Radio Resource Management for Green 3GPP Long Term Evolution Cellular Networks: Review and Trade-offs

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Abstract

Conventional design of cellular systems aims to maximize the system capacity and spectral efficiency due to sustainable growth of data rate requirements. As the energy consumption becomes relatively high, energy-efficient design for cellular systems is highly required to save energy as well as reducing the undesirable carbon dioxide emitted by these systems. However, reducing the energy consumption will degrade other system performances such as the data rate and quality of service. Therefore, joint optimization for overall system performances should be achieved. In this paper, the energy-efficient radio resource management (RRM) for Long Term Evolution (LTE) systems is addressed. After a brief introduction to LTE radio resource block and LTE frame, different types of energy efficiency metrics are defined to give a better understanding to the energy efficiency perspectives. The energy-efficient approaches related to link adaptation and RRM are explained. The state-of-the-art energy-efficient schedulers are also discussed, and a comprehensive comparison between them is adopted in this paper. Moreover, many trade-offs, challenges, and open issues are addressed to optimize the system performances.

Keywords

Adaptive modulation and coding, Energy efficiency, Green communication, Link adaptation, Multi-input-multi-output, Orthogonal frequency division multiple access, Resource allocation, 3GPP long term evolution.

1. Introduction

Escalation of wireless and cellular systems continues to stir up new research avenues that enable these systems to meet the growing demands and to work under various limitations. "Green Radio Technology" [1,2] is among areas which have been adopted recently to overcome the limitations in the radio spectrum as well as reducing the energy consumed by the wireless systems.

The limitation in radio spectrum comes from the fact that the spectrum is fixed and it is not free. The more wireless applications and technologies used, the more bandwidth required. Wireless data traffic has increased in recent years due to the variety of applications and smart software and devices. It has also increased due to the presence of many social networking applications through the internet, such as Facebook and Twitter. Moreover, it has been expected that this growth will continue increasing exponentially, especially with the exploitation of the 3GPP Long Term Evolution (LTE)-Advanced cellular networks, which should support up to 1 Gbps in the downlink transmission. Therefore, the radio spectrum resources should be utilized as efficiently as possible to overcome the bandwidth limitations.

On the other hand, the continuous growth in wireless data traffic results in the increase of energy consumed by wireless networks, which leads to undesirable increase in carbon dioxide (CO_2) emission. For example, the total energy consumed by a network of 20,000 3G base stations is about 58 MW, resulting in an annual cost of $62 million and a carbon footprint of 11 tons for each cell site [3]. The CO_2 emission is considered as the chief greenhouse gas that resulted from wireless networks and other human activities, and causes the global warming and climate changes. Stephen Ruth in [4] has investigated several leading approaches that have been used to reduce the CO_2 emitted by information and communications technology. Although there are serious efforts to reduce the amount of CO_2 emission per mobile subscriber, as shown in Figure 1 [5], cleaner and efficient solutions for wireless communications is urgently required.

The cellular network power consumption can be classified into five categories as shown in Figure 2 [6]. These categories give us an insight into the possible research avenues for reducing energy consumption in cellular network. It is obviously noticed that the major amount of the cellular network power is consumed by the base stations. However, the power consumed by transmission process is also momentous due to the sustainable growth of data rate requirements. Therefore, in this paper, we will address the energy-efficient approaches that can reduce the energy consumption in the core transmission. Unlike most of the review articles available in the literature related to green communications [6,7], this paper discusses exclusively the energy-efficient link adaptation and resource scheduling techniques related to 3GPP LTE systems.

In energy-efficient link adaptation, we carry out a detailed survey on adaptive modulation and coding (AMC), power control and multi-input-multi-output (MIMO) antenna, and highlight the research opportunities that make these techniques green. Although the link adaptation needs more control signaling, it is shown that adapting some or all of these link properties will help the system to maximize its energy efficiency. Moreover, link adaptation alongside with the gain of multiuser diversity will give the cellular systems more flexibility to make a proper decision in allocating the radio resources among users. Therefore, energy-efficient radio resource management (RRM) is also discussed in this paper. A comparison between the state-of-the-art energy-efficient resource schedulers is carried out. Furthermore, many types of trade-offs between the energy efficiency, spectral efficiency, fairness, and delay are investigated to meet the 3GPP LTE requirements.

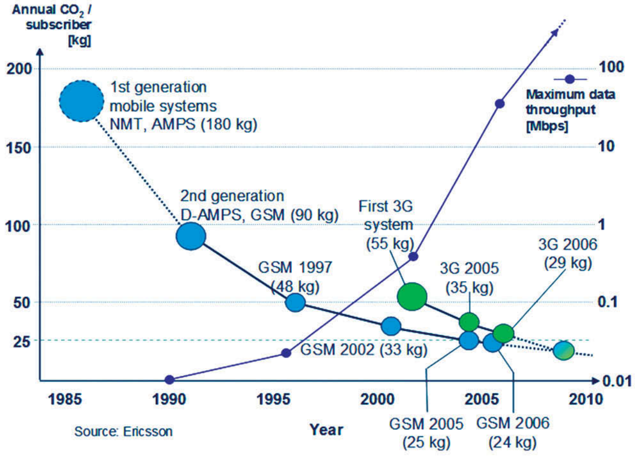

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Figure 1: The amount of CO_2 emitted per subscriber [5].

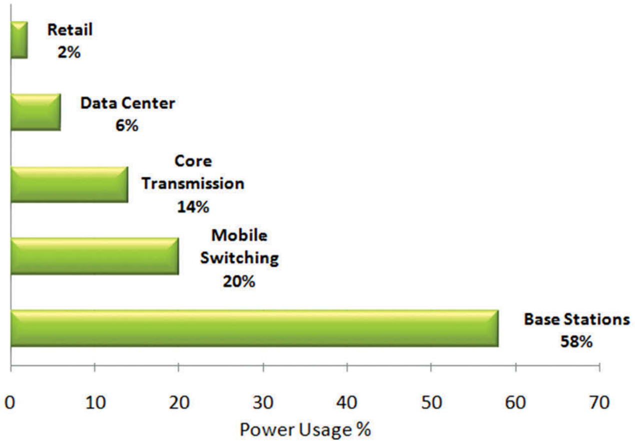


Figure 2: Power consumption of a typical wireless cellular network.

