS are required. In this section, the most popular wireless access technologies will be described briefly to provision a conceptual view for readers. Three major technologies will be discussed in this section are WiMAX, LTE, and WLAN. Note that there are other wireless technologies in practice such as: WPAN, Digital Video Broadcasting-Terrestrial (DVB-T), etc., which are more and more deployed all over the world. Another promising wireless access technology is cognitive radio. While the cellular networks occupy licensed bandwidth for their radio communication, the cognitive radio will attempt to access the licensed bandwidths without impacting to the cellular networks.

WiMAX has been considered as a candidate for the future of wireless mobile access networks. It is designed for multi-services over a broadband wireless network. In physical layer, scalable Orthogonal Frequency Division Multiplexing Access (OFDMA) technology is adopted so that channel bandwidth can be adjusted from 1.25 MHz to 20 MHz. Although WiMAX systems are based on IEEE 802.16 standard, WiMAX forum—an industrial organization—is responsible for certifying WiMAX systems. To be approved by WiMAX forum, a system has to satisfy specified parts of IEEE 802.16 standard and performance tests, thus the terms IEEE 802.16 and WiMAX can be used interchangeably. In 2001, the first IEEE 802.16 standard for Line-of-sight (LOS) scenarios which exploits Single-Carrier modulation in 10-66 GHz frequency range was approved. In 2003, non-LOS scenarios were addressed in the IEEE 802.16a, and thus it can be applied to last-mile fixed broadband access. IEEE 802.16e, also called as Mobile WiMAX, was approved in 2005 to support mobility. In physical layer, IEEE 802.16e adopts a faster Fast Fourier Transform (FFT) and variable FFT sizes, Multiple-Input Multiple-Output (MIMO) spatial multiplexing, and beam-forming technologies to enhance performance. In Medium Access Control (MAC) layer of IEEE 802.16e, a retransmission scheme, named Hybrid ARQ, is deployed to enhance the link reliability. Moreover, each frame can be modulated with different types to different groups of sub-carriers allocated to different users. The summary of standardization process of IEEE 802.16 can be found in [59].

Long Term Evolution (LTE) is a successful descendent of $3G$ networks. With the peak data rates for downlink and uplink up to 100 Mbps and 50 Mbps respectively, LTE can support to various services effectively. LTE-Advance (LTE-A) supports the same range of carrier components (CCs) bandwidths (1.4 MHz, 3 MHz, 5 MHz, 10 MHz, 15 MHz, and 20 MHz) as in LTE Rel.8. With each CC in LTE-A being LTE Rel.8 compatible, carrier aggregation allows operators to migrate from LTE to LTE-A while continuing to support services to LTE users. Moreover, the eNodeB and Radio Frequency (RF) specifications associated with LTE Rel.8 remain unchanged in LTE-A. By reusing the LTE design on each of the CCs, both implementation and specification efforts are minimized. However, the introduction of carrier aggregations (CAs) for LTE-A has required the introduction of new functionalities and modifications to the link layer and radio resource management (RRM).

WLANs have had tremendous growth in the recent years along with the popularity of IEEE 802.11 devices. The first standard appeared in 1997 supports transmission rate up to 2 Mbps on Industrial, Scientific and Medical (ISM) bands. The two access mechanisms of IEEE 802.11 are Distributed Coordination Function (DCF) and Point Coordination Function (PCF). The fundamental access mechanism DCF adopts Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol designed for Best Effort services [98], therefore it is unsuitable for real-time applications such as voice and video streaming. The IEEE 802.11e amendment was approved to offer QoS support in WLANs. In IEEE 802.11e amendment, the services are differentiated into four Access Categories (ACs) and novel access mechanism, named Hybrid Coordination Function (HCF), was defined. IEEE 802.11e amendment, however, is unable to guarantee QoS in strict QoS requirement applications [85], especially when the saturation occurs [29, 102]. To support high requirements of multimedia applications, the first generation of high throughput WLANs, known as IEEE 802.11n, was developed in 2009 that have the data rate up to 600 Mbps by adopting multi-input multi-output (MIMO) technology. Three main enhancements in MAC layer of IEEE 802.11n are Aggregation MAC Service Data Unit (A-MSDU), MAC Protocol Data Unit (A-MPDU), and Block Acknowledgement (BA). MSDU aggregation allows multiple MSDUs with the same receiver to be concatenated into a single MPDU whereas MPDU aggregation combines multiple MPDUs and sends with single PHY header. Furthermore, the two amendments IEEE 802.11ad and IEEE 802.11ac with the peak data rate 1Gbps and 7 Gbps for multi-users are released. Moreover, IEEE 802.11aa standard enhances the reliability and quality of multicast multimedia streaming.

In the conventional networks, each type of wireless access networks was designed for a unique service. Also, in the previous decade, users' devices were equipped with one radio interface; therefore a mobile terminal can connect to only one wireless access network. However, along with recent significant breakthroughs in integrated circuit, the ability of simultaneous connecting to different networks is realistic. Moreover, there are widespread overlapping deployments of wireless networks with different technologies. These wireless networks co-exist in the same area and form a heterogeneous wireless networks (HWNs). In HWNs, a mobile terminal can access to only one network at a time or connect to multiple networks simultaneously. The capability of accessing multiple network of mobile terminal offers more radio resources in wireless access networks. However, resource managing in heterogeneous wireless network is more complicated than homogeneous networks. The first challenge is the difference characteristics between types of networks. For example, WLAN is for low mobility, low cost, and high bandwidth communications, meanwhile cellular networks support users that have high mobility, high cost (both energy and money), and medium bandwidth services. The other point is that each user can exploit multiple applications simultaneously which has different requirements. Therefore, in recent studies, resource managing in heterogeneous networks has been intensively discussed [32, 33, 40, 56, 60] that consider both perspective of network operators and experience of users.

2.2 Layer-based Resource management classification

Although the wireless access technologies have had breakthroughs in recent years, they may not satisfy high requirements of multimedia applications in bandwidth, strict end-to-end delay, etc. Meanwhile, upgrading wireless access systems can cost an enormous amount of money and time. An alternative solution is deploying an efficient resource management scheme in the wireless access networks that can optimize the performance of networks and experience of users.

There are various types of resource in the wireless access networks. They can be available channels, bandwidth, time-slot, cache memory in the server, queue, and etc. In this survey, a categorization relied on the layer where specific resources are controlled is proposed. This categorization is helpful for engineers who want to implement the resource management in the practical systems, which are usually separated into layers. A router, for example, is a network-layer device which controls the paths in the networks. The path management should be implemented in the routers. Meanwhile, an access point (AP), a data-link layer device, controls the medium access of others device, consequently a bandwidth management or scheduling can be implemented on AP.

The upper layer resource management, which consists of layers from transport layer to application layer, is independent of topology and type of networks. For instance, a cache management in application layer should not take the number of hops between source and destination into accounts. As a result, this type of resource management can be adopted by different technologies. Contrarily, the lower layer resource management, which involves in physical layer, data-link layer, and network layer, depends on topology and type of networks.

Obviously, resource management schemes that take into account multiple layers can achieve better performance in wireless access networks. Subsequently, numerous studies have been conducted in recent years. Although the benefits of cross-layer resource management schemes are significant, the implementations of these schemes are more complex.

2.3 Quality assessment

In recent years, there is an increasing recognition that QoE is more accurate measurement to evaluate the quality perceived by users. While the network-oriented parameters, such as delay, jitter, packet loss, etc. are the fundamental metrics in QoS schemes, the QoE is based on feelings of users. Although a better network QoS can lead to better QoE, fulfilling all QoS parameters may not guarantee a satisfied user. Moreover, even with a bad QoS metrics, the fine QoE results, in fact, can be achieved [9]. Subsequently, QoE attracts significant concern from both industrial and academic sites. As a result, ITU standardization bodies spent a significant attention to the QoE issue and related branches. The ITU-T Study Group 12 (SG12) studies on performance of QoS and QoE, and defines a large number of high priority questions that are being addressed in collaboration with several ICT (Information and Communication Technologies) partners.

ITU defined thus: "QoE is a measure of the overall acceptability of an application or service, as perceived subjectively by end-user". Precisely, the QoE evaluation considers factors related to both the services and users. The service factors include availability, reliability, set-up and response times, type of terminals, etc. Meanwhile, the users' factors consist of emotions, experience, motivation, and goals. The QoE measure has a distinct meaning according to the specificity of each application. A positive QoE result in voice services, for example, signifies that the call is characterized by an excellent voice transmission quality and low probability of blockage. Nevertheless, a positive QoE result in Web surfer applications can be achieved when good quality graphics and pictures are downloaded within an acceptable period of time.

The video quality measurement can be done using either objective or subjective approaches. In the objective approaches, explicit functions of measurable parameters can be exploited to evaluate satisfaction of users. Meanwhile, the subjective methods are based on evaluations given by human feelings under proper definitions and conditions. The main drawback of objective approaches is that they may be uncorrelated with human perception. The mean square error (MSE) or peak signal-to-noise ratio (PSNR) is popular objective approaches. Furthermore, other complicated methods for objective evaluation such as the moving picture quality metric (MPQM) and the normalized video fidelity metric (NVFM) were proposed. Recently, the initial waiting time and probability of interruption in video streaming were taken into account for QoE measurement [58]. On the subjective quality-assessment methods, the mean opinion score (MOS) recommended by the ITU is the common tool for video quality measurement. Even though MOS studies have provided fundamental concrete for analyzing in signal processing, it still has significant limitations: very stringent environments are required, the process cannot be automated, and it is very costly and time consuming. Consequently, MOS evaluation is impossible to be conducted in real-time. To address evaluation of MOS in real-time, Pseudo-Subjective Quality Assessment (PSQA) is a promising solution. It is based on statistic learning using random neural network (RNN) that proposed in [52]. The steps need to be done before being able to use PSQA tool for an application can be found in [68].

3 State-of-the-art on resource management

In this paper, existing resource management schemes are classified into three groups: lower layer, upper layer, and cross-layer. The lower layer resource management has been studying in numerous researches, while there is lack of researches in the upper layer group. Consequently, we focus on discussing the resource management schemes in the lower layer group to provide the up-to-date review for reader. Besides, a brief review of recent upper layer resource management scheme is also provided.

3.1 Resource management in upper layers

While the lower layer resource management schemes depend significantly on the topology and the wireless access technology, the upper layer resource management schemes take the services requirements into account. As a result, these schemes can be categorized by their services.

