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Link Adaptive Power Control and Allocation for Energy–Efficient Downlink Transmissions in LTE Systems

NADIM K. M. MADI[1], ZURINA BINTI MOHD HANAPI[1], (Member, IEEE), MOHAMED OTHMAN[2], (Member, IEEE), AND SHAMALA SUBRAMANIAM[1], (Member, IEEE)

[1]Department of Communication Technology and Networking, Universiti Putra Malaysia, Serdang 43400, Malaysia
[2]Computational Science and Mathematical Physics Laboratory, Institute of Mathematical Science, Universiti Putra Malaysia, Serdang 43400, Malaysia

Corresponding authors: Nadim K. M. Madi (nadeem.madi@gmail.com) and Zurina Binti Mohd Hanapi (zurinamh@upm.edu.my)

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ABSTRACT It is axiomatic that providing more transmission power by the cell, returns high data rates; but in contrary, more power is consumed which leads to energy exhaustion. The Quality of Service (QoS) in long term evolution urban macrocell networks gives a high concern to green communication by wisely utilizing the limited cell power to improve network performance. Nevertheless, in conventional schemes, it is observed that the maximum power assigned to the evolved Node B (eNB) is fully utilized each time transmission interval regardless the transmitted amount of data. Consequently, a high level of power dissipation commonly occurs at the eNB that is caused by either an unused allocated power or an excessive subchannel power allocation which is beyond the required portion for data blocks transmission. Therefore, in this paper, we propose an efficient scheme, namely link adaptive power control and allocation (LaPCA) to mitigate the overused transmission power of the cell, and thereby, enhancing system energy efficiency while maintaining a good QoS level. The main principle in LaPCA is to control the portion of cell transmission power to be proportional to the volume of data flows that are nominated for transmission during the scheduling process. This power is then distributed over the allocated subchannels by means of nonconvex optimization to enhance system performance. System-level simulations reveal that LaPCA achieves an outstanding energy efficiency and maintains an increased throughput level and low loss ratio as more traffic load is offered to the network.

INDEX TERMS LTE, QoS, power allocation, power control, nonconvex optimization, energy efficiency, system capacity.

I. INTRODUCTION

The era of mobile broadband communication is rapidly and tremendously evolved, hence multimedia technology vision is looking forward to the near-zero latency and data rates of tens of Gigabits per second throughout the wireless channel [1]. Based on a current study by [2], it is estimated that the number of mobile users will be as high as 11.6 billion by 2020. It is also reported by the same source that the volume of transferred data over mobile networks reached up to 63% by the end of 2016. These statistical figures reveal that *System Capacity* (SC) has been considered as a major driven key in the technology advancement, starting from the Fourth Generation (4G) to the current Fifth Generation (5G) of mobile systems. This indeed requires the mobile system to allow high orders of power to be utilized in the deployed base stations to fulfill the QoS for the demanded users traffic.

The *LTE* mobile network by Third Generation Partnership Project (3GPP)[1] is an example of the dominant 5G mobile system that vigorously thrives in multimedia communication performance. Orthogonal frequency division multiple access (OFDMA) is adopted in the downlink channel of LTE due to its ability to mitigate the multipath fading, and therefore increasing the SC [3]. It is commonly known that the steady increase in SC and coverage directly leads to high power consumption. Therefore, in the evolving 5G paradigm of LTE, the concern in this regards is twofold. A degraded level of *Energy Efficiency* (EE) is obtained regardless the

[1]http://www.3gpp.org/

quality of the channel between the mobile user and the base station. On the other hand, from an environmental and economic perspective, the issue of power dissipation severely distorts the concept of green communications.

The literature, which is discussed in the following section, presents various schemes to tackle the power management issue in OFDMA channel, majority of these existing solutions do not actually guarantee an enhanced system energy efficiency though. This is because the core concern is devoted to throughput maximization by using, for example, utility function as in [4] and [5], power saving in [6] and [7], or fairness–oriented schemes i.e [8]. In order to guarantee an enhanced level of energy efficiency that is robust against the network load, the transmission power of the base station should be wisely determined so that the ratio of high SC to low dissipated power is definitely maximized. Furthermore, subchannels should be allocated portions of power somehow to improve the users' performance, particularly those at the cell–edge.

