

# An Energy-Quality Utility-based Adaptive Scheduling Solution for Mobile Users in Dense Networks

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**Abstract**—There is an important trend in terms of user expectations of ubiquity in relation to rich media services and increase in number and range of devices with high specifications which enable access to such services, with very ambitious technical requirements. Providing this support is a very challenging issue, especially in urban dense network environments (DenseNet). Diverse solutions have been proposed, including deployment of femtocells in conjunction with the existing infrastructure, but there is still need for new approaches to balance resources and quality in current competitive market. This paper proposes an innovative three-phase adaptive scheduling solution (EQUAS), which performs trade off between service quality and energy efficiency when allocating network resources to mobile users in a DenseNet. Resource allocation is performed according to a utility function that takes into account throughput, device energy consumption and user mobility. Furthermore, adaptive reallocation is applied to increase network coverage and avoid dropping service. Testing results show how EQUAS outperforms two competitive approaches in terms of energy consumption and efficiency, data throughput and estimated user satisfaction.

**Index Terms**—Network Selection, HetNets, DenseNets, Energy Saving, Adaptive Scheduling.

## I. INTRODUCTION

**T**he increasing number of smart user mobile devices and growing demand for video-centric applications (e.g., video on demand, video games, live video streaming, video conferencing, video surveillance, etc.) accessed via existing network infrastructure make provisioning of services at high quality very challenging. Long Term Evolution-Advanced (LTE-A) [1] is a promising cellular solution in the emerging fifth generation (5G) network space that will be able to provide high quality of service levels for such applications and support increased amount of traffic at good operational costs, as demanded by the market.

The deployment of several femtocells within a macrocell served by a Base Station (BS) provides better coverage, either indoor or in the coverage holes, and guarantees an increase in system capacity by offloading some of the macrocell's traffic. Furthermore, edge-cell users connected to a femtocell

should benefit from higher data rate, low latency, and improved Quality of Service (QoS) and corresponding service Quality of Experience (QoE) levels. the adoption of advanced Radio

In such a dense environment, the adoption of advanced Radio Resource Management (RRM) procedures are necessary in order to increase the system performance and to efficiently exploit the available spectrum. Thus, RRM plays an important role in optimizing network performance by using different scheduling solutions at Medium Access Control (MAC) layer. Packet scheduling mechanisms are responsible for choosing, with fine time and frequency resolutions, how to distribute radio resources among different stations, taking into account channel condition and QoS requirements. This goal should be accomplished by providing, at the same time, an optimal trade-off between spectral efficiency and fairness.

Our research focuses on a DenseNet deployment scenario characterized by overlapping of an LTE-A macro cell and LTE-A small cells (i.e., femtocells). In this scenario, mobile users access video content and desire to have high user QoE levels and low energy consumption. In addition to increased coverage, user capacity and higher throughput, the deployment of small cells reduces the transmission power for the user mobile devices, as they are located closer to BSs/APs. Energy/power management as well as user mobility management are key challenges in the next generation mobile multimedia networks. Various research teams have proposed solutions based on innovative network selection strategies [2], economic models [3], heuristic adaptation algorithms [4], power and quality-oriented utility functions [5] or other mechanisms focused on energy-performance trade-off [6].

In this context, there is a need for a resource allocation mechanism to provide the highest available performance to the largest number of users possible. Generally, the methodology of resource allocation is to model it as an optimization problem whose objective function and constraints are determined by user requirements and network specifications. The objective function is usually referred to as a utility function which characterizes user satisfaction when allocated some resources [7] [8].

This paper proposes the Energy-Quality Utility-based Adaptive Scheduling solution (EQUAS), an innovative scheduling approach that takes into account mobility aspects when

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performing the trade-off between quality and device energy consumption when delivering video in a DenseNet. The aim of this paper is to provide an efficient RRM solution, which achieves high performance in terms of received data rate and device energy consumption, while guaranteeing good network performance (i.e., user coverage).

EQUAS considers the estimated energy consumption of the mobile device when running real-time video applications, estimated network conditions, speed of users and cell loading. It involves three phases, which allocate resources efficiently to the users in distributed manner. After a first sensing phase, during which each user collects measurement from all neighbor cells and sends *AdmissionRequest* to the nearest cell, in phase 2, EQUAS schedules users to be served and decides which resources to assign them, for each cell. The scheduling is performed according to the mobility-aware and quality-energy trade-off based utility function (eq. 1). Users with highest utility function are first served, until resources are available. However, some cells may not support this in a dense heterogeneous environment and then, in phase 3 the adaptation is performed. This adaptation involves switching user allocated resources from one network (i.e., cell) to another such as the utility associated to the users remains high, while also maintaining efficient use of network resources.

The main contributions introduced by this paper are listed below:

- introduction of an energy efficient scheduling technique;
- achieving good performance in terms of both data rate and device energy consumption;
- benefit introduced by adaptive user reallocation;
- extended coverage in terms of number of served users.

The remainder of this paper is organized as follows. In Section II, major literature research proposals related to this work are discussed. The reference system model is described in Section III, and the proposed EQUAS, its three phases and the utility function it employs are presented in Section IV. Performance evaluation is performed and analyzed in Section V, whereas conclusive remarks are summarized in Section VI.

## II. RELATED WORK

On one hand, the 5G DenseNet environment will provide increasing coverage and system capacity with respect to the current cellular networks. On the other hand, the DenseNet's associated higher complexity exacerbates problems of interference coordination, power consumption, RRM and mobility management. In such a DenseNet scenario, there is a need for proper resource allocation in order to meet both 5G requirements and user and market expectations in terms of, high QoE levels, increased power saving, reduced cost, etc. State-of-the art related to our research is discussed next. As the proposed EQUAS relies on a utility function, the focus in this related work section is on utility-based solutions.