The rest of the paper is organized as follows. In Section 2, a brief overview to LTE radio resource block (RB) and frame structure is introduced. Then, the energy efficiency with the related radio transmission metrics is defined in Section 3. In Section 4, a review of the energy-efficient cellular transmission by using energy-efficient link adaptation strategies is provided. Section 5 will cover various energy-efficient resource allocation procedures and algorithms proposed in the literature. Finally, conclusions and recommendations for future work are discussed in Section 6.

2. LTE Radio Resource Management

RRM is essential for LTE cellular networks because of the scarceness of radio resources which should be shared by multiple users. The RRM involves many strategies to utilize the limited power and bandwidth resources in an efficient way whereby a reliable transmission is satisfied. Furthermore, the radio resources can be managed to achieve a spectral-efficient transmission with high throughput and low latency, which is highly required for LTE networks. The RRM is usually categorized into two parts, scheduling and resource allocation. The scheduler normally decides which user to be served and determines the number of packets that should be scheduled in the current frame. However, the resource allocator decides which RB is assigned to the selected user, and determines the number of RBs required for satisfying the user requirements. The resource allocator assigns RBs to user with the best channel condition and/or according to their QoS requirements in order to improve the overall system performances. RB is a block of 12 subcarriers in the frequency domain and 7 (or 6) symbols in time domain. Hence, there is a grid of 84 resource elements per RB, each can be represented by 2, 4, or 6 bits depending on the type of used modulation as shown in Figure 3 [8]. In the frequency domain, the LTE transmission bandwidth can be chosen between 1.4 to 20 MHz due to the non-utilized spectrum, and thus, there will be different numbers of RBs to be allocated to the users according to the used channel bandwidth as shown in Table 1. In the time domain, the 10 ms LTE

Table 1: LTE channel bandwidth

Channel bandwidth [MHz]	1.4	3	5	10	15	20
Transmission bandwidth [MHz]	1.08	2.7	4.5	9	13.5	18

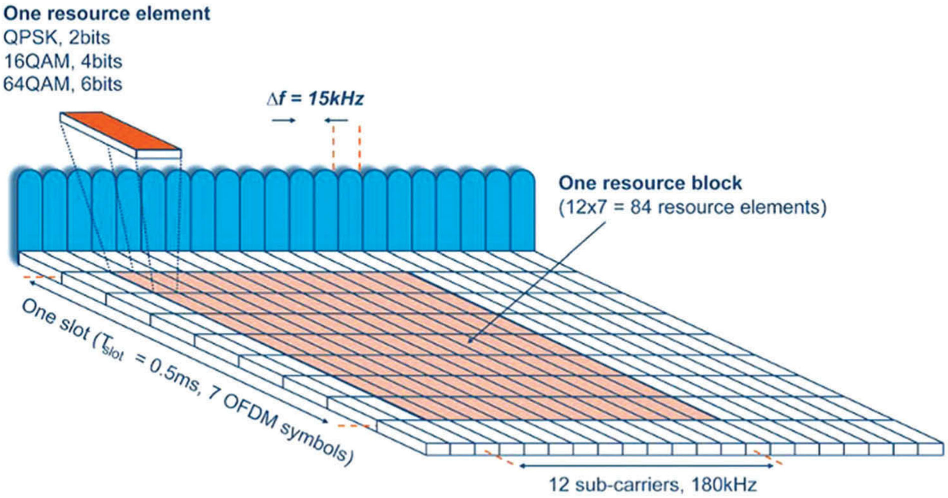


Figure 3: The LTE downlink physical resource based on OFDM.

frame is divided into 10 subframes with each consisting of two 0.5 ms time slots. The 0.5 ms time slot represents the time duration of each RB. Further information on LTE frame structure can be found on [8].

3. Energy Efficiency Metrics

In general, "The more energy-efficient the communication system is, the less energy it needs to achieve the same task" [9]. However, energy efficiency can be defined in different ways according to the purpose of designed system. And accordingly, the energy efficiency metrics can be addressed. Rather than the definition, the energy efficiency metrics should reflect how green the wireless system is. Therefore, the energy efficiency metrics can be classified into three categories [10], component-level, equipment-level, and system-level metrics.

The component-level metrics include low-level energy efficiency rating for individual parts inside the wireless equipments; antenna system, baseband processor, etc. In the equipment level, metrics should reflect the energy efficiency of whole base station or wireless access point [11]. Finally, system (network) level metrics would consider the energy efficiency for the entire network. This level metrics can be classified according to the classes of wireless network such as cellular, wireless local area network, ad-hoc, and satellite networks. In this paper, we will discuss some of these metrics which are related to data transmission of LTE cellular systems.

3.1 Transmission Energy Efficiency

The number of bits transmitted per joule of energy reflects how energy-efficient the transmission link between the base station and the user equipment is. This metric represents the transmission rate energy efficiency which is given by [12]

$$U(R) = \frac{R}{P(R)} = \frac{R}{P_t + P_c}, \tag{1}$$

where, P_c is the circuit power consumption, P_t is the transmit power, and R is the achievable data rate.