- **Video**

  The authors in [99] proposed a solution for optimizing cache memory for HTTP adaptive bit rate (ABR) video streaming over wireless networks. The video stream originates from the media cloud, and then it is transcoded into a set of media files with different playback rates. The appropriate file will be chosen corresponding to channel condition and screen format. A number of copies are stored in cache memory, however the storage capacity of media cache server is limited. Consequently, the problem is to maximize the expected QoE of users under a given amount of media cache storage. A two-step process was adopted to solve the problem. The first step is to determine the optimal playback rates for a given number of cache copies. Then, the optimal number of cache copies can be found in the second step. Although this paper considered single media cache server scenarios, it can be extended into multiple cache servers so that they can cooperate to enhance users' satisfaction.

  In fact, the high loss rate can impact negatively to quality of service, however multicast protocol does not support reliable communication. Consequently, the authors in [72] propose hierarchical adaptive mechanism for multicast video stream. The video file is encoded into two layers: base layer and enhanced layer. While base layer is transmitted through a reliable transportation, enhanced layer is for nodes with better links.

  In video streaming, the users have to wait at the beginning for initial buffering. Moreover, the interruption can occur when the number of packets in the playing buffer is empty. These problems can impact on experience of users, therefore the probability of interruption occurs and the number of initially buffered packets was considered as QoE metrics [58]. By analytical approach, the initial buffer can be determined based on the packet arrival and play back rates. Also, a trade-off between two QoE metrics curve for the infinite file size was shown. Although the paper described in detail the relation between initially buffered packets and the probability of interruption, the combination of this scheme with scalable video coding was not addressed.

  Another video streaming application is in wireless multimedia sensor networks (WMSNs). In WMSNs, the FEC coding can be modified to support QoE for Video transmission [100]. Based on type and position of video frame in a group of pictures, FEC will be added to enhance QoE. However, the proposed decision of adding FEC was not based on the real QoE which is only calculated at the destination of the stream.

- **Voice**

  Nowadays, the number of applications adopting TCP for its transport layer has been increasing. In fact, TCP can cope with practical issues such as firewall. However, the conventional TCP is not suitable for real-time applications because of its fluctuating throughput. The authors in [25] contributed a QoE-aware congestion control based on POMDP-adaptation. A two-level congestion control adaptation based on online-learning was adopted. In the first level, the sender selects its updating policy at the beginning of each epoch. In the second level, it then adapts its own congestion window by updating policy.

  In voice services, when the network suffers from congestion, the call blockage can happen. The authors in [28] conducted a study on the network utility and the number of call attempts. It is assumed that the user will terminate an ongoing call if they have to put more efforts than they could tolerate, thus the QoE is negatively correlated to the effort of user. The dilemma was modeled as a non-cooperative game, non-zero sum between provider and VoIP user. Equilibrium solutions can expect to not only increase their revenue but also reduce the number of cases when users quit out of frustration thus minimizing potential churning. The authors analysed experimental data and proved that correlation between QoE is negatively correlated to effort. Furthermore, the preliminary game model proposed in [27] was extended and generalized to adapt incomplete knowledge. The sophisticated users do fake efforts to receive the better service from the provider are also considered in this study.

- **Data**

  In [74], the authors introduced the term of Web QoE which refers to the user perceived quality of networked data services. The popular examples of such services are web browsing and file downloading. Recent studies [31, 76] showed that the utilization of the MOS methodology and Absolute Category Rate (ACR) scales from video and audio quality assessments has emerged as an actual standard for Web QoE evaluation. Moreover, although the natures of the experience in audio-video services and data services are different, [66] showed that a transfer of methods to new service categories is feasible. However, no study has been done to measure the QoE in non-multimedia services.

3.2 Resource management in lower layers

In this section, the resource management schemes operate in the lower layers will be discussed in details. The resource management schemes in lower layers aim at optimizing network operations and user perception. Furthermore, resource management schemes of both homogeneous and heterogeneous networks have been studied intensively. The major issues and existing solutions in each layer will be addressed.

3.2.1 On Physical Layer

Recently, cooperative relay and smart antenna are promising solutions to increase performance in wireless networks. The cooperative radio relay can be divided based on OSI layers. Layer 1 relay, also named Amplifier-and-Forward (AF), is a relay techniques occurring in physical layer. Layer 1 relay techniques are relatively simple that makes for low-cost implementation and short processing delays related to relaying. This technique has been used commonly in cellular networks. However, it increases inter-cell interference and noise together beside desired signal components. As a result, the received SINR is deteriorated.

In addition, the smart antenna solution can decrease interference and increase antenna gain by using directional beams, thus the bandwidth can be improved. However, when every node in the network is equipped with smart antennas, the performance will be decreased by mismatched directions between antennas [84]. Consequently, smart antenna techniques should be combined with other solutions such as routing and scheduling to achieve better performance [36, 84].

3.2.2 On Data link Layer

Data link layer is the second layer in the OSI-reference model provides services to network layer and control the physical layer. In resource management, the data link layer is responsible for bandwidth and channel allocation, scheduling, admission control, and network selection.

3.2.2.1 Admission Control

In this part, existing admission control schemes will be discussed. The basic function of admission control is estimating the state of networks and then making decision if a traffic flow can be admitted. The objectives of admission control can be the optimal utility of networks, guarantee the QoE in the networks, load balancing, etc. The wireless access networks can have multiple classes of service, thus the admission control should have capability of distinguishing between them. Then, an appropriate amount of wireless resource can be assigned to the users.

A call admission control for IEEE 802.11 single-hop networks with stochastic delay guarantees was proposed in [1]. A link-layer channel model was exploited to characterize the variations of the channel service process in a non-saturated case using Markov-modulated Poisson process model (MMPP). While stochastic delay can be guaranteed successfully as shown in the performance evaluation, other parameters such as throughput and packet loss were not mentioned. The authors in [10] proposed an admission control scheme that combined with radio interface selection in heterogeneous wireless access networks. Although the proposed scheme can only achieve a sub-optimal solution, it shows significant increase in performance and reduction in computational complexity. However, only voice traffic was studied in the research.

Although recent breakthroughs in wireless technologies boosted utilization in cellular networks, existing cellular networks can be unable to provision enough bandwidth for users. Then, WLANs can be exploited to share traffic load with cellular networks, named off-loading technology. The call admission control in combined networks of LTE and WLAN was proposed in [40]. The study, also, considers moving between cellular and WLAN areas. In this solution, WLANs have higher priority than cellular networks. When a new call occurs, the mobile terminal tries to connect to the cellular networks if there is no available resource in WLAN. Obviously, WLAN can provide enough bandwidth for user but it cannot guarantee the user's experience.

The author in [41] proposed a distributed scheme of association in the wireless access networks. The algorithm copes with several different policies in wireless access networks: rate-optimal, throughput-optimal, delay-optimal, and load-equalizing. A degree of load balancing was proposed to switch between policies. BSs periodically share their time average loads with MTs, and MTs use this information to make decision over these periods.

The aforementioned scheme was designed to aim QoS enhancements, however the QoE is more correlated to user experience than QoS. The authors in [61] adopted PSQA tool to control flow admission at the AP in IEEE 802.11 networks. When a flow requires a connection, the AP will calculate MOS of ongoing streams. If the MOS of every stream is over the acceptable level plus a threshold, the new connection will be admitted. This is a reactive scheme that only launch if there is request of connection. However, the differentiated priorities of users were not addressed in this paper.

While admission control in single-hop network makes decisions based on the local wireless conditions, admission control in multi-hop networks is based on end-to-end path status. As a result, admission control in multi-hop network can be done with path information provided by routing components in network layer or coupled with routing components. Because of relationship between admission control and routing schemes, multi-hop admission control will be discussed in detail in cross-layer section 3.3.

3.2.2.2 Network Selection

Different networks can coexist in the same region. When mobile users in an area of overlapping wireless access networks, their devices should detect and select appropriate networks automatically depending on requirements. This scenario has been motivating an enormous number of researches in network selection schemes. A brief summary of existing network selection schemes can be found in [87]. Existing approaches can be broken into three main groups: Multiple Attribute Decision Making (MADM), Game theory-based decision making, and QoE-based decision making. Fig. 1 describes the classification of existing network selection schemes.

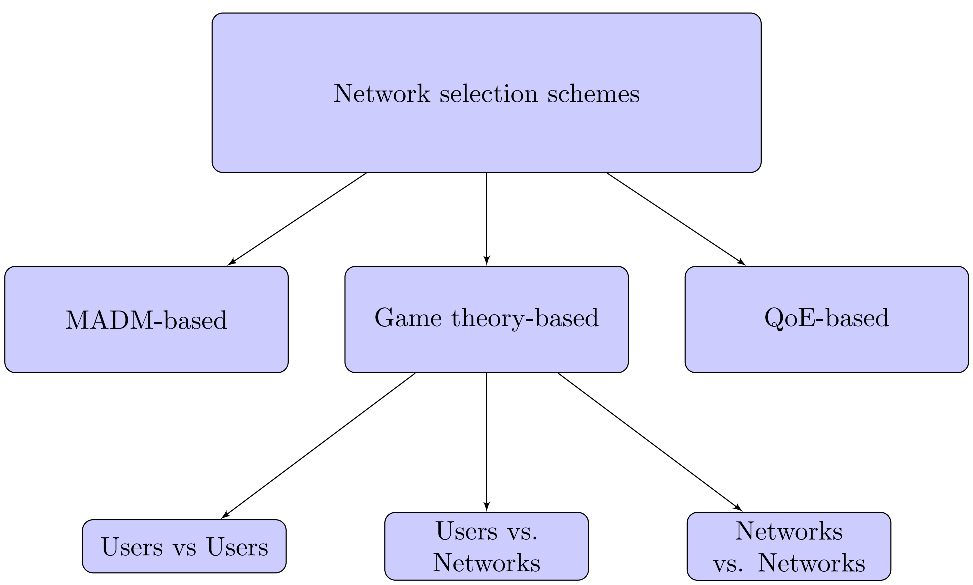

Figure 1: Classification of schemes in network selection problem

In MADM-based network selection schemes, each user adopts a joint metrics from different parameters to evaluate each network in its range. By comparing joint metrics of different networks, an appropriate network will be selected. Existing solutions in MADM group are Simple Additive Weighting Method (SAW), Technique for Order Preference by

Group	Paper	Cooperative	Non-cooperative	Input Parameters
Users vs Users	[51]		X	Number of users at AP and distance from user to AP
	[103]		X	Fixed Connection fee and bandwidth
	[56]		X	Linear pricing and bandwidth
Users vs Networks	[16]		X	QoS parameters: delay, jitter, throughput, and packet loss and Cost
	[5]	X		User and network payoff functions
Networks vs Networks	[55]		X	Throughput
	[15]	X		Datarate, packet delay, and packet dropping rate
	[4]	X		Bandwidth