Often the problem of resource allocation has been solved by employing a utility maximization framework. The network performance utility function, a concept well known in the literature, is used as an indicator of user level of "satisfaction" and is computed based on different factors including channel

quality, experienced delay and/or other QoS parameters. In [9] the authors have proposed utility-based resource allocation algorithms to perform three tasks: resource allocation between hard and soft QoS traffic; resource allocation between best effort and soft QoS traffic and resource allocation between hard QoS traffic, best effort, and soft QoS traffic. These algorithms take into account traffic type, total available resources and users' channel quality levels.

In a similar manner, [10] proposed a utility-based resource allocation algorithm for the uplink OFDMA Inter-cell Interference (ICI) limited cooperative relay network. This paper focuses on two main objectives: guaranteeing the minimum data rate requirements and maximizing the total achievable data rate. This is achieved through relay selection, subcarrier allocation and power allocation algorithms.

Load balancing has been also accomplished through utility-based network selection, as in [11] and [12]. In [11] authors take into account the real-time global traffic load on each network and different classes of traffic, when performing an adaptive real-time multi-user access network selection. Whereas, the solution proposed in [12] considers a MEW utility function that combines several inputs such as power of the received signal, throughput, packet delay, cost-per-user, the requested type of traffic, and type of device.

The trade-off between QoE and energy saving is a fundamental issue in wireless networks that use opportunistic radio resource allocation. This is addressed in [13], where authors propose an Utility-based Energy eFFicient Adaptive Multimedia Mechanism (UEFA-M) over the LTE HetNet Small Cells environment. They exploit a utility-based approach to adapt the multimedia stream in order to provide a seamless QoE to the mobile user and energy savings for their mobile devices.

The above-cited works mainly aim to maximize the utility in terms of "quality" metrics, whereas energy efficiency is becoming increasingly important and should be considered in resource allocation as well. In this regard, [14] investigates proportional-fair energy-efficient radio resource allocation problem for the uplink transmission of OFDMA smallcell networks.

Most of the works in literature deal with energy efficiency focused on network-side approaches. An energy-efficiency user-side solution was considered in [15]. In this work the authors proposed a novel Utility-based Priority Scheduling (UPS) algorithm which considers device differentiation when supporting high quality delivery of multimedia services over LTE networks. The priorities of service requests are computed by a multiplicative utility function based on device classification, mobile device energy consumption and multimedia stream tolerance to packet loss ratio. In [16], an adaptive and generic scheduling scheme (AGSS) proposed a generic resource allocation procedure that enables the implementation of state-of-the-art scheduling policies and also proposed an opportunistic PDOR aware (OPA) scheduling approach that optimizes the use of radio spectrum while providing the required quality to users.

This paper introduces EQUAS, an innovative adaptive scheduling approach that takes into account mobility aspects when performing the trade-off between quality and device

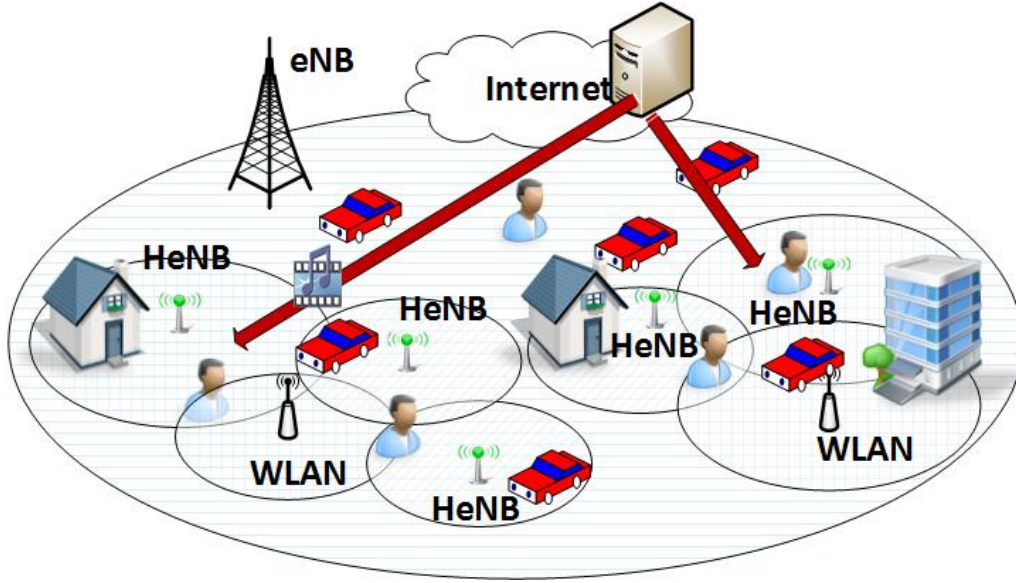


Fig. 1. EQUAS deployment scenario: a dense heterogeneous network with a macro-cell and several small cells.

energy consumption when delivering video in a DenseNet. Such a trade-off is achieved through a utility function that takes into account estimated network conditions, speed of users and user energy consumption.

### III. SYSTEM MODEL

We consider a wireless network scenario where different types of small networks (the term *cell* is also used in this paper) (e.g., femtocells) are deployed in an uncoordinated manner within a macro cellular coverage, as shown in Fig. 1.

We denote with  $\mathcal{U} = \{u_i | i = 1, \dots, n\}$  the set of Users.  $\mathcal{C} = \{C_j | j = 1, \dots, c\}$  is the set of all cells of the scenario, where  $\mathcal{C} = \mathcal{M} \cup \mathcal{F}$  and each cell  $C_j$  is supported by a Base Station (BS)  $BS_j$ . In particular,  $\mathcal{M} = \{M_1, M_2, \dots, M_m\}$  and  $\mathcal{F} = \{F_1, F_2, \dots, F_f\}$  are the sets of available LTE-macrocells (Macro) and LTE-femtocells (Femto), respectively.