3.2 Energy Consumption Rate

Energy consumption rate (ECR) is a framework for measuring the energy efficiency of network and telecom devices [13]. This metric is considered as a valid differentiator between the networking and telecom equipments. For example, equipment with lower ECR consumes less energy to drive the same amount of payload. The ECR can be defined as the consumed energy divided by the effective full-duplex throughput as given by

$$ECR = \frac{E}{T}, \tag{2}$$

where, E represents the energy consumption in watts, and T denotes the effective system throughput in bits per second. In LTE systems, it is highly required to determine the ECR corresponding to various base station equipments. The basic power consumption models of different base stations have been discussed in details in [14]. As shown in Figure 4, the basic equipments in base station are rectifier, power amplifier, baseband signal processing unit, feeder, antenna, and cooling systems. Moreover, the base station site may also incorporate other supports and/or supplementary cabinets that are not included with the base station main equipments, and it should be considered in the calculation of the ECR. Each of these equipments has different activity levels of power consumptions due to different load conditions, i.e. in LTE cellular networks, three activity levels are defined corresponding to the busy hour, medium term load, and low load [15].

3.3 Energy Reduction Gain

In order to compare between the performances of two systems, a useful metric called Energy Consumption Gain (ECG) can be used to show difference in energy consumption between the baseline and the new cellular system. In contrast, the energy reduction gain (ERG) [6] can be used to show the percentage in saving energy gain between two systems, and it can be calculated as

$$ERG = 1 - \frac{1}{ECG}, \tag{3}$$

ERG can determine the saving in energy consumption when there are two different systems having to deliver the same amount of data through the same duration of time. However, such metrics give relative measurements, and therefore, the energy-related calculations were not done in a fair manner.

3.4 Telecommunications Equipment Energy Efficiency Rating

Telecommunications equipment energy efficiency rating (TEEER) is an equipment-level metric that calculates the energy efficiency of individual pieces of cellular network equipments at various utilization levels. TEEER is proposed by Alliance for telecommunications industry solutions [16] to calculate the energy efficiency rating for specific products. Prior to calculate TEEER, the equipment under test (EUT) should be examined under three levels of utilizations which are 100%, 50%, and 25% for full-load, medium, and low utilizations, respectively. At each level, a corresponding required power should be provided to the EUT over a period of 15 minutes for stability purposes, and the value is recorded. Then, the total power consumption for this EUT can be represented by a weighting formula as

$$P_{total} = (0.35 \times P_{\max}) + (0.4 \times P_{50}) + (0.25 \times P_{sleep}), \tag{4}$$

where, P_{max}, P_{50}, and P_{sleep} are the measured input powers with the EUT while operating at maximum load, 50% of maximum load, and no activity mode, respectively. However, the weighting values may not be the same for all operators. According to the calculated value of P_{total} above, the TEEER can be calculated for different equipments according to the formulas shown in Table 2. TEEER metric is applicable for broadband, networks, and customer-premise equipments.

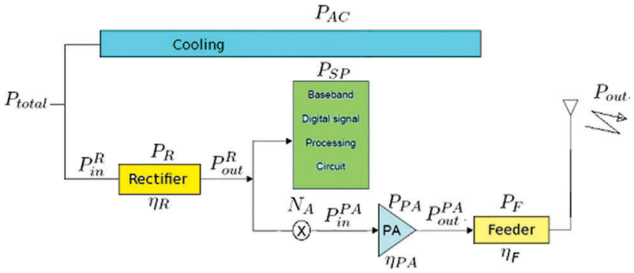


Figure 4: Power flow in the base station.

Table 2: TEEER formulas

Equipment type	TEEER formula
Soft Switch	-log(PTotal / BHCA)
Media Gateway	-log(PTotal / Throughput)
Video Multiplexer	-log(PTotal / BHCA)
Access	(Acess Lines / PTotal) + 1
Power	(POut Total / PIn Total) x 10
Power Amplifier (Wireless)	(Total RF Output Power / Total Input Power) x 10
Mechanized Distributing Frames	-log(PTotal / # of input connections)

4. Energy-efficient Link Adaptation

The link adaptation is a fundamental procedure that is related to adaptive resource scheduling [17]. It is used to adapt the link properties such as modulation and coding scheme (MCS), and MIMO rank and precoding according to the channel state. The resource scheduler will then select a user with good channel gain, and determine the required number of RBs for this user at a given transmission time interval. Thus, the required number of RBs for each user can be determined according to the used modulation order, level of transmitted power, and/or the number of transmitting antennas. Both, resource scheduling and link adaptation rely upon the available channel state information at the eNodeB. However, the adaptation in both link properties and resource scheduling is crucial for 3GPP LTE cellular systems to maximize the system performances. In this section, several energy-efficient link adaptation techniques such as AMC, power control, and adaptive transceiving antenna are discussed.

4.1 Adaptive Modulation and Coding

The most appealing feature of AMC is that it can adjust the transmission data rate and energy efficiency dynamically according to the channel condition. It is well-known that the low order modulation scheme is robust against higher level of interference; however, it provides lower bit rate. Therefore, low-order modulation is recommended when signal-to-interference-noise ratio (SINR) is low. Conversely, when the SINR is relatively high, the high modulation order will be the suitable candidate. The Channel Quality Indicator (CQI) plays an important role in determining the channel quality, and thus, the coding and modulation level can be recognized accordingly. In LTE cellular systems, it is important to know that the CQI reported by the UE is not a SINR direct indicator, but a 4-bit integer which shows the highest MCS that can be decoded by the user with a block error rate (BLER) not more than 10% [18].

The type of the receiver and number of antennas should be taken into account in the estimation process of the CQI value. By using this procedure, the UE can help the eNodeB in choosing the suitable MCS for data transmission. The LTE link level simulator presented by [19] shows the BLER-SINR curves which give the BLER value as shown in Figure 5. According to these curves, the MCS can be chosen adaptively to maintain the BLER lower than 10% as shown in Figure 6.

Most of the AMC techniques in the literature have been proposed to maximize the spectral efficiency. However, changing the constellation size has also been used to maximize the energy efficiency. In [20], the authors proposed a modulation scaling for saving energy. They proposed an energy aware packet scheduling system, and emphasized the analogy between the modulation scaling and voltage scaling. They proved that the modulation scaling exhibits benefits similar to that of voltage scaling, and, to some extent, it outperforms the voltage scaling in energy-aware systems.

