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Abstract—Radio resource management and allocation schemes are the key operational techniques that allow a wireless access network operator to optimize utilization of the available spectrum that suits its needs. Dynamic resource allocation by scheduling is particularly a popular technique that is widely proposed for packet switched networks. To this end, energy efficiency of various scheduling schemes has a paramount importance. Thus, numerous research efforts tried to improve the performance of proposed schedulers by finding optimal trade-off to minimize energy consumption based on different performance metrics. These scheduling algorithms are divided into two major parts; traditional and principal schedulers and energy aware schedulers. In spite of traditional schedulers, which were proposed regardless of energy efficiency, energy aware schedulers tried to minimize power and energy consumption while maintaining other requirements. This difference is mainly the approach to design schedulers that are more efficient in future.

Index Terms—Energy Efficiency, LTE, VoIP, Scheduler, Radio Resource Allocation, Power Consumption, Buffer Aware, Energy Saving, OFDMA.

I. INTRODUCTION

Due to the global warming and shortage of energy resources, energy efficiency is becoming increasingly important feature in communication systems. It is shown that the wireless access networks are major contributors to energy consumption in communication networks. Recent reports indicate that wireless access networks consume 80% of the total energy used by mobile communication network operators. In particular, energy consumption in base stations and downlink transmission seems to be a major area that significant conservation can be achieved. Motivated by this fact, the focus of this survey report is radio resource management and allocation functions for OFDM systems.

For evaluation of energy efficiency, to compare the performance of different scheduling schemes, definition of power consumption model of wireless access is necessary. Some power consumption models of base station in 3GPP LTE networks are proposed in [3]-[13] and will discuss in detail in the next section. In these papers, different models have been introduced to show the relationship between power consumption and transmission power of base station for evaluation of energy efficiency in wireless networks.

The bulk of the existing work on resource allocation and scheduling, focus on the traditional performance such as throughput and fairness for several schemes, as given in [14]-[16]. They evaluated the variations of some principle techniques such as Round Robin (RR), Best Channel Quality Indicator (BCQI), Proportional Fair (PF), and other schemes. However, energy efficiency of scheduling schemes has not been adequately addressed by the existing studies, to the best of our knowledge. Nonetheless, some aspects of energy efficient scheduling schemes are investigated in [17], [18], which seek to reduce energy consumption of transmission over Additive White Gaussian Noise (AWGN) channels while maintaining some sort of QoS for users by using mathematical algorithms. Some principle ideas were given in [19]-[21], which assume extension of packet transmission duration in time domain for reduction of transmission power by using some numerical algorithms for offline and online scheduling. These studies mostly consider optimum energy scheduling for single carrier systems. Some of the recent proposed schedulers [22], [23], to be evaluated in the next section, are based on trading off bandwidth for energy efficiency without considering buffer state.

Motivated by this demand, this survey report tries to give an insight on how we find the gaps to go beyond the state of the art. As we are looking to find a comprehensive energy efficient radio resource management and allocation algorithm in OFDM systems, at first we introduce a brief overview of technical specification of 3GPP LTE as an example of OFDMA, in which it adopted OFDMA in downlink. Then some power consumption modelling and energy-efficiency metrics are discussed, which is followed by some scheduling techniques in OFDMA, and finally, the energy efficient scheduling algorithms in the state-of-the-art are investigated.

II. THE STATE OF THE ART

A. OFDM and OFDMA

OFDM systems divide frequency bandwidth into many narrow band subcarriers with uniformly Spaced zero crossing at 15 kHz intervals and transmit them in parallel. In this system, each of the subcarriers is modulated with some digital modulation schemes such as QPSK, 16QAM, 64QAM in regarding to their signal quality. Thus, each OFDM symbol is a linear combination of the instantaneous subcarriers signal. In OFDM system, there are two main characteristics; first, Cyclic Prefix (CP) is used to reduce Inter Symbol Interference (ISI); then, there is no interference among adjacent subcarriers. In
this system, the entire bandwidth is assigned to each user for a period and the resources cannot share among users.