Table 1: Game theory based network selection schemes

Similarity to Ideal Solution (TOPSIS) [13, 14], Multiplicative Exponential Weighting Method (MEW), Elimination and Choice Expressing Reality (ELECTRE), and Analytic Hierarchy Process (AHP) and Grey Relational Analysis (GRA). In [19], an access technology selection in heterogeneous wireless networks and a hybrid decision method were addressed. In decision making, both cost and QoS parameters were considered and embedded into a utility function with their weights. A periodical information of network load and cost are signaled to mobile users. The proposed solution addressed benefits from both network-centric and user-centric approaches and showed the better performance than other RAT technologies. However, the study considers solely throughput to assert the quality of video streaming whereas other parameters such as packet loss rate and video coding also impact significantly to video streaming services. In [48], a radio access network selection scheme which can facilitate seamless communications, joint resource management, and adaptive quality of service was proposed. The proposed algorithm, named Radio Access Optimization (RAO), simplifies the selection process and considers the increased resource utilization and the user satisfaction. Although differences of user satisfaction functions were defined in the study, it could be not well correlated to real user experience. In [86], an energy-aware utility function for user-centric network selection strategy and multimedia delivery in a heterogeneous wireless environment was proposed. Based on the mobile device type, application requirements, network conditions and user preferences, the proposed function selects the best value network which satisfies the user needs. Practically, there are decision factors that cannot be measured accurately, thus they cannot be combined in the utility functions. Moreover, different networks can have the same decision factors that lead to challenges in network selection schemes. A median-based network selection [90] was proposed to address these obstacles. The network selection problem was formulated as a tied partial rank aggregation problem based on delay, load, packet loss, cost per bytes, and allowed bandwidth. Nevertheless, the network dynamics have not been considered in this paper. The MADM group has several advantages such as consideration of multiple criteria and easy implementation. However, each solution is only suitable for a unique type of services. A detailed comparison of solutions in MADM group can be found in [50].

An alternative decision making in network selection is game theory-based approaches. Existing researches in this group can be broken into three types based on the players: users and users, networks and users, networks and networks. In [51], the authors studied on the problem of selecting the least congestion AP in WLANs. The goal is to determine the best trade-off between the bandwidth and the effort caused by the user when travelling to the new location. The problem was formulated as a non-cooperative game between selfish users where each user makes decision independently to maximize his/her utility function. The results showed that the stability of system is high when the number of arrivals and exits are evenly mixed. The Nash equilibrium was used to derive the stability of the distribution. The study, however, did not consider a specified application and the cost function is not correlated to the satisfaction of user. A Bayesian game was exploited to select the network in case of partial given-information [103]. Each user has incomplete information of other users' preferences. Bayesian Nash equilibrium can be obtained in incomplete information scenarios. In [56], an evolutionary game was used to solve the problem. Each user observes the average utility in the network. Then, if its utility is lower than the average level, it will attempt to increase its utility by requiring more resources.

In a non-cooperative game between users and network operators, both users and the network operators attempt maximizing their utility independently. While the users want to maximize their benefits from the services, the network operators favors in the profits. A recent research [16] concentrated on congestion control mechanism which models the competitive customer-provider scenario as non-cooperative two-player game. The proposed framework consists of two games: the admission control (AC) game and the load control (LC) game. In a cooperative game, users and operators cooperate to achieve mutual satisfaction. In [5], the network selection problem and model the user-networks interaction as a cooperative repeated game where the user has four strategies: Grim strategy dictating that user is participating in the relationship but if dissatisfied he will leave the relationship forever, Cheat-and-Leave strategy gives the user the option to cheat and then leave the network after cheating, Leave-and-Return strategy dictates that in case the network cheats the user leaves for only one period and returns in the subsequent interaction, and Adaptive Return strategy in which the user returning is dictated by the normalized weight of network's past degradation behavior. The network can choose between two strategies: Tit-for-Tat strategy which mimics the action of the user, and Cheat-and-Return strategy which mimics the action of the users, and Cheat-and-Return strategy which gives the option to the network to cheat and return accepting the user's punishment. The authors show that employing the proposed Adaptive Return strategy can motivate cooperation, resulting in higher pay-offs for both players.

The network selection problem can be modeled as a game between networks. In [55], the authors proposed a radio resource management framework based on non-cooperative game theory and composed of four main components: network level allocation, capacity reservation, admission control, and connection-level allocation. The bandwidth allocation problem is modeled as a non-cooperative game between different access networks and the solution is obtained from the Nash equilibrium showing that the total network utility is maximized. A bargaining game is utilized to model the capacity reservation problem. The connection level allocation modelled as a trading market game and Nash equilibrium is obtained as the solution of the game. However, this approach considered only the whole system performance. Contrarily, a cooperative approach between networks was introduced in [15]. A combination of utility and game-theory network selection scheme was proposed. Considering the scenario of mobile user located in an area with a number of available wireless networks, the authors propose the use of a cooperative game modelled between the candidate networks in order to achieve load balancing and reduce the hand-off occurrence frequency. The strategies in the game are the set of preference values for each network. The pay-off for each candidate network is a function of the current load intensity before accepting the call request, the predefined load intensity threshold and the penalty weight of the network. The goal of the game would be to maximize the pay-off function for each candidate network. The authors in [4] introduced the formation of a coalition between individual access networks which is done based on the available resources and the pay-offs allocation method. The authors proposed the use of two pay-offs: transferable pay-off, where a network can transfer a certain amount from its own pay-off to other members of the coalition, as long as its final pay-off is greater than zero; and non-transferable pay-off which are the pay-off obtained for each member's resource contribution. The authors studied the stability of coalitions for the two types of pay-off, using the core concept.

While the above approaches were built upon the QoS parameters, the approach in [62] was based on the QoE. In the proposed method, terminals of users play active roles in the networks. The AP broadcasts its MOS to every users. The MOS was calculated by monitoring the packet loss at AP and piggybacked on Beacon and Probe Response frames. Users can connect to several APs, and they can choose the one that provide the best MOS and this MOS is over the required MOS plus the threshold. Otherwise, if there is no AP can provide appropriate MOS, user might not connect to any AP. The mobility of users, nevertheless, was not mentioned in this paper. Moreover, the ping-pong phenomenon of the AP in the overlapping region was not addressed.

3.2.2.3 Scheduling

Scheduling is one of the popular methods to distribute resources in wireless access networks. By scheduling, each user is able to access a specific radio resource in a given period of time. The scheduling strategies in wireless networks can be divided into channel-unaware, channel-aware, and energy-aware types. Fig. 2 describes the classification of scheduling problems.

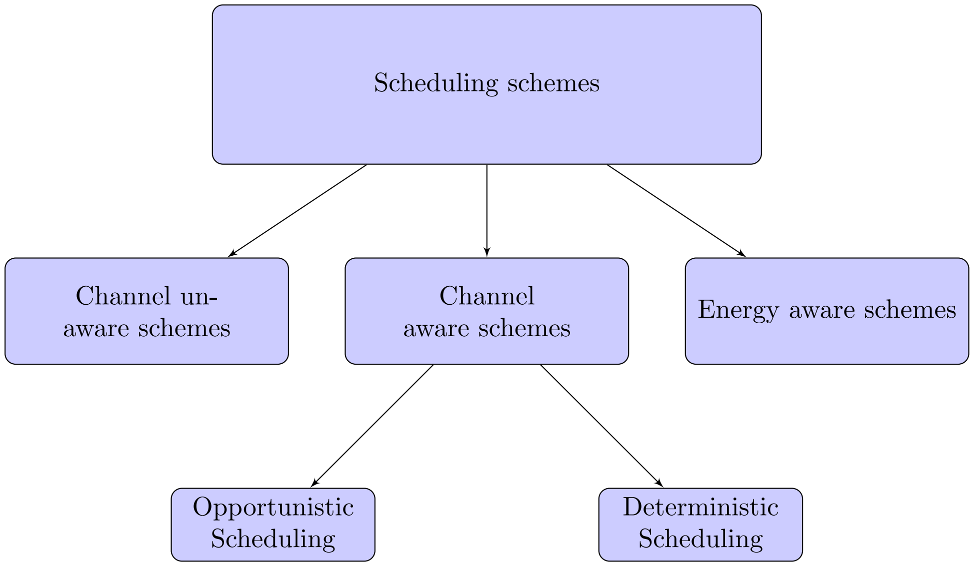

Figure 2: Classification of schemes in scheduling problems

Firstly, the channel unaware methods are based on the impractical assumptions such as time-invariant and error-free transmission. The resource requested by users can be served in First In First Out (FIFO) manner. However, this method is unfair and inefficient in the wireless networks which have different classes of users and services. Another method is the Round Robin (RR). RR offers a fair approach to deliver resource to users. Because of non-deterministic conditions of wireless environment, the throughput of each user can be quite different even though every user is assigned the same amount of time. To address the throughput fairness, the Blind Equal Throughput (BET) was proposed in [38]. The users that had lower throughput than other users will be allocated more frequently than others to achieve better throughput. In the networks with different priorities of users, the resource pre-emption method can be adopted to support QoS flows in which the high priority flows (QoS flows) can occupy the resource of lower priority (non-QoS) flows. An alternative way to embed the priority into the flows is weighted fair queuing where a weight is assigned to each flow corresponding to its service. However, the above methods cannot guarantee the delay that can be required by applications. The earliest deadline first (EDF) and largest weighted delay first (LWDF) are two methods defined for wired networks and operating systems [45, 83] that can be applied to the wireless networks.

The next group of scheduling approaches is channel-aware group which takes into account throughput, time, and frequency. The maximum throughput (MT) strategy aims to maximize the overall throughput of cells. This approach, however, can lead to an unfair resource distribution problem because the users with low quality of wireless channels can be assigned a short period to access the channel. Consequently, a combination of MT and BET, such as proportional fair (PF) scheduling, can be implemented to achieve both high utilization and fairness between users in cells. An optimization problem of assigning scheduling blocks and modulation and coding scheme (MCS) based on PF was proposed in [42]. Based on wireless channels feed-backs, an appropriate MCS and scheduling block will be assigned to the user in order to maximize the throughput in the networks with the PF manner or max-rate manner. However, the high computational complexity of integer linear programming of the proposed algorithm can lead to impractical implementation. A modified PF is Generalized Proportional Fair (GPF) [91] that considers the impact of instantaneous data rate and past achieved throughput. Consequently, the fairness of BET and the high utilization of MT can be compromised.