In addition to change of the constellation size, the authors in [21] have ensured that the transmission time and the circuit energy should be taken into account in the energy consumption analysis. They have examined the MQAM and minimum frequency shift keying (MFSK) under the delay and peak-power constraints. It has been shown that there will be an energy saving of up to 80% when the transmission time is optimized, especially in short distance transmission.

Furthermore, coding in MQAM and MFSK is also examined in [21]. Trellis-coded modulation with MQAM has been studied and it outperformed the uncoded MQAM. However, in MFSK, coding can only reduce the consumed energy in large distance transmission.

For orthogonal frequency division multiple access (OFDMA)-based wireless networks, the authors in [12] and [22] have also proved that the adaptive modulation can help to optimize the energy efficiency. Although both works have considered the circuit power consumption in their analysis, different circuit power model has been adopted by each of them. In [12], the authors considered that the total power consumed by the base station is the transmitted power plus the circuit power consumption, without taking into account their relation to the used bandwidth. However, the authors in [22] have adopted the following circuit power model:

$$P_t = W\left(p_{tr} + p_c^t\right) + P_{sta}^t, \tag{5}$$

where, W represents the bandwidth used for transmission, and p_{tr} and p_c^t are the transmitted and circuit power

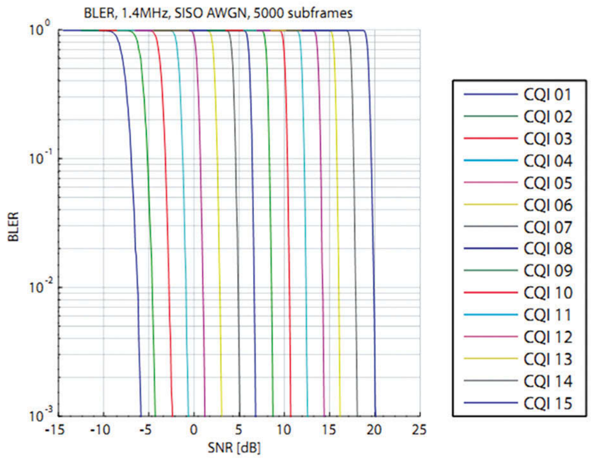


Figure 5: BLER curves in SISO AWGN simulations for all 15 CQI values. From CQI 1 (leftmost) to CQI 15 (rightmost).

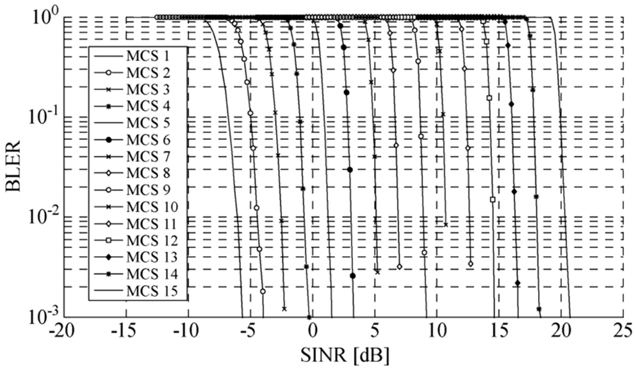


Figure 6: BLER-SNR curves for 1.4MHz with corresponding MCSs.

consumed for signal processing per unit bandwidth, respectively, which are both proportional to the transmission bandwidth. p_{sta}^t is the static power consumption that does not have any defined relation to the transmission bandwidth, i.e. the power supply and cooling systems. The latter model seems closer to the practical situation, and, by considering it in their analysis, the authors found that the modulation order should be adapted according to the channel condition to maximize the energy efficiency. As shown in Figure 7, it is clear that the system with adaptive modulation can transmit higher number of bits per Joule compared to other systems with fixed modulation order.

4.2 Power Control

Beside AMC, energy-efficient link adaptation can be obtained by adjusting other transmission parameters such as the transmitted power. Controlling the level of transmitted power can maximize the spectral efficiency [23,24], and at the same time can manage the intra-cell and inter-cell interference [25,26]. Thus, energy efficiency can also be optimized in the cellular networks by using energy-efficient power control techniques [27-29]. In [27] and [28], the game theory was proposed to solve the power optimization problem which aimed to maximize the number of bits per joule in a single-carrier, non-cooperative game scenario. For a multicarrier scenario, the authors in [29] modeled a non-cooperative game scenario whereby each user decides how much power can be transmitted over each carrier to maximize the energy efficiency. More details about other game-theoretic approaches used for energy-efficient power control can be found in [30].

The works shown previously optimize either the spectral efficiency or energy efficiency apart from showing the trade-off between them. Nevertheless, the authors in [31] address this trade-off by developing energy-efficient power optimization for a multi-cell interference limited environment. In order to understand this trade-off, the interference level can be defined as follows:

$$\alpha = \frac{\tilde{g}}{g}, \tag{6}$$

where, α is the interference coefficient, g is the channel gain per user, and $\tilde{g}$ is the interference channel gain. The increase in α may represent higher interfering scenario. Then, the energy efficiency over the entire network will become as [31]

$$u(p) = \sum_{n=1}^{N} \frac{w \log\left(1 + \frac{p_t g}{\sum_{i,i\neq n} p\tilde{g} + \delta^2}\right)}{p_t + p_c},$$

$$= \frac{Nw \log\left(1 + \frac{p_t}{(N-1)\alpha p_t + \left(\delta^2/g\right)}\right)}{p_t + p_c}, \tag{7}$$

and the network spectral efficiency will become as

$$r(p) = N \log\left(1 + \frac{p_t}{(N-1)\alpha p_t + \left(\delta^2/g\right)}\right), \tag{8}$$

where, N is the number of users, δ^2 represents the average noise power per a block of subcarriers assigned to user *n.* As shown in Figure 8, the energy efficiency is more sensitive to power optimization than the spectral efficiency, i.e. for α >0 scenario, any increase in the level of transmitted power beyond the energy-efficient optimal point will significantly hurt the energy efficiency while it slightly improves the spectral efficiency.