OFDMA in spite of OFDM benefits from sharing the bandwidth among multiple users at each time according to bandwidth requirement of each user. Unassigned subcarriers are off and it causes to reduce power consumption and interference [2]. This issue is the main concept of energy saving by using those empty resources to prepare an energy efficient system in light traffic condition. Figure 1 shows the comparison of OFDM and OFDMA in terms of radio resource assignment among users that are mentioned with different colours.

![Comparison of OFDM and OFDMA](image)

Fig. 1. Comparison of OFDM and OFDMA in terms of radio resource allocation

3GPP LTE is a good example, which adopts OFDMA for multiplexing scheme in downlink. Thus, this technology is briefly discussed in this report.

**B. 3GPP LTE Technical Specification**

Long Term Evolution (LTE) radio access technology, which was based on the first release of the 3rd Generation Partnership Project (3GPP Rel-8), was extended in release 9 and 10. Rel-10 often refers to LTE-Advanced to extend the performance of radio access to meet all the requirements, which are defined by International Telecommunication Union (ITU). 3GPP technical specification series are categorized to five major areas as follows [2]: 1- TS 36.1XX which standardise user and base station equipment requirement; 2- TS 36.2XX which give Physical layer specification and TS 36.814 that gives further advancement in physical layer aspects; 3- TS 36.3XX explain Layer 2 and 3, which are Medium Access Control (MAC), Radio Link Control (RLC), and Radio Resource Control (RRC); 4- TS 36.4XX introduce base station and mobile terminal entities; 5- TS 36.5XX explain conformance testing procedures. We studied and focused on standards of category 1, 2, and 3, and brief overviews of these standards are given in next subsections.

1) **LTE Network Architecture:** An overall architecture of LTE network is shown in Figure 2. The Evolved Universal Terrestrial Radio Access Network (E-UTRAN) NodeBs (eNodeBs) are connected to each other through X2 interface and by S1 interface to Mobility Management Entities (MME) and Serving Gateway (S-GW).

An Orthogonal Frequency Division Multiple Access (OFDMA) scheme is used by the eNodeB to serve multiple users according to the LTE standard. The concept of resource allocation is shown in Figure 3, where the time and frequency of the channel are divided into multiple Physical Resource Blocks (PRB). The time axis is divided into frames with durations of 10 ms. Each frame consists of 10 Transmission Time Interval (TTI) of duration of 1 ms, which is also known as a sub-frame as depicted in Figure. Each TTI has two time slots of 0.5 ms, equivalent to the transmission time of 6 or 7 OFDM symbols [2].

![An Overall Architecture of LTE Network](image)

Fig. 2. An Overall Architecture of LTE Network [2]

![Structure of OFDMA Physical Resource Block](image)

Fig. 3. Structure of OFDMA Physical Resource Block

In frequency domain, the LTE system bandwidth varies from 1.25 MHz to 20 MHz, depending on implementation. A PRB consists of 12 consecutive sub-carriers in the frequency domain, which have 15 KHz bandwidth. Thus, each PRB has 180 KHz bandwidth and in the LTE system the number of PRBs varies from 6 to 100 as shown in Table 1.
TABLE 1

<table>
<thead>
<tr>
<th>LTE BANDWIDTH/RESOURCE CONFIGURATION [2]</th>
</tr>
</thead>
<tbody>
<tr>
<td>System Bandwidth(MHz)</td>
</tr>
<tr>
<td>Sub-carriers Bandwidth(MHz)</td>
</tr>
<tr>
<td>PRB Bandwidth(MHz)</td>
</tr>
<tr>
<td>FFT Size</td>
</tr>
<tr>
<td>Number of Available PRBs</td>
</tr>
</tbody>
</table>

2) CSI Feedback: The allocation of PRBs is decided by a scheduler at the BS side. The general framework of an OFDMA scheduler is shown in Figure 4. The arriving data packets for the individual users are buffered in the BS, where they wait for transmission to the corresponding UEs. Simple schedulers make decisions without taking into account the Channel State Information (CSI) or Buffer State Information (BSI). However, some sophisticated schemes may utilize BSI or CSI. If CSI is required, the information is sent back to the base station via a Channel Quality Indicator (CQI) channel over the reverse link, which is called Physical Uplink Control Channel (PUCCH) in 3GPP LTE standard. Different scheduling schemes may use CSI and BSI in different ways to assigns PRBs in each TTI. In LTE there are two types of feedback; periodic and aperiodic and UE can report CQI in both wide-band and sub-band level. Despite the sub-band, which UE reports CQI for each sub-band, in wide-band UE reports one CQI for whole system bandwidth.