Beside using MT and BET strategies, game-based strategy is another promising solution because of its moderate complexity and high accuracy. In [95], the up-link scheduling in LTE problem was formulated as a cooperative bargaining problem, where user's goal is to maximize its own utility. A Nash bargaining solution was derived for the resource allocation problem under power transmission constraint. In the proposed game model, centralized scheduling model where the BS was assumed to enforce the cooperative solution was considered. However, the distributed scenarios where clients take part in giving scheduling decisions are expected in the real implementation. Furthermore, inter-cell interference was not mentioned in this paper. A combination of scheduling and power allocation can be considered in future studies. The authors in [8] considered a general wireless scenario where the inter-user interference is the dominating factor impacting to transmission performance. An extension of Nash bargaining for log-convex utility sets and PF on the log-SIR region were adopted to solve the problem.

Group	Paper	Inputs	Objectives
Deterministic Scheduling	[11, 42]	Scheduling blocks and MCS	maximize throughput
	[64]	Data rate	Fairness
	[21]	Channel condition, modulation and coding schemes, and power transmission	Average packet delay
	[95]	Resource blocks and transmission power	Maximize utility
	[8]	Location	Maximize utility
Opportunistic Scheduling	[57]	Location of users	Optimize spectral efficiency
	[94]	channel state	Fairness and throughput
	[96]	Interference and transmission power	Maximize utility
	[89]	Channel gain	Throughput

Table 2: Scheduling schemes

The opportunistic scheduling mechanisms were proposed in [57,89,94,96]. A distributed scheduling for uplink OFDMA was proposed in [94]. Based on their channel state on each sub-carrier, users are broken into three groups with different priority levels. The higher priority users are given the privilege of transmitting before others. They, also, have more chance to be assigned a sub-carrier than lower priority users. The results showed that the performance of the proposed scheduling mechanism leads to high throughput with reasonable fairness towards users that are far from the base station. One of the drawbacks of the paper is from assumption that users are close to each other in order to detect the beacon signal from another one. Moreover, because of various characteristic of wireless environment, the channel-state indicator, which is derived from pilot signal, can be valid in a short period. That, nevertheless, was the key factor to decide the priority of users, then causing blockage in long period of low priority users. In [96], two modified PF scheduling schemes named proportional fairness in frequency (PFF) and proportional fairness in time and frequency (PFTF) combined with probabilistic interference avoidance scheme for multi-cell OFDMA networks was proposed. The BS measures the interference on each sub-carrier and makes an opportunistic shut-down decision based on the level of interference. By preventing transmission on high interference channel actively, the proposed scheme led to better results in average cell throughput and cell energy efficiency. However, this scheme can lead to low utilization of frequency resources. On multicast scheduling problems, existing multicast schemes transmit data at a fixed rate that can accommodate the farthest located users in a cell. However, users belonging to the same multicast group can have widely different channel conditions, thus existing scheme are too conservative by limiting the throughput of users close to the base station. The proposed scheme in [92] can adapt to dynamic channel states with two scheduling strategies: Inter-group Proportional Fairness (IPF) and Multicast Proportional Fairness (MPF).

In [89], a distributed opportunistic access schemes for single-carrier and OFDMA systems was proposed. By designing a novel back-off scheme utilizing the channel information, the multi-user diversity gain can be achieved. That study considered both homogeneous and heterogeneous networks. While the back off design criterion is to maximize the sum throughput of all users in homogeneous systems, the back-off design, in heterogeneous systems, is performed for each user type separately as in a homogeneous system. For OFDMA systems, two distributed opportunistic access schemes analogous to those designed for single-carrier systems to utilize multiuser and multichannel diversity gains was proposed. Users contend on all sub-channels in contends all sub-channels (CAC) scheme and on the β strongest sub-channels (CSC) scheme. CAC outperforms CSC since more users can introduce more diversity gain. The proposed scheme reduces overhead and achieves a better spectral efficiency. In [57], the author analyzed the spectral efficiency performance of opportunistic scheduling and spectrum reuse techniques for relay-based cellular networks in downlink mode. The study provided insights on the potential performance enhancements from multi-hop routing and spectrum reuse policies in the presence of multi-user diversity gains from opportunistic scheduling and helps to identify a number of key design trade-offs associated with resource allocation and interference management in relay-based cellular networks. Significant spectral efficiency gains can be achieved through spectrum reuse by the BS and relay terminals (RTs) in the same cell (and sector) favoring simultaneous transmission protocols over orthogonal transmission protocols, even in the absence of scheduling coordination between the BSs and RTs to control the resulting intra-cell interference. The differentiated services, however, was not addressed in this research.

A group of channel-aware strategies was designed for enhancing QoS. A joint time and frequency domain strategy was proposed to guarantee end-to-end delay in [53]. First, in time domain, users with unsatisfied bit-rate flows will be arranged into high priority set, while other users will be arranged into low priority set. The high priority set uses BET algorithm and the low priority set exploits PF algorithm. Next, in the frequency domain, the proportional fair scheduler assigns available resource to users. Other similar approaches can be found in [81, 97]. For guaranteeing delay, the modified largest weighted delay first provides a delivery scheme that can guarantee bounded packet [3]. In [67], non-realtime and realtime flows are treated differently by Exponential/PF (EXP/PF). A two-level framework was proposed in [63]. In [35], a cooperative game-theory scheme performs resource sharing combining the EXP rule with a virtual token mechanism. The scheme works in two-phases. In the first stage, available resources are distributed to different groups of flows. Second, EXP rule combined to a virtual token mechanism, in order to meet bounded delay requirements and to guarantee minimum throughput. A less complex scheme, Delay-Prioritized Scheduler (DPS) was proposed in [71]. In specific applications such as VoIP, a solution for optimizing network performance with VoIP traffic and best-effort flows was presented in [17, 20, 54, 65].

Besides, scheduling can be exploited to enhance energy efficiency in the wireless networks. In LTE networks, enhancing energy efficiency solutions can be deployed at both eNodeB and user equipments (UEs). The authors in [22, 49] considered relationship between traffic, energy consumption, and environment impacts which showed negative results. Therefore, the green networking have been receiving concerns from both network operators and researchers [26]. Another research confirmed that high data rate transmission can save energy of eNBs by switching them into sleep mode frequently [69].An alternative approach, named Bandwidth Expansion Mode, can be used to enhance energy efficiency of eNB in the low traffic scenarios [88]. Moreover, the energy efficiency can be improved when the resource allocation is implemented in time domain [24].

3.2.2.4 Bandwidth and channel allocations

In this part, recent bandwidth allocation schemes in both homogeneous and heterogeneous networks are discussed. In [93], the author suggested a resource allocation based on maximizing the weighted sum rate under a total power constraint. This approach does not guarantee fairness, since the users with the best channels get most of the resources. In homogeneous network, a novel allocation sub-channels to users in OFDMA networks were proposed in [70]. The problem were formulated as a cooperative game in which a pair of users will negotiate with each other to achieve an acceptable MOS level. The MOS was calculated based on packet error rate and bandwidth by adopting equations in [73]. Although the efficiency and fairness in the networks was addressed, the reaction of the proposed scheme to congestion was not studied. Moreover, using the objective approach to measure MOS can be inaccurate. The aforementioned scheme was built up on the assumption that QoE model and the type of traffic are known in advance. However, in incomplete information scenarios, both QoE models and type of traffic can be unknown.

To address incomplete information scenarios, the authors in [101] proposed two algorithms based on stochastic analysis. The paper also studied on the unkown playout time. The authors proposed an online-test optimization strategy which spends a period of time at the beginning of streaming to determine QoE model. Then, it will optimize the total MOS of all users during remaining time. The longer time is used for testing, the shorter time is used for optimizing MOS. A new metric, named loss function, was introduced to measure the performance deterioration caused by mismatched QoE model. Consequently, the objective is to find a resource allocation strategy to minimize the supermum value of loss function. The first discussed scenario was that QoE model was given but the parameters was unknown. The author proposed dynamic resource allocation strategy (DRAS) to solve the problem in this scenario. The DRAS consists of 2 phases: test and optimization. In the first phase, the proposed scheme will learn the QoE model of users by testing different allocation resources R_n in test interval t_n. Then, in the second phase, DRAS will seek the optimal resource solution. The second scenario was introduced with the assumption of unknown QoE model and playout time. The authors proposed Blind-DRAS(BDRAS) to address the problem. The test domain is larger than DRAS then 2 objectives: the test time must be long enough to have an accurate QoE, and reducing the test time will not lead to reducing accuracy significantly. Through mathematical analysis, the paper determined the upper bound of the loss in case of DRAS and BDRAS.

Nowadays, mobile equipments can be equipped with two or more radio interfaces. To overcome the bandwidth bottleneck, multi-homing is a promising solution. Multi-homing users can connect to different networks simultaneously so that the total bandwidth can be satisfied. In [32], the author proposed two algorithms to allocate bandwidth in heterogeneous networks containing MTs with single-network and multi-homing services. The first one is centralized optimal resource allocation (CORA). Resource management is controlled by a central entity which can be a device of network operator. The second one is decentralized sub-optimal resource allocation (DSRA) in which MTs play active roles in the resource allocation operation whether by selecting the best available wireless network for single-network services or by determining

Wireless Networks	Paper	Decision	Single network	Multi-homing	Serives
Cellular networks	[93]	Data rate	X		Not mentioned
	[70]	Explicit QoE-based functions	X		Audio, Video, Best Effort
	[101]	Implicit QoE-based functions	X		Multimedia
Cellular networks and WLANs	[32]	Utility function based (cost and bandwidth)	X	X	Call
	[33]	Utility function based (cost and bandwidth)		X	CBR, VBR
Cognitive radio networks	[37]	Continuity of channels	X		Multimedia

Table 3: Bandwidth allocation schemes

the required bandwidth share from each available network for multi-homing services. However, heterogeneous services and the cost of changing networks were not discussed in this paper. As a result, the paper [33] proposed a distributed algorithm so that each network/bs can perform its own resource allocation to support the MTs according to their services classes for multi-homing in heterogeneous wireless access networks. Each user is associated to a home network. The required bandwidth can be provided through multiple radio interfaces. The utility function was derived from the bandwidth and the cost of the allocated bandwidth. The problem was formulated as a mixed integer linear programming that aims to optimize the total utility function in a given area under constraints of bandwidth of BS/APs. A dual decomposition was adopted to form a distributed solution.

Cognitive radio is one of promising solutions for higher radio bandwidth utilization and better quality of wireless applications [75]. A novel channel allocation scheme for the QoE-driven multimedia transmission over the cognitive radio networks was proposed in [37]. The approach incorporates the perception multimedia quality of end users into the channel allocation design for the cognitive radio networks. The analytical and simulation results showed the proposed channel allocation scheme can significantly improve the multimedia QoE performance of the priority-based secondary users with respect to the MOS, PSNR quality, blocking probability, dropping probability and throughput. However, the mobility of nodes was not mentioned.