$\tau$  is the time interval (TTI) in between regular system updates. Each  $i$ -th UE  $u_i$  collects measurements from all cells which it is able to sense. Hence the following set of available cells is created  $\mathcal{A}_{u_i} = \{A_{1,u_i}, A_{2,u_i}, \dots, A_{a,u_i}\}$ , where  $\mathcal{A}_{u_i} \subseteq \mathcal{C}$ . The useful received power by the user  $u_i$  at a generic distance  $d$  from  $BS_j$  can be expressed as  $P_{R_{j,i}}(d) = P_{T_{j,i}} \cdot h_{j,i}(d)$ , where  $P_{T_{j,i}}$  is the transmitted power from  $BS_j$  and  $h_{j,i}(d)$  is the channel gain from  $BS_j$  to user  $u_i$  located at distance  $d$ . In the channel gain coefficient are included all the losses due to the path loss attenuation, shadowing and other factors such as fading and multipath. Resource allocation is accomplished through computing of a utility function  $\Phi$  (section III-A) that takes into account the energy consumption of the mobile device when running real-time video applications, estimated network conditions and speed of users. Adaptation is performed based either on resource reallocation, in order to increase the amount of users served during each TTI, or according to the Datarate Quality Mapping Table, which includes the datarates  $b_{r_l}$  required to

receive the video content at  $l$ -th Quality Level (QL). Table II is an illustration of such a table, which has five quality levels.

#### A. Utility Function

The utility function is defined for each Radio Access Network (RAN)  $RAN_j$  in eq. (1) [17]:

$$\Phi_j = \phi_{q_j}^{\omega_q} * \phi_{e_j}^{\omega_e} * \phi_{s_j}^{\omega_s} \quad (1)$$

where  $j$  represents the candidate network,  $\Phi_j$  is the overall score function for  $RAN_j$  and  $\phi_q$ ,  $\phi_e$ ,  $\phi_s$  are the utility functions defined for video service quality, device energy consumption and user speed, respectively.  $\omega_q$ ,  $\omega_e$ ,  $\omega_s$  are weights for the considered criteria, representing the importance of the associated parameter in the decision algorithm, where  $\omega_q + \omega_e + \omega_s = 1$ .

1) *Quality Utility  $\phi_q$* : The zone-based quality sigmoid utility function introduced in [18] and presented in eq. (2) is used to map the throughput to user satisfaction.

$$\phi_q = \begin{cases} 0, & \text{for } Th < Th_{min} \\ \frac{-\alpha * Th^2}{\beta + Th}, & \text{for } Th_{min} \leq Th < Th_{max} \\ 1, & \text{otherwise} \end{cases} \quad (2)$$

The minimum throughput ( $Th_{min}$ ) is a threshold to maintain the multimedia service at a minimum acceptable quality level. Values below this threshold result in unacceptable quality levels.  $Th_{req}$  is the required throughput in order to ensure high quality levels for the multimedia service. Whereas values above the maximum throughput ( $Th_{max}$ ) threshold will not add any noticeable improvements in the user perceived quality. The quality utility has values in the [0,1] interval and no unit. In order to determine the exact shape of the utility function the values of  $\alpha$  and  $\beta$  need

to be calculated. Knowing that: (1) for  $Th_{max} = 3500$  kbps the utility has its maximum value; (2)  $Th_{req} = 500$  kbps;  $\alpha$  and  $\beta$  are determined by performing some mathematical computations of [18] and their values are 1.64 and 0.86, respectively.

2) *Energy Utility  $\phi_e$* : The estimated energy consumption for a real-time application is computed using equation (3), as defined in [19]:

$$E = t(r_t + Th_{rec} * r_d) \quad (3)$$

where  $t$  represents the transaction time, which can be estimated from the duration of the video stream;  $r_t$  is the mobile device energy consumption per unit of time (W),  $Th_{rec}$  is the received throughput (kbps),  $r_d$  is the energy consumption rate for data/received stream (J/Kbyte), and  $E$  is the total energy consumed (J). The two parameters,  $r_t$  and  $r_d$ , are device specific and differ for each network interface. They were determined by running different simulations for various amounts of multimedia data (i.e., quality levels) while measuring the corresponding energy levels and then used to define the energy consumption pattern for each interface/scenario [20]. Based on the estimated energy consumption  $E$ , the utility for the energy criteria  $u_e$  is computed using eq. (4) [21]:

$$\phi_e = \begin{cases} 1, & \text{for } E < E_{min} \\ \frac{E_{max} - E}{E_{max} - E_{min}}, & \text{for } E_{min} \leq E < E_{max} \\ 0, & \text{otherwise} \end{cases} \quad (4)$$

where  $E_{min}$  and  $E_{max}$  are computed considering  $Th_{min}$  and  $Th_{max}$ , respectively.

3) *Speed Utility  $\phi_s$* : The mathematical definition of the speed utility is given in eq. (5):

$$\phi_s = \begin{cases} 1, & \text{for } S < S_{min} \\ \frac{S_{max} - S}{S_{max} - S_{min}}, & \text{for } S_{min} \leq S \leq S_{max} \\ 0, & \text{otherwise} \end{cases} \quad (5)$$

subject to  $u_s = 1$ , if  $i \in \mathcal{C}_M$  (6)

where  $S_{min}$  is the pedestrian speed (i.e. 3 km/h) and  $S_{max}$  is the urban vehicular speed limit (e.g. 50 km/h in many countries). This utility considers urban dense networks only. Eq. (6) does not affect the overall utility function if the target cell is a Macro cell. This is because the cell range is large and UEs with high mobility should not perceive differences in their transmissions. The consequence is that fast users (more than 50 km/h) could connect with the Macro cell, whereas femtocells accept users with low speed only. Moreover, the lower the user speed is, the higher is the utility score from the femtocells.