3) Propagation Loss and Channel Model: According to [24]–[26], for modelling the channel, there are different types of channel model such as: AWGN, Flat Rayleigh, Block fading, Fast fading, ITU-R models, 3GPP model, 3GPP SCM, 3GPP SCME, and WINNER. Based on [26], the propagation loss can be modelled as follows.

The Signal to Noise Ratio (SNR) for user $i$ on $PRB_j$ is given by:

$$SNR_{(i,j)} = \frac{P_{RX_{(i,j)}}}{N_0B_j}, \quad N_j = N_0B_j$$

(1)

$$P_{RX_{(i,j)}}(dB) = P_{TX_j} - L_i - T_i - S_{(i,j)}$$

(2)

where $P_{TX_{(i,j)}}$, $P_{RX_{(i,j)}}$, $B_j$, $N_0$ are the transmitted and received power at user $i$ on $PRB_j$, bandwidth of $PRB_j$, power spectral density of white noise, respectively. $L_i$, $T_i$, and $S_{(i,j)}$ are path loss, shadowing loss, and loss due to fast fading, respectively, all in dB. Path loss can be modelled by free space loss model or complex models that can be found in the literature depending on the propagation environment. For instance, in this report we use path loss model for macro cell in urban and suburban area, which is modelled with $L = 128.1 + 37.6 \log_{10} d$, where $d$ is the distance between the user and the BS. Users are considered as being uniformly distributed in maximum 1000 m cell radius. Shadow fading is modelled by lognormal distribution with 0 mean and 10 dB of standard deviation. The fast fading component for land mobile applications is usually is modelled by a Rayleigh fading, where the instantaneous power gain of the channel is an exponential random variable, and the received signal envelope is a random variable with Rayleigh distribution.

4) AMC: According to the received information of users in form of Channel Quality Indicator (CQI) link adaptation, which uses Adaptive Modulation Coding (AMC) allow eNodeB to select proper modulation and coding during the radio resource allocation procedure. In LTE, the mapping of the SNR to the CQI can be estimated through a linear function, which is derived from Block Error Rate (BLER) and SNR curve as shown in Figure 5 for BLER=0.1. After selection of proper Modulation and Coding Scheme (MCS), BS calculates the Transport Block Size (TBS) for each user, which is the number of bits that can be transmitted by the allocated $PRB$ at a given Transmission Time Interval (TTI). This calculation is performed by using lookup tables as shown in Table 2.
C. Power Consumption Modelling

Based on the literature [3]-[13], we found some power consumption modelling and energy efficient metrics that are given in the following subsections. In power consumption modelling, there are two interesting areas, which are based on performance improvements of power amplifier (PA) and baseband (BB) function. There are four types of power consumption modelling, which are based on modelling the effect of different elements of each BTS or eNodeB. Due to different kind of traffic and coverage situation, there are different types of base station such as indoor, outdoor, centralized, distributed, micro, pico, and femto. In each of these types, there are some common elements and other extra components. For example, indoor sites have to have an external cooling system in container or room, its power consumption does not include in the base station power consumption modelling and for outdoor sites, cooling system or climate control included, and it affects the power consumption of the base station. Another part of base station that attracted some part of research is baseband function [10]-[12]. The aim is to find out power hungry blocks and baseband functions for saving more energy, as a result less power consumption will be gained. In [13] power consumption breakdown for different types of base station have been discussed and summarised as shown in Figure 6. It shows that PA is the major part in the macro and micro sites, and BB is the dominant part in pico and femto sites. In the next sub section, some models are presented.