4.3 Adaptive Transceiving Antenna

MIMO is a well-known strategy which can be used to increase the spectral efficiency of wireless systems. In 3GPP LTE, both an alamouti-based Space-Frequency Block Coding (SFBC) and spatial multiplexing (SM) are proposed [32].

To further improve the cell edge throughput and the coverage, coordinated multipoint (CoMP) has been proposed in 3GPP LTE-Advanced [33]. Although MIMO techniques showed a significant improvement in spec-

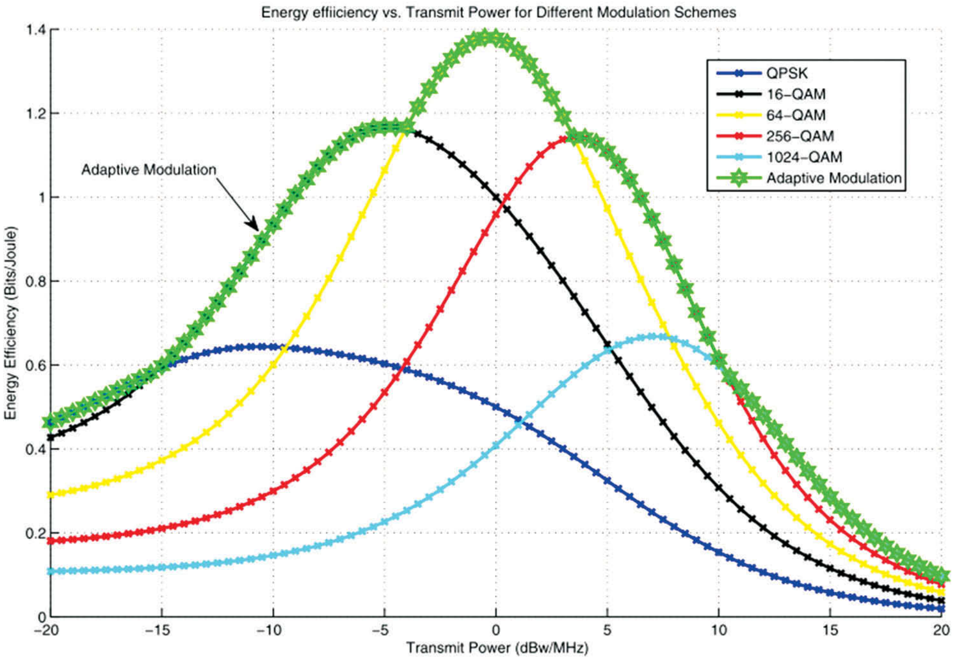


Figure 7: The energy efficiency performance versus the transmit power for different modulation schemes [22].

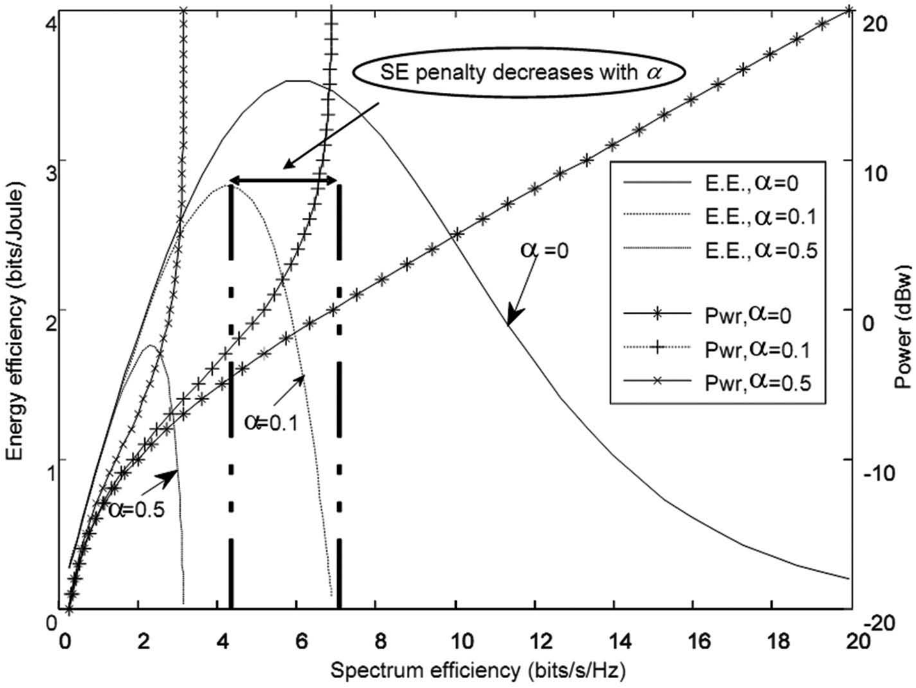


Figure 8: Tradeoff of energy efficiency and spectral efficiency with different interfering scenarios [31].

tral efficiency, energy efficiency can also be increased. MIMO can enhance both the spectral and energy efficiencies by providing diversity and SM gains. This assumption is true if the circuit power consumption is not considered in the calculation of energy efficiency. In other words, MIMO systems are not always more energy-efficient than SISO systems. Therefore, the authors in [34] have discussed the trade-off between the circuit power consumption and the transmission power in terms of energy required per bit. It is shown that the MIMO systems are less energy-efficient than SISO for short ranges unless the adaptive modulation is used to balance the circuit and transmit power consumption. In [35], a number of MIMO precoding techniques, which can be potentially applied to LTE, are examined in terms of their combined spectral and power-saving efficiency. These techniques are SFBC, Random Beamforming, Layered Random Beamforming, SU-MIMO, and MU-MIMO. The authors proposed a cost metric which is the aggregated power required for achieving a specific spectral efficiency, and they proved that MU-MIMO is the most power-efficient scheme. In addition to that, MU-MIMO is preferred in low mobility scenarios as the inter-user interference is small as shown in Figure 9. When the moving speed is high, on the other hand, the inter-user interference with MU-MIMO becomes more tangible, and therefore, the SU-MIMO will be the suitable scheme as shown in Figure 10. According to these facts, the authors in [36] proposed an adaptive switching technique to switch between the transmitting antenna modes according to the speed (value of interference) and the distance from base station. This switching technique proved a significant improvement in energy efficiency over the entire system. However, the energy efficiency for MIMO channels is fully analyzed in [37-39].