#### IV. ENERGY SAVING QUALITY-BASED UTILITY ADAPTIVE SCHEDULING SOLUTION (EQUAS)

The proposed EQUAS involves three phases as follows (see Fig. 2):

- (i) *sensing phase*;
- (ii) *scheduling and resource allocation phase and*
- (iii) *adaptive reallocation phase*.

i) During the **sensing phase**, at every TTI each UE  $u_i$  collects measurements from all cells which it is able to sense. Hence, the set of available cells  $\mathcal{A}_{u_i} = \{A_{1,u_i}, A_{2,u_i}, \dots, A_{a,u_i}\}$ , where  $\mathcal{A}_{u_i} \subseteq \mathcal{C}$  is created.

Next, UEs create the Selection Tables  $\mathbf{T}_{u_i}$ :

$$\mathbf{T}_{u_i} = \begin{bmatrix} A_{1,u_i} & \Phi_{1,u_i} & r_{1,u_i} \\ A_{2,u_i} & \Phi_{2,u_i} & r_{2,u_i} \\ \vdots & \vdots & \vdots \\ A_{a,u_i} & \Phi_{a,u_i} & r_{a,u_i} \end{bmatrix}$$

Each such Selection Table  $\mathbf{T}_{u_i}$  is sorted in descending order according to the  $\Phi_{j,u_i}$  column. In this way the cells with the best  $\Phi$ -scores are in the first rows, where 1 and  $a$  are the indexes of the cells with the highest and the lowest value of  $\Phi_{j,u_i}$ , respectively. This table will be used in phase 3 of EQUAS, as described later on.

Each UE sends an *AdmissionRequest* message to the  $j$ -th cell  $\in \mathcal{A}_{u_i}$ , from which it senses the most powerful signal. Additionally, each cell  $C_j \in \mathcal{C}$  collects the received *AdmissionRequest* messages and creates the Requests Tables  $\mathbf{R}_j$ :

$$\mathbf{R}_j = \begin{bmatrix} u_1 & \Phi_{j,1} & r_{j,1} & mcs_{j,1} \\ u_2 & \Phi_{j,2} & r_{j,2} & mcs_{j,2} \\ \vdots & \vdots & \vdots & \vdots \\ u_l & \Phi_{j,l} & r_{j,l} & mcs_{j,l} \end{bmatrix}$$

Let be  $\mathcal{B}_j = \{u_j | j = 1, \dots, l\}$ , with  $\mathcal{B}_j \subseteq \mathcal{U}$ , the set of users sending a request to the  $j$ -th cell. Where  $l \leq n$  is the number of UEs trying to access the  $j$ -th cell  $C_j$ .  $\Phi_{j,k}$  and  $r_{j,k}$ , with  $k = \{1, \dots, l\}$ , are the Utility score and resources which the  $k$ -th UE can receive from the cell  $C_j$ , respectively. Each of the  $mcs_{j,k}$  values from the last column refers to the MCS level associated to user  $k$  in the downlink channel from cell  $C_j$ .

ii) In the second phase of the algorithm, cells perform **user scheduling and resource allocation**. Each  $j$ -th cell selects the UEs to serve in order to maximize the Cost Function from equation (7):

$$\mathcal{F}_j = \sum_{k=1}^l \Phi_{j,k} \quad (7)$$

under the constraint from equation (8):

$$\sum_{k=1}^l r_{j,k} \leq BW(j) \quad (8)$$

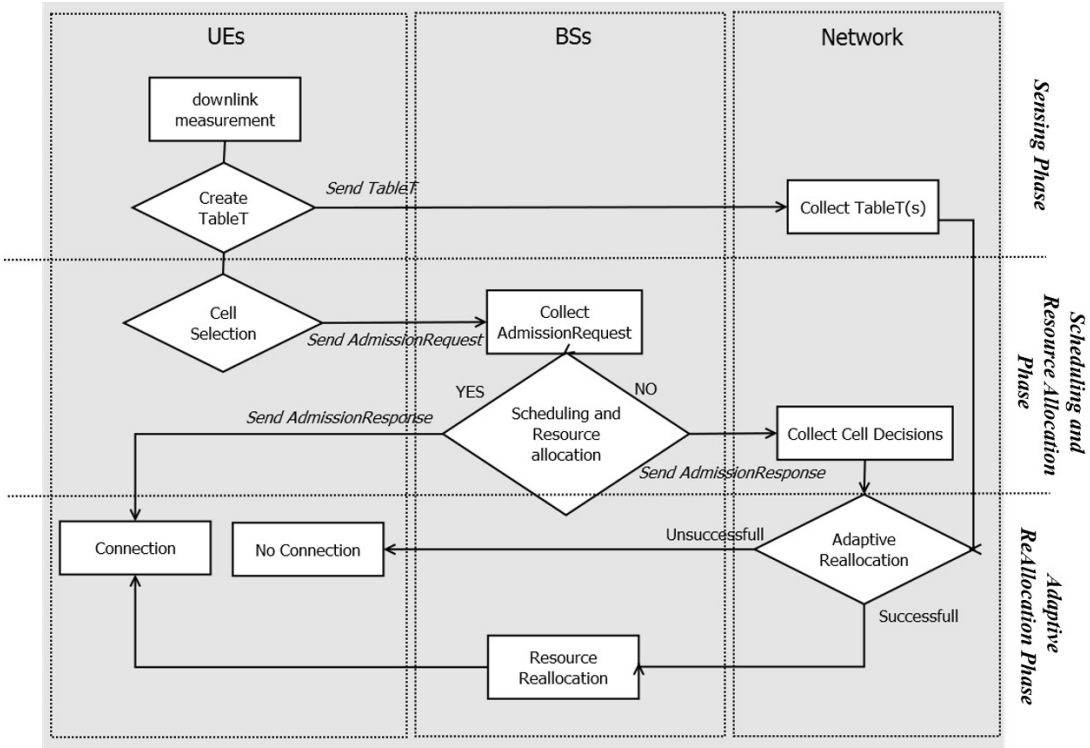


Fig. 2. EQUAS flowchart.