3.2.2.5 Multiple objectives resource management solutions

In fact, a better resource management strategy can be achieved when multiple problems are taken into account simultaneously. A novel resource manage scheme for single-network services that considers both resource allocation and user association in heterogeneous cellular networks (HeteNets) was proposed in [23]. A HeteNet consists of several pico-cells coexisting in the same region of a macro-cell as described in Fig. 3. Each pico-cell is managed by a pico-BS while a macro-cell is managed by a macro-BS. Three channel allocation schemes in HeteNets were discussed: co-channel deployment (CCD), orthogonal deployment (OD), and partially shared deployment (PSD). In OD, all pico-BSs share K sub-channels while other sub-channels are utilized by the macro BS. Meanwhile, in the CCD, all BSs in the region (both pico BSs and the macro BS) share all sub-channels. The last one is PSD in which all BSs share K sub-channels and the macro BS use others. The main objective is to assign throughput fairly to all users in the networks. In case of multimedia services, because the throughput is not well correlated to user' experience, it can be replaced by MOS. Recently, thanks to development in integrated circuit, mobile devices can be equipped with two or more radio interfaces. As a result, the selection of an appropriate radio interface or a set of radio interfaces for a service is necessary. A radio interface and channel selection scheme was mentioned in [18]. An optimal solution for parallel multi-radio access (MRA) scheme to maximize system capacity was introduced. The results provided useful and insightful information in designing efficient MRA systems. However, the high complexity of algorithm can lead to obstacles in practical implementation.

A radio-resource and network-selection scheme in heterogeneous wireless networks was proposed in [60]. Based on economic model, radio resource was allocated for heterogeneous networks of CDMA networks and WLANs. Because larger bandwidth can increase network utility but users have to pay more to the network service provider, a joint metric of network utility and the cost was proposed. The authors in [60], hence, studied on sharing up-link bandwidth between CDMA and WLANs. The inter-networking between cellular and WLANs can either be a tightly coupled case or a loosely

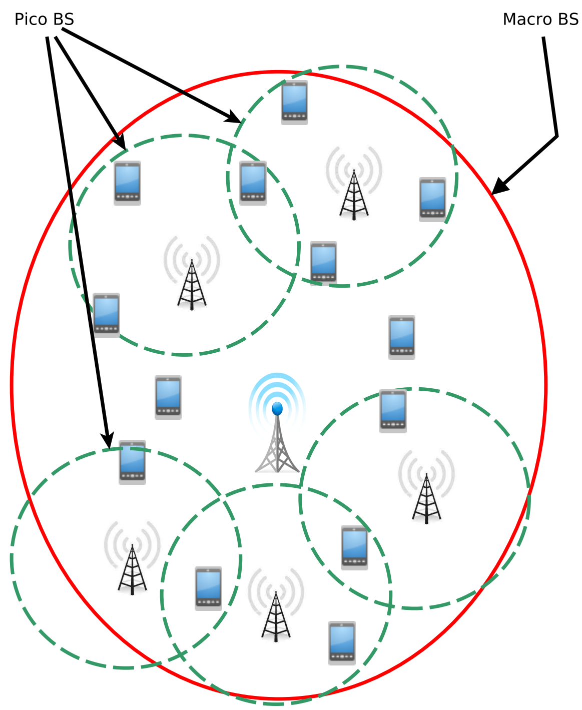

Figure 3: Heterogeneous cellular networks topology

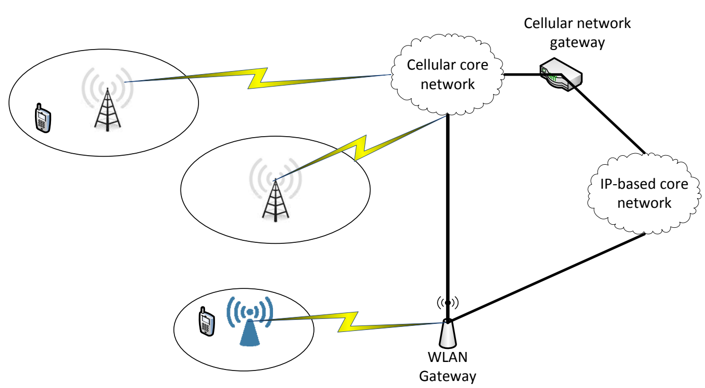

Figure 4: Cellular and WLAN inter-operation

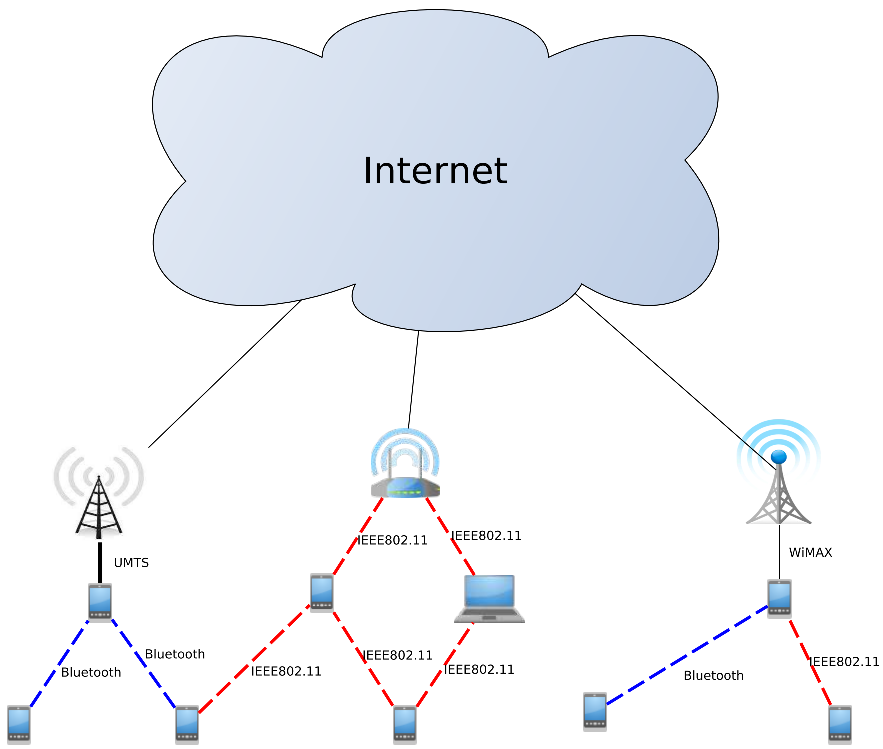

Figure 5: Multihop multipath heterogeneous connectivity

coupled case, as shown in Fig. 4. In the tightly coupled integration, the access point (AP) of the WLAN directly connects to the cellular core network, then they have to share the entities of authentication, mobility management, and radio-resource allocation. As a result, the WLAN has to exchange control messages with the cellular core network. This approach imposes a higher processing load to the cellular core network but leads to shorter hand-off latency and more flexible QoS management. In the loosely coupled integration, the WLAN requires no direct links to the 3G cellular network, and less control overhead is needed for internet-working. However, the hand-off latency is high and packets may be dropped during the hand-off period.

3.2.3 Network Layer

Network layer is responsible for relaying packets from the source to the destination. In network layer, resource management schemes focus on how to determine the optimal end-to-end paths. A scheme for assigning relay nodes to enhance throughput was proposed in [77]. The objective is to optimize max-min data rate in the networks by selecting the set of relay nodes. The problem was formulated as mixed integer linear problem. To address computational complexity, a combination of Branch and Bound - Cutting Plane (BB-CP) and Feasible Solution Construction (FCS) was exploited to achieve solution timely. However, the proposed algorithm requires a central entity which is responsible for calculating the near-optimal set of relay nodes and announcing to every node in the networks. In [79], a resource allocation in network layer for surveillance camera application was proposed. A monitoring system including multiple cameras deployed over flexible and low-cost multi-hop wireless networks was considered. Three approaches were proposed including a centralized optimization, a decentralized game-theoretic, and a distributed greedy ones. Performances of proposed approaches were compared through four metrics: total video quality, computational complexity, and control information overhead, timely adaptation to the network and source variation. The video quality, nevertheless, was not taken into account for determining the path.

A multi-hop multipath heterogeneous connectivity (MMHC) routing algorithm proposed in [6]. Three characteristics including mobility of intermediate nodes, throughput of links, energy of intermediate nodes were considered. Fig. 5 describes an example of practical scenario of multi-hop and multipath heterogeneous connectivity. The study considered

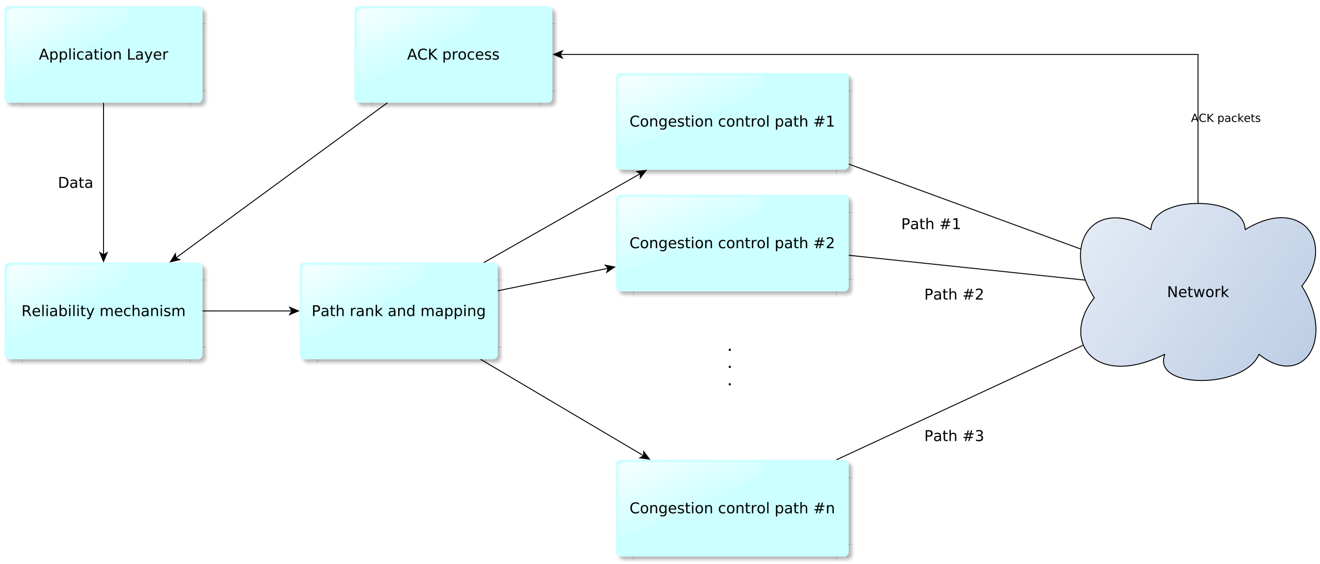

Figure 6: MPLOT design

routing with different objectives: shortest path, maximum throughput, energy fairness based on average path energy, and mixed strategy. The proposed algorithm can be extended by adopting the QoE to select the path.