Although there was an extensive research on energy efficient link adaptation schemes, there are still more issues need to be considered to improve the energy efficiency. First, a near-exact power consumption modeling needs to be constructed for different network scenarios. Accordingly, the optimal energy efficient link properties can be obtained. For energy-efficient MIMO schemes, utilizing the spatial resources to maximize the energy efficiency and to mitigate the interference in a multi-cell environment is still an open issue. Furthermore, the closed-loop MIMO schemes were also proposed to enhance the spectral efficiency. However, the enhancement of closed-loop over open-loop SM MIMO schemes on the energy efficiency needs more investigation.

5. Energy-efficient Resource Allocation

Due to the high data rate requirements, OFDMA is proposed to represent the physical layer of LTE cellular systems. The bandwidth and power resources should be allocated to the users according to the designed system requirements. Most of the resource optimization problems that have been covered in the literature are to utilize the system bandwidth efficiently in order to maximize the sum of data rate capacity, which is known as “rate adaptive” [40-50]. Another resource optimization problem is known as "margin adaptive," which aims to achieve the minimum power consumption that guarantees the QoS requirements for all users [51-58]. A comprehensive overview of rate-adaptive and margin-adaptive for OFDMA resource allocation has been covered in [59,60].

However, the orthogonal frequency division multiplexing (OFDM) system, which is a basic element in OFDMA, addresses a big challenge from power consumption point of view. It requires RF power amplifier with high peak-to-average-power ratio as well as the complex electronic components including the fast Fourier transform

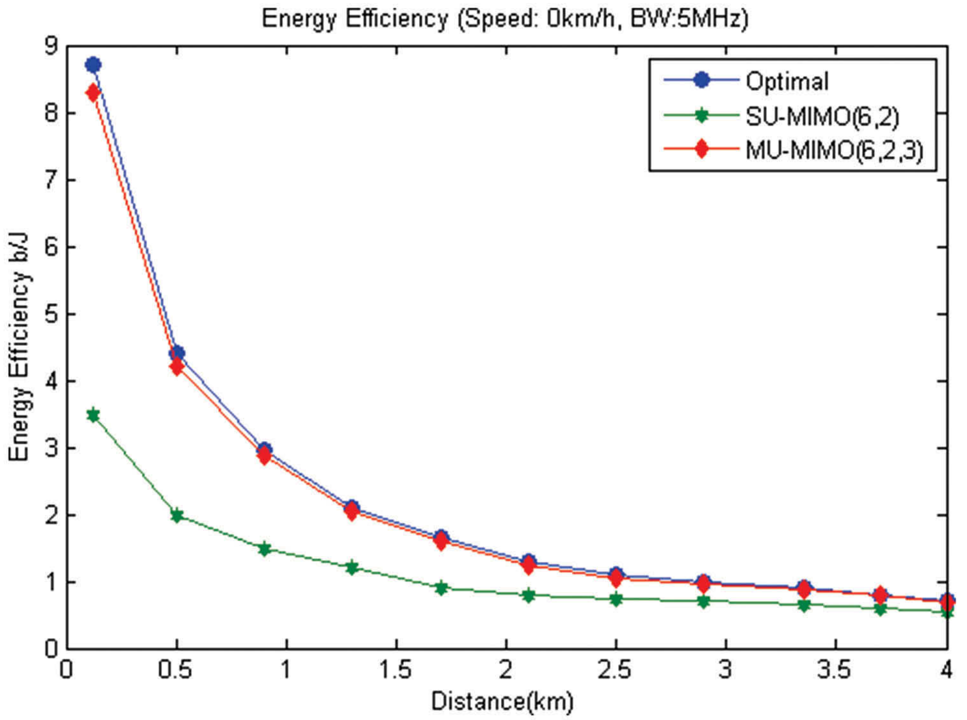


Figure 9: Energy efficiency in low speed mobility for MIMO switching mode.

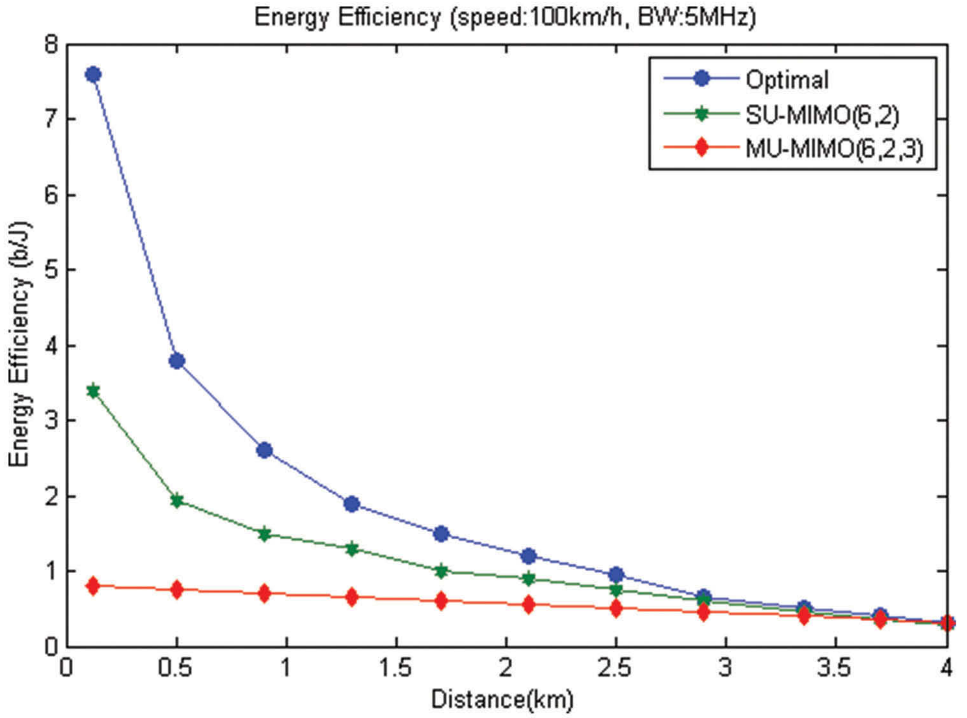


Figure 10: Energy efficiency in high speed mobility for MIMO switching mode.