where  $\Phi_{j,u_i} = \phi_q^{\omega_q} * \phi_e^{\omega_e} * \phi_s^{\omega_s}$ , with  $j = 1, \dots, a$ , denotes the Utility score computed by user  $u_i$  associated to the  $j$ -th cell  $\in \mathcal{A}_{u_i}$  (eq. 1), as described in the section III-A.  $r_{j,u_i}$  are the resources that the  $j$ -th cell could guarantee to user  $u_i$ .  $BW(j)$  is the maximum available bandwidth of the  $j$ -th cell.

iii) When a user's *AdmissionRequest* is rejected, the third phase of the algorithm (**adaptive reallocation phase**) takes place.

Let denote with  $u_r$  the user whose request is rejected, with  $\mathbf{T}_{u_r}$  the Selection Table of user  $u_r$  and  $\mathbf{R}_j(u_r)$  the Requests Table of the cell  $A_{j,u_r} \in \mathcal{A}_{u_r}$ , corresponding to the cell to which  $u_r$  has sent the *AdmissionRequest*.

Then, the Adaptive scheduling algorithm tries to reallocate resources to enable user  $u_r$  connectivity. Hence, a set of possible new solutions  $\bar{\mathbf{S}}$  is defined. It is composed by a set of Utility Score-Loss, each referring to a different resource allocation choice. Let  $\lambda$  be the Loss in terms of Utility score, computed as the difference between the former and the new utility score.  $\bar{\mathbf{S}}$  is hence created as follows.

**Option 1.** The algorithm looks for a potential new cell which connects  $u_r$  to. The table  $\mathbf{T}_{u_r}$  is skipped until the first cell  $A_{x,u_r}$  that has got enough resources to assign to  $u_r$  is found. This means that the following condition should be verified:

$$r_{x,u_r} \leq BW(A_{x,u_r}). \quad (9)$$

When the condition (9) is verified,  $\Phi_{x,u_r}$  is the potential new utility score achieved by the user  $u_r$  and the  $x$ -th cell

$A_{x,u_r}$  of the Table  $\mathbf{T}_{u_r}$  is the potential cell to which connect  $u_r$ . Hence,  $\lambda_{u_r} = \Phi_{1,u_r} - \Phi_{x,u_r}$  is added to  $\bar{\mathbf{S}}$ .

**Option 2.** According to Table II, the datarate required by user  $u_r$  is decreased to the lower level until the necessary resources to receive that level are lower or equal to the available resources of the cell  $A_{1,u_r}$ . Based of the new accepted datarate, a new Utility score  $\Phi_{1,u_r}^*$  is computed and  $\lambda_{u_r}^* = \Phi_{1,u_r} - \Phi_{1,u_r}^*$  is added to  $\bar{\mathbf{S}}$ .

**Option 3.** Let  $\mathcal{D} = \{u_1, u_2, \dots, u_d\}$  be the subset  $\mathcal{D} \subseteq \mathcal{B}_j$  of the users accepted by the cell  $A_{1,u_r}$ . For each  $t$ -th user  $u_t \in \mathcal{D}$ , with  $t = 1, 2, \dots, d$ , the algorithm finds in its Selection Table  $\mathbf{T}_{u_t}$  a potential second cell  $A_{y,u_t}$  to which it could be connected, as done in the Option 1. Hence the tables  $\mathbf{T}_{u_t}$  of each  $t$ -th UE  $\in \mathcal{D}$  are skipped from the second row until the following condition is verified:

$$r_{y,u_t} \leq BW(A_{y,u_t}). \quad (10)$$

If eq. (10) is verified,  $\Phi_{y,u_t}$  is the new utility score  $\forall u_t \in \mathcal{D}$ . Hence  $\lambda_{u_t} = \Phi_{1,u_t} - \Phi_{y,u_t}$ , with  $t = 1, 2, \dots, d$  are added to  $\bar{\mathbf{S}}$ . This means that the algorithm looks for the possibility of moving one other user out from the cell  $A_{j,u_r}$  in place of user  $u_r$ .

Following the application of the three options, the set of the new possible solutions is  $\bar{\mathbf{S}} = \{\lambda_{u_r}, \lambda_{u_r}^*, \lambda_{u_t}, \text{ for } t = 1, 2, \dots, d\}$ .

In order to maximize the sum of the utility score, the lowest value  $\lambda_{min}$  of  $\bar{\mathbf{S}}$  is selected. Therefore, the allocation choice related to  $\lambda_{min}$  is carried out. Although there is a Loss in terms of Utility scores, it is only a local loss, related to the user

that is affected by the adaptation or reallocation. Nevertheless, EQUAS guarantees to serve more users. Therefore, thanks to the reallocation phase, EQUAS achieves a higher sum of utility scores, since it avoids users rejections.