<table>
<thead>
<tr>
<th>MSC Index</th>
<th>Modulation</th>
<th>SNR (dB)</th>
<th>Coding Rate</th>
<th>Efficiency (bits/symbol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>32QAM</td>
<td>10.0</td>
<td>1/2</td>
<td>0.12</td>
</tr>
<tr>
<td>2</td>
<td>32QAM</td>
<td>10.0</td>
<td>1/2</td>
<td>0.12</td>
</tr>
<tr>
<td>3</td>
<td>64QAM</td>
<td>10.0</td>
<td>1/2</td>
<td>0.12</td>
</tr>
<tr>
<td>4</td>
<td>QPSK</td>
<td>5.0</td>
<td>1/2</td>
<td>0.12</td>
</tr>
<tr>
<td>5</td>
<td>QPSK</td>
<td>5.0</td>
<td>1/2</td>
<td>0.12</td>
</tr>
</tbody>
</table>

In micro base station modelling, there is not any cooling system and battery backup. In general, there are one sector and one PA, and the transmit power is less than macro site and coverage radius is up to 100 m. In the micro site, the dominant part is baseband part in contrast to macro sites that PA is dominant part in dependent of different load. For this reason, it is divided into static and dynamic part as following formulas:

\[
P_{(BS, Micro)} = P_{(static, Micro)} + P_{(dynamic, Micro)}
\]

\[
P_{(static, Micro)} = (\frac{P_{TX}}{\mu_{PA}}) C_{TX, static} + P_{SP, static}(1 + C_{PS})
\]

\[
P_{(dynamic, Micro)} = (\frac{P_{TX}}{\mu_{PA}})(1 - C_{TX, static})
\]

\[
C_{TX, static} = N_{Sector} N_{PAPSec} \frac{P_{TX}}{\mu_{PA}} (1 + C_{C})(1 + C_{PSBB})
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\[
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\]

\[
C_{TX, static} = N_{Sector} N_{PAPSec} \frac{P_{TX}}{\mu_{PA}} (1 + C_{C})(1 + C_{PSBB})
\]

1) Arnold (Alcatel-Lucent) Model: This model can be used for both macro and micro sites. In this model, power consumption is divided into two parts, which are constant or variable. The constant parts make static power consumption, and dynamic part will be affected by variation of power consumption of some elements in the different load situations of base station. Each site’s signal can be broadcasted via some sectors and in each of them, there is some similar equipment such as feeder, antenna and these elements did not include in this model. However, the PA of each sector can be different. Therefore, in the macro site, it can be modelled based on the number of sectors, the number of PAs, the output power of TRX, the signal processing overhead, the cooling loss, the battery backup, and the power supply losses, which are shown in Table 3 and the following formula [3]:

\[
P_{(BS, Macro)} = N_{Sector} N_{PAPSec} \frac{P_{TX}}{\mu_{PA}} \frac{1}{(1 + C_{C})(1 + C_{PSBB})}
\]

### Table 3

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>N_{Sector}</td>
<td># Sectors</td>
<td>N_{PAPSec}</td>
<td># PAs per sector</td>
</tr>
<tr>
<td>P_{TX}</td>
<td>TX Power</td>
<td>\mu_{PA}</td>
<td>PA efficiency</td>
</tr>
<tr>
<td>P_{SP}</td>
<td>Signal processing overhead</td>
<td>C_{PS}</td>
<td>Cooling loss</td>
</tr>
<tr>
<td>C_{PSBB}</td>
<td>Battery backup and power supply loss</td>
<td>\mu_{PA}</td>
<td>PA efficiency</td>
</tr>
</tbody>
</table>

Fred Richter et al. [4]-[6] have extended this model, and they suggest that power consumption is divided into two constant and variable components. The constant part makes static and load independent power consumption; the dynamic part is associated with variation of load in distinct conditions.

2) ETSI Model: This model is based on ETSI recommendation [7] for different types of macro sites like concentrated and distributes base station for different types of radio access
such as GSM/EDGE, WCDMA, and WiMAX. The differences between concentrated and distributed base station are in the usage of some units in remote distance from main equipment, and it causes more power consumption items. The power consumption is modelled based on three different load situation of high, medium, and low. The average power consumption of centralized base station equipment is modelled as follows:

\[ P_{\text{equipment}} = \frac{P_{BH} T_{BH} + P_{med} T_{med} + P_{low} T_{low}}{T_{BH} + T_{med} + T_{low}} \]  

(7)

where \( P_{BH} \), \( P_{med} \), and \( P_{low} \) are power consumption and \( T_{BH} \), \( T_{med} \), and \( T_{low} \) are time duration in high, medium, and low load respectively. After calculation of equipment power, base station power can be modelled as:

\[ P_{\text{site}} = P_{\text{equipment}} P_{SF} C_F \]  

(8)

where \( P_{SF} \) and \( C_F \) are power supply and cooling factor respectively. This model can be extended to distributed model by increasing the effect of remote equipment to centralized part. \( P_{SF} \) is 1.0 for AC and 1.1 for DC power supply. \( C_F \) is 1.05, 1.5, 1.1 for indoor sites with fresh fan, indoor sites with air conditioner, and outdoor base station respectively.