and forward error correction which are not energy-efficient. Therefore, energy-efficient resource allocation has been adopted recently to accommodate the green wireless communications requirements. Energy-efficient resource allocation is a process by which the RBs, or subcarriers, would be allocated to users such that the bits transmitted per joule will be maximized over the entire network as given by

$$\max_{p,X[k]} \frac{\left(\sum_{j=1}^{J}\sum_{n=1}^{N}\log_2\left(1+\frac{p_n[k].g_{j,n}[k]}{\delta^2}\right).x_{j,n}[k]\right)}{P_c+\sum_{n=1}^{N}p_n[k]}, \qquad (9)$$

s.t.

$$\sum_{n=1}^{N}\log_2\left(1+\frac{p_n[k].g_{j,n}[k]}{\delta^2}\right).x_{j,n}[k]\geq R_j^{req},\forall j,$$

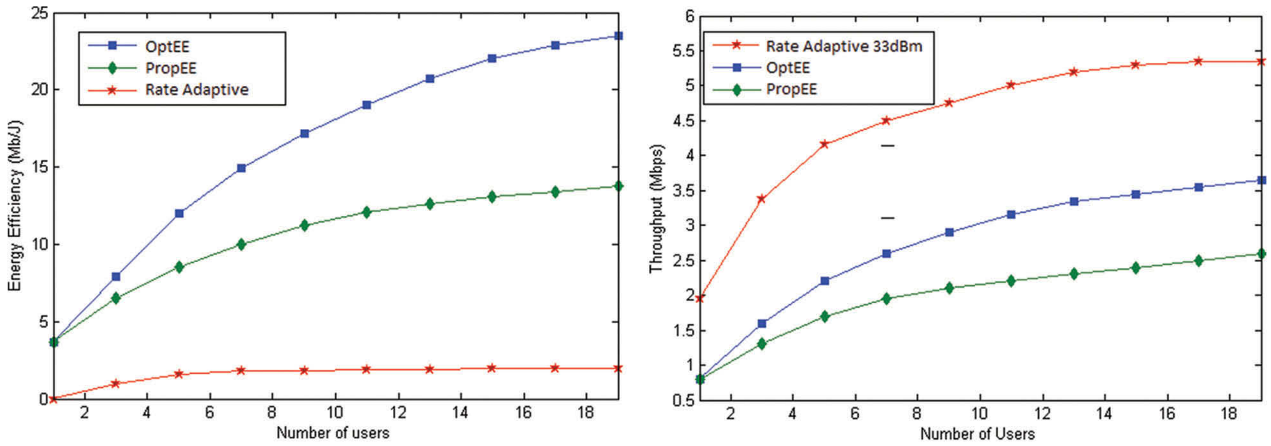
$$\sum_{j=1}^{J}x_{j,n}[k]\leq 1,\forall n,$$

where, J is the number of users, N is the number of RBs, δ^2 represents the average noise power per RB, p_n is the amount of transmitted power, and g_n is the average channel gain. The first constraint (10) guarantees the QoS requirements, while the second constraint (11) assures that the RB would be allocated to one user exclusively.

The initial work in this area has been done by authors in [12,61]. The authors proposed an energy-efficient resource scheduling algorithm for flat and selective fading OFDM channels. According to (9), the optimal energy efficiency (OptEE) is obtained by using an energy-efficient scheduler as shown in Figure 11. The OptEE has proposed that each user adapts the modulation order according to its channel condition by using AMC. Then, according to the used MCS, the number of RBs is assigned to each user. Each user, however, can choose the best RB which maximizes the energy efficiency over the entire system. Therefore, the OptEE scheduler achieves the best energy efficiency compared to rate adaptive scheduler with the fixed transmitted power of 33 dbm as shown in Figure 11a.

Although this approach can maximize the energy efficiency, it is not fair for users whose channel gain is low. In other words, the users with good channel gain will consume most of the RBs available greedily. Therefore, the proportional fairness alongside with the energy-efficient transmission (PropEE) algorithm has been applied to achieve fair resource allocation among users while achieving near-optimal energy efficiency [12]. While the energy efficiency can be optimized by using an energy-efficient resource scheduling, there will be a certain degradation in data throughput as shown in Figure 11b. Therefore, a trade-off between the energy efficiency and throughput should be defined according to the required QoS [62].

A latest work that considered the trade-off between energy efficiency and fairness for OFDMA systems is proposed by the authors in [63]. The authors have formulated the energy-efficient resource allocation by using game theory optimization. Normally, the resource allocation game considers the users as the players of the game. Each user can select the transmit power strategy due to his observation. Once the RB is included in the allocation process, the user is very unlikely to choose the best RB due to incongruity with the exclusive RB allocation. Therefore, by considering the RBs as non-cooperative players, the authors in [63] used energy-efficient correlated equilibrium (CE) to help the RBs to choose the most satisfying users. In other words, the CE is achieved when no user would want to deviate from the recommended RB. In order to implement the CE in [63], a linear programming optimization and a distributed algorithm based on the regret-matching procedure is used. Although this technique addresses high



(a) (b)

Figure 11: Comparison between OptEE, PropEE, and RA schedulers.

complexity compared to the energy-efficient scheduler with proportional fairness, it is a plausible concept which ensures Pareto optimality and fairness for any number of RBs and users.