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**Algorithm 1** Energy saving Quality-based Utility Adaptive Scheduling algorithm (EQUAS) -  $2^{nd}$  Phase

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EQUAS - Phase 2

- 1: **Define:**  $\mathcal{B}_j = \{u_i | i = 1, \dots, l\}$ , with  $l =$  number of users sending admission request to  $j$ -th cell;
  - 2:
  - 3: **Scheduling and Resource Allocation phase:**
  - 4: **for** ( $j = 1 \rightarrow c$ ) **do**
  - 5:     **Determine:**  $\mathcal{B}_j$ ;
  - 6:     **Compute:**  $\max \mathcal{F}_j$ , according to (7) and (8);
  - 7:     **for** ( $i = 1 \rightarrow l$ ) **do**
  - 8:          $j$  sends *AdmissionResponse* to  $u_i$ ;
  - 9:     **end for**
  - 10: **end for**
- 

## V. PERFORMANCE EVALUATION

An extensive numerical evaluation is conducted using Matlab. The performance analysis is performed following the guidelines for the LTE system model in [22]. The main simulation parameters are listed in Table I. The parameters for the LTE system are set according to [1].

In the considered scenario (Fig. 1) several small cells are deployed within the coverage of a LTE macrocell. The coverage area of the Macrocell is 500x500 m. The number of the small cells within the macrocell is set to 50. An example of the simulation area could be found in Fig. 3.

TABLE I  
MAIN SIMULATION PARAMETERS

| Parameter                                | Value                       |
|--|-----------------------------|
| MacroCell Radius                         | 500 m                       |
| Frame Structure                          | Type 2 (TDD) [1]            |
| TTI                                      | 1 ms                        |
| Cyclic prefix/Useful signal frame length | 16.67 $\mu$ s/66.67 $\mu$ s |
| Macrocell TX Power                       | 46 dBm                      |
| Femtocell TX Power                       | 20 dBm                      |
| Macrocell Downlink Channel Bandwidth     | 20 Mhz                      |
| Femtocell Downlink Channel Bandwidth     | 5 Mhz                       |
| Noise power                              | -174 dBm/Hz                 |
| Path loss (macrocell)                    | 15.6 + 35 log(d), dB        |
| Path loss (femtocell)                    | 38.46 + 20 log(d), dB       |
| Target Bit Error Rate                    | 10 x 10 <sup>-5</sup>       |
| Simulation Time                          | 3 mins                      |
| Number of Macrocells                     | 1                           |
| Number of Femtocells                     | 50                          |
| Number of Users                          | [50:10:200]                 |
| Users' speed                             | [3-60] km/h                 |

A dense urban scenario was considered where users' speed values are uniformly distributed from 3 km/h to 60 km/h. The simulations are carried out in a time interval of 3 minute, with users downloading a real-time video. Video features are

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**Algorithm 2** Energy saving Quality-based Utility Adaptive Scheduling algorithm (EQUAS) -  $3^{rd}$  Phase

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EQUAS - Phase 3

- 1: **Define:**  $\mathcal{R} = \{u_r | r = 1, \dots, s\}$ , with  $s =$  number of users receiving a *Rejection* message;
  - 2: **Define:**  $\bar{\mathcal{S}}_{u_r}$  the set of possible new solutions for  $u_r$ -*Rejection* message;
  - 3: **Define:**  $\mathcal{D} = \{u_t | t = 1, \dots, d\}$ , where  $\mathcal{D} \subseteq \mathcal{B}_j$ , with  $d =$  number of user accepted by the cell that has rejected the  $r$ -th user  $u_r$ ;
  - 4:
  - 5: **Adaptive Reallocation Phase:**
  - 6: **for** ( $r = 1 \rightarrow s$ ) **do** (*Skip Set*  $\mathcal{R}$ )
  - 7:
  - 8:     **Option 1:**
  - 9:     **for** ( $j = 1 \rightarrow a$ ) **do** (*Skip Table*  $T_{u_r}$ )
  - 10:         **if** ( $r_j \leq BW(j)$ ) (9) **then**
  - 11:             **Compute:**  $\lambda_{u_r} = \Phi_{1,u_r} - \Phi_{j,u_r}$ ;
  - 12:             **Add**  $\lambda_{u_r}$  to  $\bar{\mathcal{S}}_{u_r}$ ;
  - 13:             **break;**
  - 14:         **end if**
  - 15:     **end for**
  - 16:
  - 17:     **Option 2:**
  - 18:     **Determine:** new  $b_r =$  datarate of the  $(l-1)$ -th level (Table II);
  - 19:     **Compute:** new  $\Phi_{u_r}^*$ , according to (1);
  - 20:     **Compute:**  $\lambda_{u_r}^* = \Phi_{1,u_r} - \Phi_{1,u_r}^*$ ;
  - 21:     **Add**  $\lambda_{u_r}^*$  to  $\bar{\mathcal{S}}_{u_r}$ ;
  - 22:
  - 23:     **Option 3:**
  - 24:     **for** ( $t = 1 \rightarrow d$ ) **do** (*Skip Set*  $\mathcal{D}$ )
  - 25:         **for** ( $j = 1 \rightarrow a$ ) **do** (*Skip Table*  $T_{u_t}$ )
  - 26:             **if** ( $r_j \leq BW(j)$ ) (10) **then**
  - 27:                 **Compute:**  $\lambda_{u_t} = \Phi_{1,u_t} - \Phi_{j,u_t}$ ;
  - 28:                 **Add**  $\lambda_{u_t}$  to  $\bar{\mathcal{S}}_{u_r}$ ;
  - 29:                 **break;**
  - 30:             **end if**
  - 31:         **end for**
  - 32:     **end for**
  - 33:
  - 34: **end for**
  - 35:
  - 36: **Find:**  $\min \{\bar{\mathcal{S}}_{u_r}\}$ ;
  - 37: **Allocate** resources according to the solution:  $\min \{\bar{\mathcal{S}}_{u_r}\}$ ;
- 