In [80], a multi-route distance vector routing (MDVR) where the routing table was placed between the routing and link layer was proposed. The transmission cost was derived from the link state. Consequently, each node in the network attempts to reduce the total transmission cost by finding the optimal traffic load distribution through different paths. The transmission cost consists of two parts: the link cost and the multi-route cost. Contrast to the link cost, the multi-route cost is unable to measure accurately in real-time. Moreover, MDVR takes into account only the traffic load which is not well correlated to user experience.

3.3 Cross-layer resource management existing solutions

An effective utilization of available bandwidth in the heterogeneous networks with lossy links, named multipath loss-tolerant (MPLOT), was proposed in [78]. In the proposed scheme, the congestion and reliability are controlled separately. The source will estimate the packet loss and add redundancy to create a proactive block. The length of proactive block will be $B = F + K$, where F is the number of packets received from the upper layer and K is the number of packets created by block erasure coding. Therefore, at the destination, data can be recovered if at most K packets of proactive block are corrupted in transit. If the number of corrupted packets is K' larger than K, the destination will inform the source by SACK. Then, the source will create $K' - K$ reactive FEC packets. Fig. 6 describes the operation of MPLOT algorithm.

The authors in [30] presented an optimization-based formulation for scheduling and resource allocation in the uplink OFDMA network. Compared to the downlink, the uplink has more computational challenges due to the power constraints of users' devices. A high complexity optimal algorithm and a family of low complexity heuristics were proposed. The proposed algorithms can also be applied to downlink transmissions in multi-cell OFDM systems.

The authors in [82] studied on admission control and scheduling in multi-hop networks. The revenue of each user was determined by the assigned data rate and the fee that user has to pay. The proposed algorithm can differentiate the flows in the networks, so the required data rate can be allocated to appropriate flows based on their services. The flows with higher priority can have the lower end-to-end delay. However, the revenue based on the data rate can be inaccurate in case of multimedia services.

The author in [43] proposed an algorithm that combines scalable video coding (SVC) and adaptive modulation and coding schemes (MCS) in wireless multicast networks with heterogeneous devices. In this paper, an appropriate MCS is selected for each video layer, then optimizing resource allocation among video sessions. However, the above problem is a NP-hard problem and is impossible to solve in real-time because of its high computational complexity. Therefore, a two-step decomposition technique [46] was adopted to achieve dynamic programming solution with pseudo-polynomial time complexity.

A centralized admission control mechanism based on the graph theory was proposed in [44]. The authors used a contention graph to formulate the contention in multi-hop networks. Moreover, a mathematical estimation capacity of each maximal clique in the contention graph was shown. When the aggregated traffic load is less than the estimated network capacity, a new session can be admitted. The main drawback of the proposed scheme, nevertheless, is high complexity. An alternative combination of call admission control and routing was proposed in [47]. Based on local information, the residual bandwidth of the path can be estimated. Moreover, it can be embedded in existing routing protocols. In [39], a Fuzzy QoS admission control protocol was proposed. The control of traffic regulation rate and congestion control of multimedia applications were improved. By adopting explicit rate congestion notification, the source nodes are more responsive to sudden changes. Nevertheless, the route failure was not studied in the research. In [12], a QoS-support distributed admission control for MANET (DACME) was proposed. In DACME, while the source node performs path probing to obtain QoS measurement from different paths, the destination node give source feedback about path conditions, avoiding sending information over path possibly unavailable. DACME can be compatible with IEEE 802.11 prioritized medium access. In [2], a distributed algorithms for joint admission control, rate, and power allocation aiming at maximizing the throughput was proposed. The admission decision based on statistical information of the channel and buffer states of communication pairs and on the exact knowledge of them. The mobility scenarios were not considered in that study.

4 Conclusion and Open Issues

The objective of this layer-based survey is to provide a brief summary of existing resource management solutions on each of the network architecture. The first part of this survey presented the few existing algorithms operating in upper layers. These algorithms focus on managing resources such as cache memory and congestion window. The existing solutions in the second group manage the resource in lower layers with major challenges in resource management at data-link layer. The main problems at this layer are admission control, network selection, packet scheduling, and bandwidth or channel allocations whereas the one in network-layer is routing. There are also joint problems with the goal to enhance the performance of networks by solving multiple problems simultaneously. Finally, the third group of resource management solutions is dedicated to cross-layer algorithms that interfere on multiple layers in order to achieve better performance.

As it can be seen in the survey, although a number of studies have been conducted to manage resources in wireless networks, most of them are based on QoS metrics to control resources and evaluate performance. However, it has be demonstrated that the QoS metrics may not correlate well with the experience of users. As a result, QoE-based resource management schemes attract interest from both researchers and engineers. This first version (version 1.0) of the survey presented all current existing QoS-based and QoE based solutions for each layer of the network architecture. Nevertheless, the heterogeneous wireless scenarios and cooperative networks bring more challenges to the resource management studies. This survey will be udpated peridocally by including new solutions to those challenges and by taking into account comments of readers as well. In the following, we present some of the topics that are remaining for investigation.

- **QoE-based resource management in heterogeneous networks and services**

  The emergence of QoE concept has changed the way of evaluating the quality of multimedia services. Moreover, the QoE concept can be extended to other non-multimedia applications such as web browsing and file transferring. Although some studies have been done in QoE-based resource management in homogeneous networks, it is not the case in heterogeneous networks. Consequently, the research on mixed streams over heterogeneous wireless networks is necessary in order to figure out the optimal resource management in practical scenarios.

- **Resource management in cooperative distributed networks**

  In the future, ubiquitous appearances of mobile devices will allow forming cooperative networks where devices can cooperate to relay a packet from the source to the destination. Adjacent nodes can cooperate to arrange their transmission time-slots and channels in order to optimize the network performance. Also, the spatial diversity can be exploited in cooperative networks through MIMO antenna systems. For instance, the smart antenna can be combined with MIMO to increase the transmission gain. Consequently, the data rate can be improved. However, without having an effective management scheme, the performance can be deteriorated significantly by interference. Furthermore, in the application layer, the capacity of cache memory can impact strongly the performance of multimedia streaming but the storage of cache is limited. As a consequence, the copies of multimedia files should be distributed over multiple cache servers. A cross-layer of distributed management cache can hence be a promising solution.

- **Resource management in wireless multimedia sensor networks**

  Beside conventional multimedia networks such as UMTS, WLAN, and WiMAX, the demand of transmitting video and voice through the wireless sensor networks (WSNs) is present. By adopting multimedia transmission through WSNs, the level of collected information can be upgraded and can be applied into environment monitoring, intrusion surveillance, smart parking, traffic control, smart cities and others [34]. This type of networks is called wireless multimedia sensor networks (WMSNs). However, there are several obstacles in WMSNs: bandwidth, resource limitation (energy and hardware), and communication range. Consequently, an optimization with multiple objectives and constraints is expected in WMSNs. Moreover, the video transmission over wireless networked robotics (WNR) is promising with the real demand of applications [7]. Appearances of new services over wireless sensor networks urge the extension of QoE concept into this technology. Although, the QoE was built for multimedia services, it can be extended to other services as well, for example, the e-health or smart-grid network.

References

[1] A. Abdrabou and Weihua Zhuang. Stochastic delay guarantees and statistical call admission control for IEEE 802.11 single-hop ad hoc networks. *IEEE Transactions on Wireless Communications*, 7(10):3972–3981, 2008.

[2] S. Akbarzadeh, L. Cottatellucci, and C. Bonnet. Low complexity cross-layer design for dense interference networks. In *International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks*, pages 1–10, 2009.

[3] M. Andrews, K. Kumaran, K. Ramanan, A. Stolyar, P. Whiting, and R. Vijayakumar. Providing quality of service over a shared wireless link. *IEEE Communications Magazine*, 39(2):150–154, 2001.

[4] Josephina Antoniou, Ioannis Koukoutsidis, Eva Jaho, Andreas Pitsillides, and Ioannis Stavrakakis. Access network synthesis game in next generation networks. *Computer Networks*, 53(15):2716 – 2726, 2009.

[5] Josephina Antoniou, Vicky Papadopoulou, Vasos Vassiliou, and Andreas Pitsillides. Cooperative usernetwork interactions in next generation communication networks. *Computer Networks*, 54(13):2239 – 2255, 2010.

[6] P. Bellavista, A. Corradi, and C. Giannelli. Differentiated management strategies for multi-hop multi-path heterogeneous connectivity in mobile environments. *IEEE Transactions on Network and Service Management*, 8(3):190–204, 2011.

[7] Bego Blanco, Fidel Liberal, and Ianire Taboada. Suitability of ad hoc routing in WNR: Performance evaluation and case studies. *Ad Hoc Networks*, 11(3):1165 – 1177, 2013.

[8] H. Boche and M. Schubert. Nash bargaining and proportional fairness for wireless systems. *IEEE/ACM Transactions on Networking*, 17(5):1453–1466, 2009.

[9] P. Brooks and B. Hestnes. User measures of quality of experience: why being objective and quantitative is important. *IEEE Network*, 24(2):8–13, 2010.

[10] J. Buhler and G. Wunder. An optimization framework for heterogeneous access management. In *IEEE Wireless Communications and Networking Conference*, pages 1–6, 2009.

[11] F.D. Calabrese, C. Rosa, K.I. Pedersen, and P.E. Mogensen. Performance of proportional fair frequency and time domain scheduling in lte uplink. In *European Wireless Conference*, pages 271–275, 2009.

[12] C.T. Calafate, M.P. Malumbres, J. Oliver, J.-C. Cano, and P. Manzoni. QoS support in MANETs: a modular architecture based on the ieee 802.11e technology. *IEEE Transactions on Circuits and Systems for Video Technology*, 19(5):678–692, 2009.

[13] I. Chamodrakas, I. Leftheriotis, and D. Martakos. In-depth analysis and simulation study of an innovative fuzzy approach for ranking alternatives in multiple attribute decision making problems based on TOPSIS. *Applied Soft Computing*, 11(1):900 – 907, 2011.