3) Deruyck Model: This model [8], [9] can be used for both macro and micro sites. It describes the relation between average radiated power and input power of macro and micro base stations using the aforementioned power consumption model. For macro site, it can be written as following:

\[ P = a_{ma} P_{tx} + b_{ma} \]  

(9)

where \( a_{ma} \) is dependent to all of the elements of the first aforementioned model except the signal processing and other part, which are independent of transmit power and are accounted as \( b_{ma} \). Micro site modelling based on the first aforementioned model assumption can be written as:

\[ P = (a_{ma,dyn} L + a_{ma,stat}) P_{tx} + (b_{ma,dyn} L + b_{ma,stat}) \]  

(10)

where \( L \) is the load condition, which has a variation from 0 to 100 per cent. \( a_{ma,dyn}, a_{ma,stat}, b_{ma,dyn}, \) and \( b_{ma,stat} \) are load dependent and independent coefficients respectively. One example of these parameters is depicted in Table 4.

<table>
<thead>
<tr>
<th>BS Type</th>
<th>( P_{max} ) [W]</th>
<th>( P_{O} ) [W]</th>
<th>( \Delta_{p} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macro</td>
<td>40</td>
<td>712</td>
<td>14.5</td>
</tr>
<tr>
<td>Micro</td>
<td>6.3</td>
<td>106</td>
<td>6.35</td>
</tr>
<tr>
<td>Pico</td>
<td>0.25</td>
<td>14.9</td>
<td>8.4</td>
</tr>
<tr>
<td>Femto</td>
<td>0.1</td>
<td>10.1</td>
<td>15</td>
</tr>
</tbody>
</table>

D. Energy Efficiency Metrics

In this section, we give a brief overview of energy efficiency or energy consumption metrics, which are introduced by many papers, where the most important of them can be found in [27], [28]. According to these references, three types of metrics have been defined as follows;

1) Energy Consumption Rate (ECR) or energy per bit: It can be derived from the ratio of the average network power to the average data rate, and can be formulated as following:

\[ ECR = \frac{P}{R} \text{(Jules/bit)} \]  

(12)

2) Power per area unit, which is defined as division of the average network power usage by the coverage area of the network and can be measured by Watt per m² (W/m²).

3) Energy Reduction Gain (ERG) in percentage: It shows the percentage of saved energy in each network and is formulated as follows:

\[ ERG = 1 - \frac{ECR_{Ref}}{ECR_{Test}} \% \]  

(13)

where \( ECR_{Ref} \) is the ECR value in case of fixed transmit power and \( ECR_{Test} \) is the ECR value in operation case with required transmit power.

E. Scheduling and Radio Resource Allocation Algorithms

Radio resource management and allocation schemes are the key operational techniques that allow a wireless access network operator to optimize utilization of the available spectrum that suits its needs. Dynamic resource allocation by scheduling is particularly a popular technique that is widely proposed for packet switched networks. Figure 7 depicts the LTE functional split between eNodeB and EPC (Evolved Packet core), where yellow boxes show the logical nodes, white boxes depict the functional entities of the control plane, and blue boxes depict the radio protocol layers. Scheduler is located in eNodeB and that is why we focus on eNodeB to review existing radio resource allocation algorithms in LTE. In this section, brief overview of some defined schedulers [29]–[31] is given.