In this article, we stress on the issue of power control and allocation described above with the main aim of enhancing energy efficiency by introducing an effective solution for downlink OFDMA channel in macrocell urban LTE system. As the name states, in our proposed scheme (LaPCA), the amount of transmission power is dynamically determined at the base station based on the volume of active subchannels that are assigned to users flows each scheduling interval. Then, this allocated power is distributed over subchannels in a further phase to ensure a long–term EE enhancement over the network states. For that, the contributions of this work are stated as follows:

- Proposing a novel power control mechanism for energy saving as the first phase of LaPCA, The allowed eNB power in this phase is effectively controlled by a formula that considers the amount of utilized subchannels and a geometric additive power for which is leveraged at the power optimization phase.
- Formulating the objective function of the non–convex subchannel power allocation and transform it into a convex problem by means of nonlinear fractional programming. We proof that by using dual decomposition optimization, an optimal solution of the problem is possibly obtained under the time-sharing condition of the wireless channel.
- Proposing a subchannel power allocation mechanism as the second phase of LaPCA. Wherein conforming to the determined eNB transmission power by the prior phase, the convex power allocation problem is solved using a binary iterative method with constraints that guarantee high QoS level for users over the entire cell area in order to harvest the maximum energy efficiency.
- Extensive system level simulations for QoS metrics are measured to effectively evaluate the performance of LaPCA in enhancing EE. From the comparison–based evaluation with relevant power allocation schemes, the conceived performance findings are promising for LaPCA, whereby energy efficiency is enhanced by reducing the power dissipation and maximizing the aggregated throughput.

The remainder of the paper is organized as follows: Section II elaborates about the related works of the proposed solutions to the relevant power allocation issue in LTE OFDMA system. In Section III the involved downlink system model is elaborated. Section IV the power allocation problem is formulated and thereupon. The proposed LaPCA scheme is comprehensively explained as a solution in Section V. Section VI, describes the simulation scenario, experiments parameters, handles a discussion of the numerical results obtained. Finally, a conclusion of the introduced power allocation scheme is drawn in Section VII.

II. RELATED WORKS

The literature comprises several studies that investigate on transmission power control and allocation in wireless channels. In particular, OFDMA channel of LTE grabs the highest concern, since the power consumption at eNB side is usually common. Recently, motivated by environmental concerns, the concept of green mobile networks receives a high audience volume [9], [10]. Whereby, solutions to operate the base stations with lowest power consumption are compensated from natural sources such as solar, water, wind, and geothermal power. A survey on energy management by [11] classified energy–efficient resources allocation as a domain under dynamic power [2] consumption in LTE networks.

The straightforward goal of figuring out the power allocation is by reducing the transmitter energy consumption. Among the several energy-saving concepts which have been introduced for Radio Resource Management (RRM), *Power Control* (PC) is used to be the most known in the relevant literature [12]. PC rigorously strikes a restriction on expensive power dissipation, and tightly handles interference avoidance.The state–of–art power control algorithms are investigated in [13] and [14] by considering the impact of their resultant outage probability on the wireless channel. Similarly, Huang *et al.* [15] derived a Bit Error Rate based (BER–based) binary model to reduce the consumed power under Multi-Input Multi-Output (MIMO) system. Furthermore, in [16], a spectral efficiency expression was formulated for Rayleigh fading channel and accordingly a power control algorithm was designed using max–min QoS optimization. Realizing the significance of circuit power consumption, Discontinuous Transmission (DTX) became a popular approach PC under wireless scenarios. In principle, DTX activates and deactivate the transmitter's power based on the channel status (active or idle). In [17], Holtkamp *et al*. advised a DTX algorithm in the transmitter side (eNB) by solving a convex subproblem under constant channel gains which is not a common characteristic of the variability nature of the wireless channel though. Later on, similar works with DTX–based

[2] Dynamic power here is defined as the communication transmission power that is provided by the base station to the mobile user.

power control schemes were implemented under Space Division Multiple Access (SDMA) [18], and OFDMA with the water–filling algorithm [6]. In both schemes, DTX induces eNB to enter a sleep mode when there are no scheduling tasks. It is observed from the above proposals that a mutual aim is to reduce the power consumption to an extent that could be even obtained at the expense of poor SC and QoS. Nonetheless, this balance relation between SC and power saving is maintained to some extent when DTX is jointly combined with the power control.