Bandwidth Expansion Mode (BEM) is another approach that has been proposed in the design of energy-efficient resource allocation for LTE systems [64]. This approach can be used to save energy when the network is not fully loaded, whereby more RBs are not utilized by any user. In this case, the authors in [64] have suggested to trade-off the non-utilized bandwidth for the transmitted power by allocating more RBs to the users and switching back to lower modulation index, and hence lower transmitted power can be obtained. By considering the advantage of link adaptation, multi-user diversity, and allocation of spare spectrum, this algorithm has showed 79 to 86% energy reduction over a conventional non-energy aware scheduler throughout the day. Beside AMC, antenna adaptation is also examined with BEM algorithm by [64]. It has been revealed that MIMO with low modulation order is more energy-efficient than SISO with high modulation order. However, SISO is preferred for LTE when low spectral efficiency is required.

While more signaling overhead is required by BEM, the time compression mode (TCoM) that is complementary to BEM is another resource allocation approach proposed by authors in [65] to reduce the consumed energy by the signaling overhead. It allows the scheduler to reduce the number of allocated RBs to a user to save energy when the energy consumption is dominated by the signaling overhead. In this case, the authors in [65] proposed an energy-efficient score-based scheduler alongside with BEM and TCoM that should work together to reduce the energy consumption, while not compromising the fairness and data throughput. By using TCoM, the underutilized RBs are grouped together and turned off to conserve energy that would otherwise be wasted in control channel transmissions. The fully utilized RBs, on the other hand, are grouped together and a higher modulation order is used. A significant energy saving of 38% has been achieved by combining TCoM with BEM and EESBS compared to the frequency selective proportional fair which is proposed by [66]. A comprehensive summary for the aforementioned resource schedulers is shown in Table 3.

Although some researches on energy-efficient resource allocation have been done, there are many trends and challenges that need more exploration. For the time being, the energy-efficient RB allocation should consider the interference management and handoff strategies in a multi-cell environment, i.e. reducing transmitted power would save more energy and reduce the interference while sacrificing the cell-edge user performances. Moreover, the relay-cooperative cellular networks can also enhance the energy efficiency in addition to increasing in coverage area. However, the energy-efficient joint optimization of RBs along with the cooperative relays is still not cleared. Nevertheless, the resource allocation

Table 3: Energy-efficient resource schedulers, comparison

Scheduler	OptEE	PropEE	BEM	TCoM	EECE
Author (s)	Miao *et al*.- 2008 [12,61]	Miao *et et al* -2008 [12,61]	Han *et al*. -2011 [64]	Videv *et al*. -2012 [65]	Wu *et al*. -2012 [63]
Objective	To optimize the overall bits transmitted per Joule of energy in a network	To optimize both energy efficiency and fairness in a network	To maximize the EE with guaranteed QoS	To optimize energy efficiency, throughput and fairness	To balance the tradeoff between the total energy efficiency and the fairness
Solution	Energy-efficient resource scheduler	Energy-efficient scheduler with fairness	Power efficient link adaptation, exploitation of multi-user diversity and trading BW for energy efficiency	Trading BW for energy efficiency, controlling the overhead signals to save energy	Energy-efficient resource allocation scheme by using the correlated equilibrium (CE)
Methodology	Sorting-Search algorithm, and link adaptation (AMC)	Combined sorting-search algorithm, AMC, and proportional fairness	Allocating the spare (non-utilized) RBs, and switch to lower MCS	bandwidth expanded mode (BEM), and Time compression mode (TCoM)	Game theory, linear programming method and a distributed algorithm based on the regret matching procedure
Trade-off	Energy efficiency vs. Throughput (bpJ- bps)	Energy efficiency vs. Throughput (bpJ- bps)	Power vs. Bandwidth	Power vs. bandwidth, Energy efficiency vs. overhead	Energy efficiency vs. fairness
Enhancement	Highest energy efficiency can be obtained compared to PropEE, Round Robin energy-efficient scheduler RREE	Better energy efficiency than round robin energy-efficient scheduling and fairness guaranteed among users	Significant energy saving (up to 86%) over a conventional non-energy aware scheduler without losses in throughput when the network is not fully loaded	Energy saving of 38% over a frequency selective proportional fair (FsPF)	Good convergence, Pareto optimality and fairness

AMC – Adaptive modulation and coding; MCS – Modulation and coding scheme; PropEE – Energy efficient with proportional fairness; RREE – Round robin energy efficient scheduler; EE – Energy efficiency; QoS – Quality of service; BW – Bandwidth; RBs – Resource blocks process would affect the end-to-end service delay, and hence, another possible trade-off between the energy efficiency and service delay is addressed as discussed in [67,68].

6. Conclusion and Suggestions for Future Work

There is an imperative need to improve the energy efficiency in the overall communication networks due to the negative impact of emitted CO_2 on the environment. The radio transmission is among the main contributors of energy consumption inside the cellular systems. In this paper, the optimization of radio transmission is addressed by using the energy-efficient approaches, such as link adaptation and resource allocation. In link adaptation, we outlined the methodologies used in the literature to maximize the energy efficiency, such as AMC, MIMO, and power control. Beside the link adaptation, the RRM is addressed. It shows a considerable improvement in system performance when it works together with link adaptation. Furthermore, other system performances, such as the spectral efficiency and QoS, are investigated alongside with the energy efficiency by considering the trade-off between them. Nevertheless, many challenges still exist and require more investigation. For instance, the effect of inter-cell interference on energy efficiency in a MIMO-OFDM multi-cell scenario needs further study. Besides, the energy-efficient resource allocation with cooperative relay has not been considered in most of the previous work. The OFDM-relay technology is proposed for LTE-Advanced cellular systems to improve the cell-edge throughput. Therefore, the number of relays along with the other radio resources should be optimized to maximize the energy efficiency as well as improving cell coverage area.

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