TABLE II  
QUALITY LEVELS TABLE

| Video Codec       | Quality Level | Screen Resolution [pixels] | Datarate required [kbps] |
|-------------------|---------------|----------------------------|--------------------------|
| H.264 /MPEG-4 AVC | QL1           | 240p                       | 250                      |
|                   | QL2           | 360p                       | 500                      |
|                   | QL3           | 480p                       | 1000                     |
|                   | QL4           | 720p                       | 2000                     |
|                   | QL5           | 1080p                      | 3500                     |

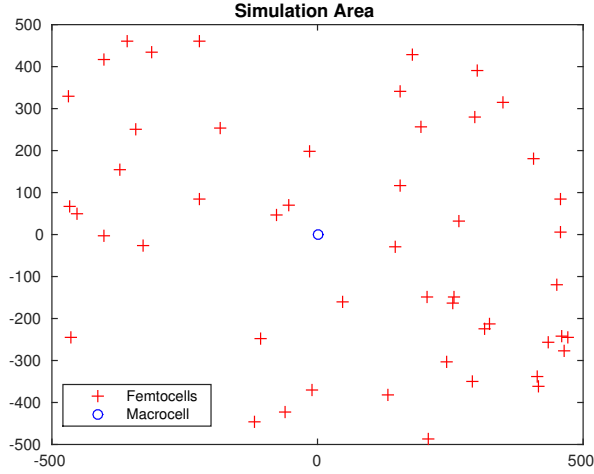


Fig. 3. Simulation Area.

described in Table II. According to the data rate of the selected cell, a corresponding QL for the video delivery is used.

The proposed EQUAS algorithm performance was compared with a classic scheduling algorithm denoted "Proportional Fair" (PF), and with an Adaptive Generic Scheduling Scheme (AGSS) [16]. PF aims to provide data-rate distribution among users in a fair way.

The following simulation metrics have been considered:

- *Aggregate Data rate (ADR)*: the sum of the throughput of the users among overall system;
- *Average Throughput*: the average quality of transmission accomplished to users;
- *User Satisfaction*: the estimated satisfaction perceived by users measured in terms of the ratio between the data rate received and the data rate required by each user;
- *estimated Device Energy Consumption*: the estimated energy consumption of the devices when downloading a video flow;
- *Energy Efficiency*: the energy efficiency is defined as the aggregate bit rate that is achievable over 1Hz nominal bandwidth while consuming a given power - thus measured in bits per second per Hertz per kilowatt [23].
- *Percentage of coverage*: the percentage of users served among all users within the system.

Fig. 4 shows the aggregate data-rate of the system. As it can be noted, EQUAS achieves greater aggregate data rate than PF and AGSS. Even though the gain seems negligible with few users in the system, it linearly increases when increasing the number of users within the system. This results in enhanced load balancing.

The results provided by ADR are confirmed by the average throughput analysis (Fig. 5). Indeed, the average throughput received by users decreases when increasing the number of users. It could be expected because of the resource contention. Average throughput improves of 1% when employing EQUAS in comparison with the cases when the other two algorithms are used. This is thanks to the resource allocation carried out

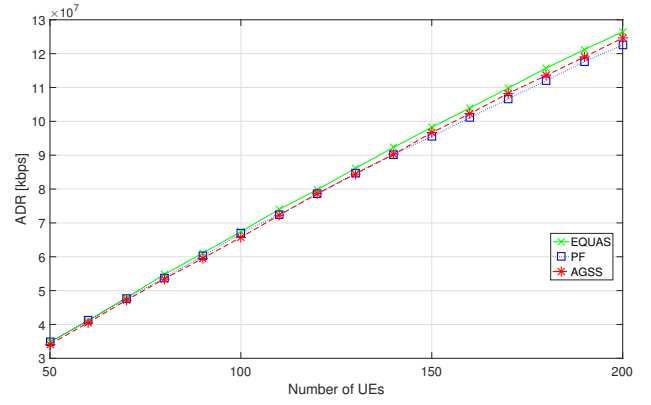


Fig. 4. Aggregate data-rate.

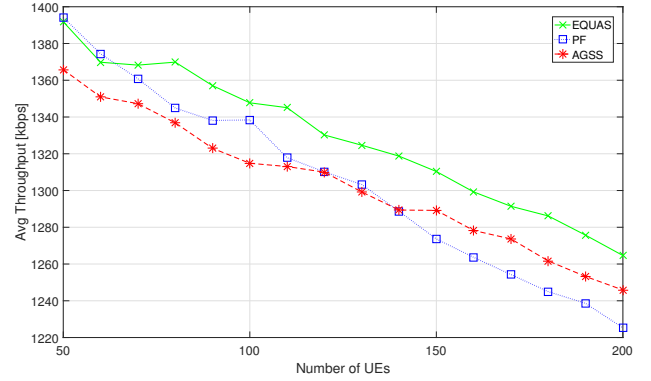


Fig. 5. Average User Throughput.

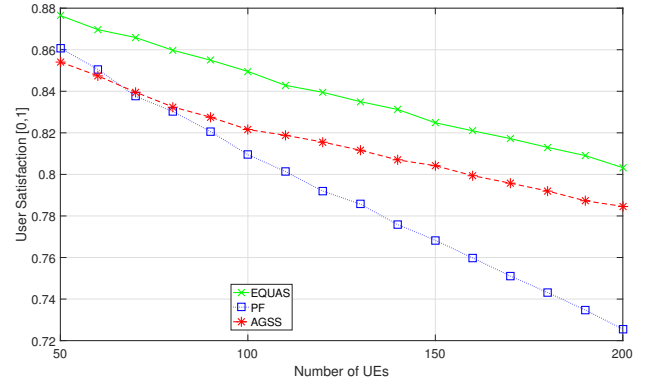


Fig. 6. Users' satisfaction [0,1].

by EQUAS, which allows users to be served by the cell that guarantees better performance in terms of throughput-energy consumption trade-off. Moreover, the resource allocation guarantees to the users data rates closer to the target of their service requirements. Although the advantage introduced by EQUAS in terms of average throughput seems numerically poor, the proposed approach results in higher estimated user satisfaction. As illustrated in Fig. 6, it is shown a gain between 2% and 3% with respect to AGSS, whereas this gap reaches the 8% when comparing EQUAS with the PF algorithm.