In [29], a good survey about scheduling algorithms has been done. It categorized schedulers to time and frequency opportunistic in uplink and downlink. Despite 3GPP Release 6 HSDPA, which uses time opportunistic schedulers, 3GPP LTE uses both frequency and time by adopting FDMA techniques. Although both time and frequency schedulers can be used in uplink and downlink, the main difference of them is that in uplink, it is not needed to report channel quality status. These schedulers were defined to maximize some objective function.
such as overall system throughput or fairness-sensitive metrics in regard to or regardless of channel quality status feedback. For instance, Round Robin (RR), which is a basic scheduler is blind to channel variations but has maximum fairness. The performances of different aspects of schedulers in various scenarios for diverse service such as VoIP, web browsing, and so on have been discussed in this survey paper.

In [30], some scheduling techniques such as Proportional Fair (PF) and Best Channel Quality Indicator (BCQI) were discussed and a new scheduler, which used Mutual Information Effective SNR Mapping (MIESM) for calculation of the average CQI value is proposed and compared its performance with other schedulers.

Some schedulers were discussed for IEEE 802.16 network [31], and a novel scheduler for non-real-time polling service based on the cross layer scheme, which consider both Automatic Repeat request (ARQ) mechanism at the media access control layer and the adaptive modulation and coding technique at the physical layer. Some of the principle schedulers, which are introduced in those papers, are summarized in the following subsection.

The main concept of scheduling is the allocation of each PRB to the appropriate user who has the best performance according to defined utility function or metrics. In general, there are two different types of schedulers; channel aware and regardless of channel condition. Conventional Round Robin is an example of regardless of channel quality, and Proportional Fair (PF) and Best Channel Quality Indicator (BCQI) are sensitive to channel conditions. In [18]–[20] some of these schedulers in DL have been discussed and their performances from different point of view such as throughput, fairness, and Quality of Service (QoS) requirement have been compared. Besides the channel condition, buffer status also included in scheduling decision [32]. Therefore, in the next subsections, three samples of these principle schedulers are discussed in detail.

1) Round Robin (RR) Scheduler: In this scheduling scheme, all of users have similar priority, and it assigns PRBs in fair turn to all active users as shown in Figure 8.

2) Proportional Fair (PF) Scheduling: PF scheme selects users based on normalized achievable rate at each time slot. The normalized achievable rate for each user on each PRB is calculated by dividing the rate that can be achieved according to the value of SNR on that particular PRB to the average throughput of the users up to that particular time slot. In other words, the decision parameter for user \( k \) at TTI \( t \) is given by \( R_k(t)/T_k(t) \), where \( R_k(t) \) is the achievable rate according to the SNR value, and \( T_k(t) \) is moving average of the instantaneous rate of user \( k \), given by:

\[
T_k(t + 1) = \begin{cases} 
(1 - \frac{1}{T_c})T_k(t) + \left(\frac{1}{T_c}\right)R_k(t), & k = k^* \\
(1 - \frac{1}{T_c})T_k(t), & k \neq k^* 
\end{cases}
\]  

where \( T_c \) is the time constant of moving average filtering. \( R_k(t) \) is equal to \( R_k(t) \) if user \( k^* \) is selected at TTI \( t \), and 0, otherwise. This scheduling techniques is summarized in Figure 9.
3) Best Channel Quality Indicator (BCQI) scheduler: BCQI scheduler selects the user with the highest Channel Quality Index (CQI) at each TTI for each PRB. The flowchart for this technique is depicted in Figure 10.

F. Traffic models

According to review of traffic models in LTE, there are five traffic categories [33], [34], summarized in Table 6.

<table>
<thead>
<tr>
<th>Application</th>
<th>Traffic Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>FTP (UL/DL)</td>
<td>Best effort</td>
</tr>
<tr>
<td>Web Browsing / HTTP (UL/DL)</td>
<td>Interactive</td>
</tr>
<tr>
<td>Video Streaming (UL/DL)</td>
<td>Streaming</td>
</tr>
<tr>
<td>VoIP (UL/DL)</td>
<td>Real-time</td>
</tr>
<tr>
<td>Gaming (UL)</td>
<td>Interactive real-time</td>
</tr>
</tbody>
</table>

Each traffic model is defined by appropriate distribute function and their relevant parameters. VoIP, which is selected for our research is defined as a 2-state Markov model for ON/OFF VoIP traffic, as shown in Figure 11. The probability of being in active and inactive states denoted by $P_0$ and $P_1$ respectively, which is given by:

$$P_0 = \frac{a}{(a + c)}, \quad P_1 = \frac{c}{(a + c)}$$ (15)

where $a$ and $c$ are probability of transition from state 1 to 0 and vice versa. The source rate is 12.2 Kbps and generates voice frame every 20 ms with 244 bits in active state. The total protocol overhead per voice frame is 76 bits. Thus, a total number of 320 bits (244+76 bits) is transmitted over the air interface per frame.