Power Allocation is commonly implemented in LTE systems to maximize the SC. For example, in [19], a heuristic power allocation algorithm was proposed for ICI avoidance by adopting the reported Channel Quality Indicator (CQI) from User Equipments (UEs) and service–based power function. Another power control algorithm [20] was delivered for self–organizing networks, hence a multi–objective transmission power adaption method is implemented with the aim of improving SC by degrading ICI. In [5], [21], and [22], a graph–based interference mitigation algorithm is developed using game theory where maximum service rates of different traffic classes are taken as thresholds. The power allocation solution in all cases is obtained once Nash equilibrium state is existed. In addition, works in [4] attempted to maximize the SC by optimizing the power allocation problem using the default condition of Karush–Kuhn–Tucker (KKT). Su *et al.* [23] proposed a power allocation using Cross-tier signal–to–leakage–plus–noise (SLNR)–based water filling model to improve the performance of cell–edge users. From the aforementioned power allocation schemes, an overall observation can be made that the utilized power at the eNB is always equivalent to the maximum allowed power value. This means that a surplus power amount is dissipated since the SC level is arbitrarily known to be upper bounded.

When SC is considered as the main objective of the power allocation, service fairness is expected to be compromised. With that, a part of the literature reveals power allocation proposals with a major endeavor on service fairness among different users. For instance, distance–based power planning [24], [25] is considered by adaptively tuning the eNB power to detect and connect UEs in handover scenarios, so that fair service is guaranteed. Piro *et al*. [8] designed a straightforward power model wherein the statically determined eNB power is distributed among the available subchannels (including the inactive ones) in an equal manner. In spite of the simplicity and the service fairness theme, the model incurs a high power consumption level with a low network gain. Utility–based approaches are commonly adopted to solve the power allocation issue, hence it is flexible to ensure fairness based on a specific set of predefined criteria. For instance, in [26] and [27], a sigmoidal–like utility proportional fairness function was proposed, such that the percentage of successfully transmitted packets of the corresponding modulation scheme is attempted to be maximized. Tekbiyik *et al.* [28] performed a study by which a biconvex power allocation problem was constructed and solved with an algorithm sticking to the assumption that energy is a deterministic value and can be known in prior before the frame transmission.

Recently, there has been some research works investigating on the EE optimization issues to overcome the scarcity of radio resources and to cope with the green networking paradigm. For example, in [29]–[31], energy models were proposed to guarantee fairness among links of different qualities by optimizing EE using different fairness standards. These algorithms however highly compromise on the overall network EE to improve the single–link case (low CQI), which also leads to weak SC and EE in high network loads. Besides, the global system energy efficiency over coordinated MIMO eNBs scenario is discussed in [32], while in [7] Ng *et al.* considered an iterative inner–outer loop–based resource allocation algorithm to solve the transformed EE optimization problem on a single eNB system; the SC is severely decreased with no limit that maintains a balance with the obtained EE though. Later on, in [33], EE algorithm was introduced by solving a mixed–integer nonlinear fractional problem as well as an iterative method to select Modulation and coding schemes(MCS) in OFDMA system. Nonetheless, neither traffic QoS nor performance over a loaded network was considered. A joint Fractional Frequency Reuse (FFR) for cell–center users selection and power allocation scheme to improve overall system's EE was presented in [34]. Besides, the study in [35] argued that complexity is a major constraint in when solving EE problems, and thereupon, advised a power allocation model based on semidefinite relaxation with Gaussian randomization to solve the non–convex EE problem. A common observation on the above algorithms is that they consider EE enhancement over a limited network load state where SC does not converge to its upper bound to evaluate the long–term EE behavior.