Next, considerations about energy consumption are presented. According to eq. 3, a higher received data rate corresponds to higher device energy consumption. It is worth noting

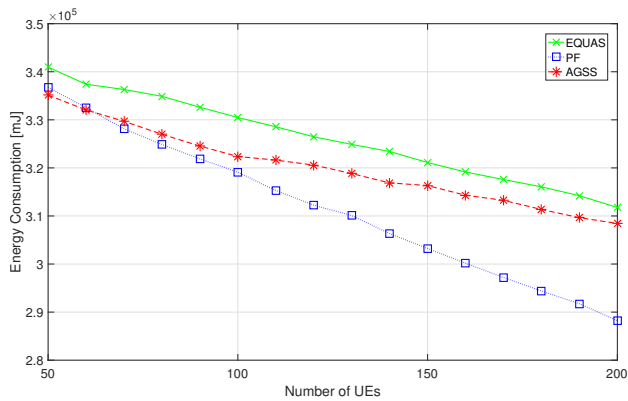


Fig. 7. Device energy consumption.

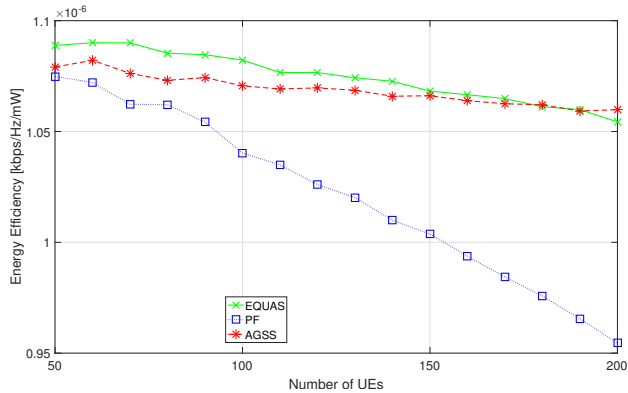


Fig. 8. Energy Efficiency.

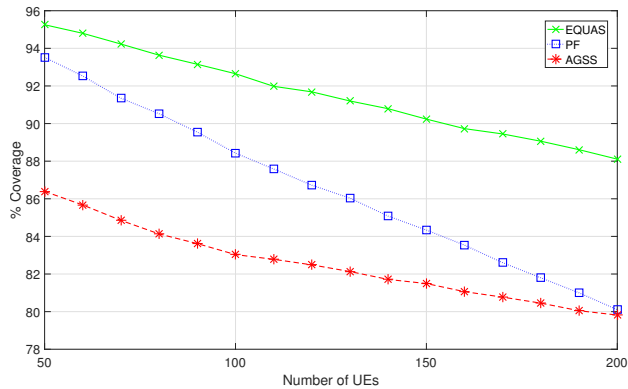


Fig. 9. System coverage.

that the device power consumption depends on receive (Rx) and transmit (Tx) power levels, uplink (UL) and downlink (DL) data rate, and RRC mode [24]. Uplink transmit power and downlink data rate greatly affect the power consumption, while uplink data rate and downlink receive power have little effect. In this work, we deal with the downlink side, so we focus only on the power consumption contribution related to the down link data rate. Therefore, the energy consumption defined by eq. (3) refers only to the downlink data-rate energy consumption.

Nevertheless, the trade-off between data-rate achieved and device energy consumption is represented by the energy efficiency shown in Fig. 8. EQUAS achieves until to 10% gain

with respect to classic PF algorithm, thanks to the smart load balancing which both considers throughput and device energy consumption when performing the resource allocation. A slight gain is still achieved also with respect to AGSS. Indeed, since the energy efficiency formula takes into consideration also the wasted bandwidth, figure 8 well represents the benefits introduced by EQUAS. That is a resource allocation strategy well performing a trade-off between throughput and device energy consumption, while guaranteeing a good user satisfaction and bandwidth utilization.

Finally, the system coverage is illustrated in Fig. 9. As it can be seen, EQUAS achieves a gain between 8% and 9% with respect to AGSS in all traffic load conditions, whereas the gain with respect to PF ranges from 2% in low traffic conditions to 8% in high traffic conditions. This is thanks to the phase 2 of the algorithm, which performs the re-allocation of users. Hence, users that could suffer from out-of-service situations are re-allocated to other cells, or take the place of other users just reallocated. Although some users are re-assigned to cells which do not represent their first choice, the proposed algorithm maintains good performance in terms of both average throughput and estimated user satisfaction.

## VI. CONCLUSIONS

This paper introduced EQUAS, a three-phase energy-quality adaptive scheduling solution, which performs network resource allocation in order to achieve trade-off between energy consumption and service quality in a dense network environment. Extensive testing involving a simulation environment which consists of a LTE macro-cell and several femtocells with increasing number of mobile users were performed. Comparison-based testing showed how EQUAS outperforms two other competitive approaches in terms of throughput, energy consumption and efficiency, and estimated user satisfaction with the service.

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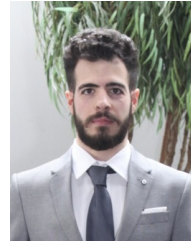
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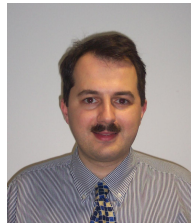
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