[14] Ioannis Chamodrakas and Drakoulis Martakos. A utility-based fuzzy TOPSIS method for energy efficient network selection in heterogeneous wireless networks. *Applied Soft Computing*, 12(7):1929 – 1938, 2012.

[15] Chung-Ju Chang, Tsung-Li Tsai, and Yung-Han Chen. Utility and game-theory based network selection scheme in heterogeneous wireless networks. In *IEEE Wireless Communications and Networking Conference*, pages 1–5, 2009.

[16] DimitrisE. Charilas, AthanasiosD. Panagopoulos, Panagiotis Vlacheas, OuraniaI. Markaki, and Philip Constantinou. Congestion avoidance control through non-cooperative games between customers and service providers. In Fabrizio Granelli, Charalabos Skianis, Periklis Chatzimisios, Yang Xiao, and Simone Redana, editors, *Mobile Lightweight Wireless Systems*, volume 13 of *Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering*, pages 53–62. Springer Berlin Heidelberg, 2009.

[17] Sunggu Choi, Kyungkoo Jun, Yeonseung Shin, Seokhoon Kang, and Byoungjo Choi. MAC scheduling scheme for VoIP traffic service in 3G LTE. In *IEEE Vehicular Technology Conference*, pages 1441–1445, 2007.

[18] Yonghoon Choi, Hoon Kim, Sang wook Han, and Youngnam Han. Joint resource allocation for parallel multi-radio access in heterogeneous wireless networks. *IEEE Transactions on Wireless Communications*, 9(11):3324–3329, 2010.

[19] M. El Helou, M. Ibrahim, S. Lahoud, and K. Khawam. Radio access selection approaches in heterogeneous wireless networks. In *IEEE 9th International Conference on Wireless and Mobile Computing, Networking and Communications*, pages 521–528, 2013.

[20] Yong Fan, P. Lunden, M. Kuusela, and M. Valkama. Efficient semi-persistent scheduling for VoIP on EUTRA downlink. In *IEEE Vehicular Technology Conference*, pages 1–5, 2008.

[21] H. Fattah and H. Alnuweiri. A cross-layer design for dynamic resource block allocation in 3G Long Term Evolution system. In *IEEE International Conference on Mobile Adhoc and Sensor Systems*, pages 929–934, 2009.

[22] A. Fehske, G. Fettweis, J. Malmodin, and G. Biczok. The global footprint of mobile communications: The ecological and economic perspective. *IEEE Communications Magazine*, 49(8):55–62, 2011.

[23] D. Fooladivanda and C. Rosenberg. Joint resource allocation and user association for heterogeneous wireless cellular networks. *IEEE Transactions on Wireless Communications*, 12(1):248–257, 2013.

[24] P. Frenger, P. Moberg, J. Malmodin, Y. Jading, and I. Godor. Reducing energy consumption in LTE with cell DTX. In *IEEE Vehicular Technology Conference (VTC Spring)*, pages 1–5, 2011.

[25] O. Habachi, Yusuo Hu, M. van der Schaar, Y. Hayel, and Feng Wu. MOS-based congestion control for conversational services in wireless environments. *IEEE Journal on Selected Areas in Communications*, 30(7):1225–1236, 2012.

[26] Z. Hasan, H. Boostanimehr, and V.K. Bhargava. Green cellular networks: A survey, some research issues and challenges. *IEEE Communications Surveys Tutorials*, 13(4):524–540, 2011.

[27] J.A. Hassan, M. Hassan, S.K. Das, and A. Ramer. Managing user irritation in wireless VoIP using noncooperative games. In *IEEE Wireless Communications and Networking Conference (WCNC)*, pages 1–6, 2010.

[28] J.A. Hassan, M. Hassan, S.K. Das, and A. Ramer. Managing quality of experience for wireless VOIP using noncooperative games. *IEEE Journal on Selected Areas in Communications*, 30(7):1193–1204, 2012.

[29] Ching-Ling Huang and Wanjiun Liao. Throughput and delay performance of IEEE 802.11e enhanced distributed channel access (EDCA) under saturation condition. *IEEE Transactions on Wireless Communications*, 6(1):136–145, 2007.

[30] Jianwei Huang, V.G. Subramanian, R. Agrawal, and R. Berry. Joint scheduling and resource allocation in uplink OFDM systems for broadband wireless access networks. *IEEE Journal on Selected Areas in Communications*, 27(2):226–234, 2009.

[31] E. Ibarrola, F. Liberal, I. Taboada, and R. Ortega. Web QoE evaluation in multi-agent networks: Validation of ITU-T G.1030. In *International Conference on Autonomic and Autonomous Systems*, pages 289–294, 2009.

[32] M. Ismail and Weihua Zhuang. Decentralized radio resource allocation for single-network and multi-homing services in cooperative heterogeneous wireless access medium. *IEEE Transactions on Wireless Communications*, 11(11):4085–4095, 2012.

[33] M. Ismail and Weihua Zhuang. A distributed multi-service resource allocation algorithm in heterogeneous wireless access medium. *IEEE Journal on Selected Areas in Communications*, 30(2):425–432, 2012.

[34] Almalkawi IT, Zapata MG, Al-Karaki JN, and Morillo-Pozo J. Wireless multimedia sensor networks: current trends and future directions. *Sensors*, 10:6662–6717, 2010.

[35] M. Iturralde, Anne Wei, T. Ali Yahiya, and A. L Beylot. Resource allocation for real time services using cooperative game theory and a virtual token mechanism in lte networks. In *IEEE Consumer Communications and Networking Conference*, pages 879–883, 2012.

[36] Vivek Jain, A. Gupta, and D.P. Agrawal. On-demand medium access in multihop wireless networks with multiple beam smart antennas. *IEEE Transactions on Parallel and Distributed Systems*, 19(4):489–502, 2008.

[37] Tigang Jiang, Honggang 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*, 30(7):1215–1224, 2012.

[38] P. Kela, J. Puttonen, N. Kolehmainen, T. Ristaniemi, T. Henttonen, and Martti Moisio. Dynamic packet scheduling performance in UTRA Long Term Evolution downlink. In *International Symposium on Wireless Pervasive Computing*, pages 308–313, 2008.

[39] Lyes Khoukhi and Soumaya Cherkaoui. Intelligent QoS management for multimedia services support in wireless mobile ad hoc networks. *Computer Networks*, 54(10):1692 – 1706, 2010.

[40] Duk Kyung Kim, D. Griffith, and N. Golmie. A new call admission control scheme for heterogeneous wireless networks. *IEEE Transactions on Wireless Communications*, 9(10):3000–3005, 2010.

[41] Hongseok Kim, G. de Veciana, Xiangying Yang, and M. Venkatachalam. Distributed α -optimal user association and cell load balancing in wireless networks. *IEEE/ACM Transactions on Networking*, 20(1):177–190, 2012.

[42] R. Kwan, C. Leung, and Jie Zhang. Proportional fair multiuser scheduling in LTE. *IEEE Signal Processing Letters*, 16(6):461–464, 2009.

[43] Peilong Li, Honghai Zhang, Baohua Zhao, and S. Rangarajan. Scalable video multicast with adaptive modulation and coding in broadband wireless data systems. *IEEE/ACM Transactions on Networking*, 20(1):57–68, 2012.

[44] Yuxia Lin and Vincent W.S. Wong. An admission control algorithm for multi-hop 802.11e-based WLANs. *Computer Communications*, 31(14):3510 – 3520, 2008.

[45] D. Liu and Y.-H. Lee. An efficient scheduling discipline for packet switching networks using earliest deadline first round robin. In *International Conference on Computer Communications and Networks*, pages 5–10, 2003.

[46] Jiangchuan Liu, Bo Li, Y.T. Hou, and I. Chlamtac. Dynamic layering and bandwidth allocation for multisession video broadcasting with general utility functions. In *INFOCOM 2003*, volume 1, pages 630–640 vol.1, 2003.

[47] Tehuang Liu, Wanjiun Liao, and Jeng-Farn Lee. Distributed contention-aware call admission control for IEEE 802.11 multi-radio multi-rate multi-channel wireless mesh networks. *Mob. Netw. Appl.*, 14(2):134–142, April 2009.

[48] Weizhi Luo and E. Bodanese. Radio access network selection in a heterogeneous communication environment. In *IEEE Wireless Communications and Networking Conference*, pages 1–6, 2009.

[49] V. Mancuso and S. Alouf. Reducing costs and pollution in cellular networks. *IEEE Communications Magazine*, 49(8):63–71, 2011.

[50] J.D. Martinez-Morales, U. Pineda-Rico, and E. Stevens-Navarro. Performance comparison between MADM algorithms for vertical handoff in 4G networks. In *Electrical Engineering Computing Science and Automatic Control (CCE), 2010 7th International Conference on*, pages 309–314, 2010.

[51] Kimaya Mittal, Elizabeth M. Belding, and Subhash Suri. A game-theoretic analysis of wireless access point selection by mobile users. *Computer Communications*, 31(10):2049 – 2062, 2008.

[52] S. Mohamed and G. Rubino. A study of real-time packet video quality using random neural networks. *IEEE Transactions on Circuits and Systems for Video Technology*, 12(12):1071–1083, 2002.

[53] G. Monghal, K.I. Pedersen, I.Z. Kovacs, and P.E. Mogensen. QoS oriented time and frequency domain packet schedulers for the UTRAN long term evolution. In *IEEE Vehicular Technology Conference*, pages 2532–2536, 2008.

[54] Guillaume Monghal, D. Laselva, Per-Henrik Michaelsen, and J. Wigard. Dynamic packet scheduling for traffic mixes of best effort and VoIP users in E-UTRAN downlink. In *IEEE Vehicular Technology Conference*, pages 1–5, 2010.

[55] D. Niyato and E. Hossain. A noncooperative game-theoretic framework for radio resource management in 4G heterogeneous wireless access networks. *IEEE Transactions on Mobile Computing*, 7(3):332–345, 2008.

[56] D. Niyato and E. Hossain. Dynamics of network selection in heterogeneous wireless networks: An evolutionary game approach. *IEEE Transactions on Vehicular Technology*, 58(4):2008–2017, 2009.

[57] O. Oyman. Opportunistic scheduling and spectrum reuse in relay-based cellular networks. *IEEE Transactions on Wireless Communications*, 9(3):1074–1085, 2010.

[58] A. ParandehGheibi, M. Medard, A. Ozdaglar, and S. Shakkottai. Avoiding interruptions - a QoE reliability function for streaming media applications. *IEEE Journal on Selected Areas in Communications*, 29(5):1064–1074, 2011.