G. Energy efficient Scheduling Algorithms

Energy efficiency of various scheduling schemes has a paramount importance. The existing scheduling schemes traditionally are optimized to improve spectral efficiency of access networks. In the following section, we want to review some papers to define the state-of-the-art algorithms in energy efficient scheduling. In this area [22], [23], there were two main ideas; first, bandwidth trade-off; then, adaptive multi-user resource and power allocation. We discuss these two ideas in more detail in the following subsections.

1) Bandwidth Trade-off: The basic idea of the proposed scheduling scheme [22] stemmed from the fundamental trade-off between bandwidth and transmission power according to Shannon’s capacity model for a point to point communication system over an AWGN channel between a transmitter (Tx) and a receiver (Rx), given by:

$$C = B \log_2(1 + SNR) = B \log_2(1 + P_{RX}/N),$$ (16)
where $C$ is the link capacity in bits per second. $B$ is the channel bandwidth in Hertz; SNR is the signal to noise power ratio at the input of the detector at the Rx side; $P_{RX}$ is the power of the received signal and $N$ is the power of additive noise, both at the receiver side. Although this equation is only a theoretical bound, we can see that if $C$ is fixed and the transmission bandwidth ($B$) is increased, the required SNR or transmit power can be decreased to preserve transmit energy. They made a theoretical treatment and defined a score based algorithm and compared their performance in terms of energy consumption gain and data rate.

2) Adaptive Multi-User Resource and Power Allocation: In this paper [23], the authors present some radio resource management strategies in order to lower the power consumption of BS in terms of aforementioned Joules/bit metric. These strategies adopted link adaptation (LA), multi-user diversity, and trading bandwidth for energy saving. By taking account of these strategies, they proposed a multi user adaptive power and resource scheduling algorithm by maintaining the same level of the service requirement for the user. They applied their strategies to downlink LTE and gained up to 86% energy saving according to traffic load conditions.

In both of the aforementioned algorithms, there are some drawbacks and gaps that mentioned as following and that is the start point of our research.

- Rate adaptation was considered, which is unsuitable for delay tolerant traffic such as VoIP as they aim to satisfy rate requirements of the users, not delay.
- A constant rate per user traffic model is used and there is no difference between traffic sources such as real time(VoIP), unreal time, video streaming, online gaming, FTP, WWW, and Email.
- Full buffer for arrival packet was assumed, and they can use ON/OFF traffic source instead for low load condition.
- Full buffer for arrival packet was assumed, and they can use ON/OFF traffic source instead for low load condition.
- They did not evaluate the PDR (Packet Drop Rate) due to the buffer overflow as a QoS metric and only throughput was mentioned.
- The effect of users’ buffer length was not considered, and it is the important difference between our proposed algorithm and this technique.
- Energy consumption of BS was not measured in each TTI.
- Power consumption model, which simulates effects of BS power consumption elements such as cooling system, power amplifier, and so on in their numerical results was not mentioned.

3) Scheduling based on power consumption: In this patent [44] power efficient scheduling technique for transmission of application data over a radio interface in network node of a wireless communications system is proposed. This scheduling algorithm has four steps to transmit an amount of data in a time interval;

- Information about power consumption profile of a transmit unit is received.
- Information about estimated required average output transmission power is received.
- Make scheduling decision.
- Provide scheduling order to transmit unit.

The proposed scheme in this patent saves energy in both uplink and downlink to increase battery life of mobile and decrease power consumption of BS. Power consumption of transmit unit is linear function of output transmission, i.e.,

\[
\text{ConsumedPower} = \text{Constant} + K \times \text{TransmissionPower}
\]

The proposed scheme in this patent has some drawbacks as follows.

- This technique is only power aware and it is not fair scheduler.
- They did not evaluate PRB assignment.
- The impact of buffer length was not considered.
- The QoS metrics did not include.