[59] Daan Pareit, Bart Lannoo, Ingrid Moerman, and Piet Demeester. The history of WiMAX: A complete survey of the evolution in certification and standardization for IEEE 802.16 and WiMAX. *IEEE Communications Surveys Tutorials*, 14(4):1183–1211, 2012.

[60] Xuebing Pei, Tao Jiang, Daiming Qu, Guangxi Zhu, and Jian Liu. Radio-resource management and access-control mechanism based on a novel economic model in heterogeneous wireless networks. *IEEE Transactions on Vehicular Technology*, 59(6):3047–3056, 2010.

[61] K. Piamrat, A. Ksentini, C. Viho, and J. Bonnin. QoE-aware admission control for multimedia applications in IEEE 802.11 wireless networks. In *IEEE Vehicular Technology Conference*, pages 1–5, 2008.

[62] K. Piamrat, A. Ksentini, C. Viho, and J. Bonnin. QoE-based network selection for multimedia users in IEEE 802.11 wireless networks. In *IEEE Conference on Local Computer Networks*, pages 388–394, 2008.

[63] G. Piro, L.A. Grieco, G. Boggia, R. Fortuna, and P. Camarda. Two-level downlink scheduling for real-time multimedia services in LTE networks. *IEEE Transactions on Multimedia*, 13(5):1052–1065, 2011.

[64] M. Proebster, C.M. Mueller, and H. Bakker. Adaptive fairness control for a proportional fair LTE scheduler. In *IEEE International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC)*, pages 1504–1509, 2010.

[65] J. Puttonen, T. Henttonen, N. Kolehmainen, K. Aschan, Martti Moisio, and P. Kela. Voice-Over-IP performance in UTRA Long Term Evolution downlink. In *IEEE Vehicular Technology Conference*, pages 2502–2506, 2008.

[66] P. Reichl, S. Egger, R. Schatz, and A. D'Alconzo. The logarithmic nature of QoE and the role of the Weber-Fechner law in QoE assessment. In *IEEE International Conference on Communications*, pages 1–5, 2010.

[67] Jong-Hun Rhee, J.M. Holtzman, and Dong-Ku Kim. Scheduling of real/non-real time services: adaptive EXP/PF algorithm. In *Vehicular Technology Conference, 2003. VTC 2003-Spring. The 57th IEEE Semiannual*, volume 1, pages 462–466 vol.1, 2003.

[68] P. Rodriguez-bocca. *Quality-centric design of Peer-to-Peer systems for live-video broadcasting.* PhD thesis, University of Rennes 1, 2008.

[69] Dario Sabella, Marco Caretti, and Roberto Fantini. Energy efficiency evaluation of state of the art packet scheduling algorithms for LTE. In *European Wireless Conference*, pages 1–4, 2011.

[70] C. Sacchi, F. Granelli, and C. Schlegel. A QoE-oriented strategy for OFDMA radio resource allocation based on Min-MOS maximization. *IEEE Communications Letters*, 15(5):494–496, 2011.

[71] K. Sandrasegaran, H.A.M. Ramli, and R. Basukala. Delay-prioritized scheduling (DPS) for real time traffic in 3GPP LTE system. In *IEEE Wireless Communications and Networking Conference*, pages 1–6, 2010.

[72] M.A. Santos, J. Villalon, and L. Orozco-Barbosa. A novel QoE-aware multicast mechanism for video communications over IEEE 802.11 WLANs. *IEEE Journal on Selected Areas in Communications*, 30(7):1205–1214, 2012.

[73] Andreas Saul and Gunther Auer. Multiuser resource allocation maximizing the perceived quality. *EURASIP J. Wirel. Commun. Netw.*, 2009:6:1–6:15, January 2009.

[74] R. Schatz, S. Egger, and A. Platzer. Poor, good enough or even better? Bridging the gap between acceptability and QoE of mobile broadband data services. In *IEEE International Conference on Communications (ICC)*, pages 1–6, 2011.

[75] S. Sengupta and K.P. Subbalakshmi. Open research issues in multi-hop cognitive radio networks. *IEEE Communications Magazine*, 51(4):168–176, 2013.

[76] Junaid Shaikh, Markus Fiedler, and Denis Collange. Quality of experience from user and network perspectives. *Annals of telecommunications*, 65(1-2):47–57, 2010.

[77] S. Sharma, Yi Shi, Y.T. Hou, H.D. Sherali, S. Kompella, and S.F. Midkiff. Joint flow routing and relay node assignment in cooperative multi-hop networks. *IEEE Journal on Selected Areas in Communications*, 30(2):254–262, 2012.

[78] V. Sharma, K. Kar, K.K. Ramakrishnan, and S. Kalyanaraman. A transport protocol to exploit multipath diversity in wireless networks. *IEEE/ACM Transactions on Networking*, 20(4):1024–1039, 2012.

[79] Hsien-Po Shiang and M. van der Schaar. Information-constrained resource allocation in multicamera wireless surveillance networks. *IEEE Transactions on Circuits and Systems for Video Technology*, 20(4):505–517, 2010.

[80] Bongjhin Shin, Jinwoo Choe, Byoungik Kang, Daehyoung Hong, and Youngsuk Park. Cross-layer resource allocation with multipath routing in wireless multihop and multichannel systems. *Journal of Communications and Networks*, 13(3):221–231, 2011.

[81] D.N. Skoutas and A.N. Rouskas. Scheduling with QoS provisioning in mobile broadband wireless systems. In *European Wireless Conference*, pages 422–428, 2010.

[82] Yang Song, Chi Zhang, Yuguang Fang, and Phone Lin. Revenue maximization in time-varying multi-hop wireless networks: A dynamic pricing approach. *IEEE Journal on Selected Areas in Communications*, 30(7):1237–1245, 2012.

[83] Alexander L. Stolyar and Kavita Ramanan. Largest weighted delay first scheduling: Large deviations and optimality. *Annals of Applied Probability*, 11:1–48, 2001.

[84] K. Sundaresan and R. Sivakumar. Cooperating with smartness: Using heterogeneous smart antennas in multihop wireless networks. *IEEE Transactions on Mobile Computing*, 10(12):1666–1680, 2011.

[85] I. Tinnirello and Sunghyun Choi. Temporal fairness provisioning in multi-rate contention-based 802.11e WLANs. In *IEEE International Symposium on a World of Wireless Mobile and Multimedia Networks*, pages 220–230, 2005.

[86] R. Trestian, O. Ormond, and G. Muntean. Power-friendly access network selection strategy for heterogeneous wireless multimedia networks. In *IEEE International Symposium on Broadband Multimedia Systems and Broadcasting*, pages 1–5, 2010.

[87] Ramona Trestian, Olga Ormond, and Gabriel-Miro Muntean. Game theory-based network selection: Solutions and challenges. *IEEE Communications Surveys Tutorials*, 14(4):1212–1231, 2012.

[88] S. Videv and H. Haas. Energy-efficient scheduling and bandwidth-energy efficiency trade-off with low load. In *IEEE International Conference on Communications (ICC)*, pages 1–5, 2011.

[89] Dandan Wang, H. Minn, and N. Al-Dhahir. A distributed opportunistic access scheme and its application to OFDMA systems. *IEEE Transactions on Communications*, 57(3):738–746, 2009.

[90] Ying Wang, Lei Zheng, Jun Yuan, and Wensheng Sun. Median based network selection in heterogeneous wireless networks. In *IEEE Wireless Communications and Networking Conference*, pages 1–5, 2009.

[91] C. Wengerter, J. Ohlhorst, and A.G.E. von Elbwart. Fairness and throughput analysis for generalized proportional fair frequency scheduling in OFDMA. In *IEEE Vehicular Technology Conference*, volume 3, pages 1903–1907 Vol. 3, 2005.

[92] Hyungsuk Won, Han Cai, Do Young Eun, K. Guo, A. Netravali, Injong Rhee, and K. Sabnani. Multicast scheduling in cellular data networks. *IEEE Transactions on Wireless Communications*, 8(9):4540–4549, 2009.

[93] I.C. Wong and B.L. Evans. Optimal downlink OFDMA resource allocation with linear complexity to maximize ergodic rates. *IEEE Transactions on Wireless Communications*, 7(3):962–971, 2008.

[94] E. Yaacoub and Z. Dawy. Distributed probabilistic scheduling in OFDMA uplink using subcarrier sensing. In *IEEE Wireless Communications and Networking Conference*, pages 1–5, 2009.

[95] E. Yaacoub and Z. Dawy. A game theoretical formulation for proportional fairness in LTE uplink scheduling. In *IEEE Wireless Communications and Networking Conference*, pages 1–5, 2009.

[96] E. Yaacoub and Z. Dawy. Proportional fair scheduling with probabilistic interference avoidance in the uplink of multicell OFDMA systems. In *IEEE GLOBECOM Workshops*, pages 1202–1206, 2010.

[97] Y. Zaki, T. Weerawardane, C. Gorg, and A. Timm-Giel. Multi-QoS-aware fair scheduling for LTE. In *IEEE Vehicular Technology Conference*, pages 1–5, 2011.

[98] Hongqiang Zhai, Xiang Chen, and Yuguang Fang. A call admission and rate control scheme for multimedia support over IEEE 802.11 wireless LANs. *Wirel. Netw.*, 12(4):451–463, July 2006.

[99] Weiwen Zhang, Yonggang Wen, Zhenzhong Chen, and A. Khisti. QoE-driven cache management for HTTP adaptive bit rate streaming over wireless networks. *IEEE Transactions on Multimedia*, 15(6):1431–1445, 2013.

[100] Zhongliang Zhao, T. Braun, D. do Rosario, E. Cerqueira, R. Immich, and M. Curado. QoE-aware FEC mechanism for intrusion detection in multi-tier wireless multimedia sensor networks. In *IEEE 8th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob)*, pages 689–696, Oct 2012.

[101] Liang Zhou, Zhen Yang, Yonggang Wen, Haohong Wang, and M. Guizani. Resource allocation with incomplete information for QoE-driven multimedia communications. *IEEE Transactions on Wireless Communications*, 12(8):3733–3745, 2013.

[102] Hua Zhu and I. Chlamtac. Performance analysis for IEEE 802.11e EDCF service differentiation. *IEEE Transactions on Wireless Communications*, 4(4):1779–1788, 2005.

[103] Kun Zhu, D. Niyato, and Ping Wang. Network selection in heterogeneous wireless networks: Evolution with incomplete information. In *IEEE Wireless Communications and Networking Conference (WCNC)*, pages 1–6, 2010.