4) Power-Aware Link Adaptation with Variable Bandwidth Allocation: The propose method in this patent [45] method is applied to reduce power consumption of mobile terminal during data transmission with energy efficient resource allocation and link adaptation, based on data rate requirement and channel quality conditions. The joint combination of transmit parameters such as modulation format, coding scheme, transmit power, and multiple antenna transmit schemes are considered to reduce energy consumption in uplink for SC-FDMA. This patent focuses on SC-FDMA for the uplink of LTE and reduces energy consumption of mobile terminals not base station.

III. BEYOND THE STATE OF THE ART

Based on the aforementioned scheduling algorithms, we found some gap in the state of the art. Therefore, finding the energy efficient scheduling scheme while considering both channel and buffer status is necessary to be aware of packet drop rate (PDR), which is affected by buffer overflow in the OFDM networks. To this end, the proposed energy efficient scheduling schemes in this research implement strategies based on observation of the outstanding demands in the data buffers. They exploit the random fluctuations of the demand to adapt the actual number of information bit transmitted per TTI from the station. Whenever the empty resource (PRB) is found in each TTI, the schedulers operate to reduce the payload of the transmission, reducing the coding rate. This allows the transmitter to reduce energy per TTI. However, we let the system operate always at full transmission bandwidth, i.e., all PRBs are always occupied. This allows the schedulers to adapt transmission power for the PRBs in each TTI, reducing energy consumption per TTI whenever possible. In other words, according to the aforementioned principle, the bandwidth is traded off for energy, whenever possible. This strategy is implemented based on the Adaptive Modulation and Coding (AMC) facility of the 3GPP LTE standard, using the information provided in Table 2. Energy efficient schedulers first decide the number of information bits that needs to be
transmitted in each TTI. Then, they decide the most energy-efficient AMC for each PRB in that particular TTI. This helps to reduce the amount of energy consumed in each TTI, resulting in overall reduction of the transmission energy. This strategy is applied to the three principle Scheduling schemes; RR, BCQI, and PF, to propose three energy efficient schedulers: 1) Energy Efficient Round Robin (EERR); 2) Energy Efficient Proportional Fair (EEPF); 3) Energy Efficient Best Channel Quality Indicator (EEBQCI) to guarantee certain fairness among users while achieving higher system throughput and fewer packet loss.

In addition, for proving the simulation results, introducing numerical analysis is another gap in this area. So, we will aim to define an objective function, which is monotonically decreasing or strictly convex, to model energy consumption in terms of transmitted power, rate, and bandwidth by using the Shannon and energy formula. We are seeking to find optimal trade off strategies between energy and bandwidth subject to some defined constraints such as maximum rate, buffer length, delay, and so on by adopting optimization algorithms such as the Lagrangian method to find the optimal solution similar to some methods that are discussed in [35]-[42]. The Lagrangian multiplier converts the constrained optimization problem to an unconstrained one.

Additionally, modification of the proposed scheme in LTE-Advanced, while taking into account carrier aggregation could prepare an appropriate research filed, that we are aim to investigate. In this standard, maximum data rate in DL is about 1Gbit/s and in UL is about 500 Mbit/s, which is prepared by introducing four major changes in comparing with LTE [43]; 1-using carrier aggregation (CA) up to 100 MHz. 2- adopting enhanced multi antenna transmission up to eight in DL and four in UL (MIMO 8*4). 3- implementation of coordinated multi point transmission and reception, which is called CoMP. 4- using relays to decrease distance between transmitter and receiver to achieve higher data rate. Therefore, we would like to evaluate the performance of our proposed schedulers and technique in this network as an example to save more energy besides the other benefits of LTE-Advanced.

IV. SUMMARY AND CONCLUSION

To summarize, most of the proposed algorithms have tried to reduce power and energy in access network area. As mentioned in this survey, improvement of radio resource management and allocation is a key performance to optimize energy and power consumption of OFDM wireless networks. Most of the recent proposed algorithms tried to enhance and define new scheduling algorithms by taking into account different metrics. Therefore, finding comprehensive energy efficient scheduler that optimize overall energy consumption, is emerging as a controversial issue.

REFERENCES