Throughout the prior discussion on the related works above, we are able to highlight some remarks which potentially define a gap that required to be figured out. Majority of the related works are found to be strictly concentrating on either SC or power/energy saving; this limits the long–term EE enhancement over different network loads. Besides, fairness–oriented power allocation schemes may establish a good energy–saving behavior, this nonetheless guarantees an enhanced EE in all cases as SC is neglected to an extent. Therefore, by proposing LaPCA, the main objective is to introduce a green–network power model that makes an efficient utilization of eNB power units to achieve the highest EE. With that, we emphasize on reducing the dissipated power and maximizing SC in order to possess a long–term EE enhancement. In the following section, we introduce the system model and the proposed LaPCA scheme.

III. SYSTEM MODEL

In this work, a typical urban scenario of single–cell with multiuser LTE OFDMA downlink system is considered, whereby an LTE–based macrocell eNB and a number of $K = \{1, .., j, .., K\}$ UEs are communicating in a direct

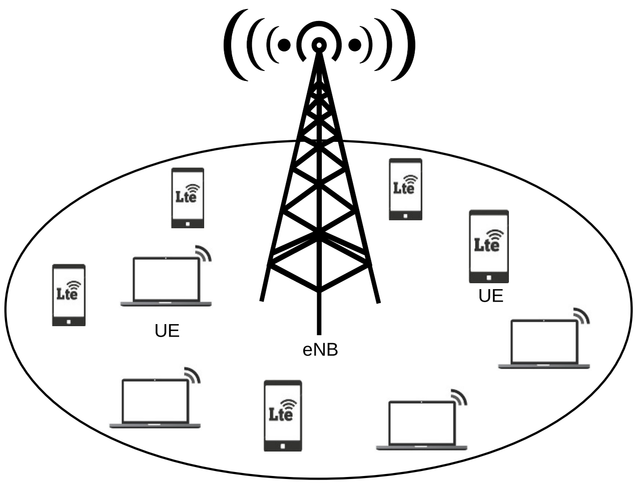


FIGURE 1. LTE system model.

manner as shown in Figure 1. All UEs are deployed with a single antenna as well as the base station. In typical LTE–based cellular systems, the channel bandwidth is divided into a number of physical resource blocks (PRB); with each lasts for 0.5 ms in Time Domain (TD) and utilizes a sub-channel size of 180 kHz in Frequency Domain (FD). Each PRB is also corresponding to 7 OFDM symbols. In fact, radio resources are usually distributed over the available sub–channels every Time Transmission Interval (TTI) that lasts for 1 ms. Therefore, different resource management procedures (in both Medium Access Control (MAC) and Physical layers) that occur in either TD or FD circle over the available sub-channels every TTI to transmit different traffic data to their respective UEs.

Considering $N = \{1, .., i, .., N\}$ number of subchannels available each TTI, the bandwidth on the subchannel i is b_i; such that $\sum_{i \in N} b_i < B$ (B refers to the total system's bandwidth) [36]. It is assumed that each user j experiences an independent fading and the perfect Channel State Information (CSI) is reported periodically to the base station each TTI. These CQI messages are sent by the connected UEs in Frequency Division Duplex (FDD). Moreover, each PRB is particularly assigned to a UE via signaling interval according to [37]. Therefore, signal-to-interference-plus-noise ratio (SINR) of subchannel i that is mapped to UE j and can be computed as follows,

$$\tau_{i,j}(t) = \frac{p_{i,j}(t).g_{i,j}(t)}{I_{i,j} + N_0} \tag{1}$$

where $p_{i,j}(t)$, $g_{i,j}(t)$, and $I_{i,j}(t)$ refer to the transmitted power level of a subchannel i for user j, channel gain, and the interference amount results of UE j on subchannel i over the t^{th} TTI, respectively. Besides, N_0 implies the spectral density of the Additive White Gaussian Noise (AWGN) power. Therefore, The maximum channel data rate that can be achieved between the eNB and the j−th UE on the i−th PRB is formulated as,

$$r_{i,j}(t) = b_i. \log_2(1 + \tau_{i,j}(t)) \tag{2}$$

In the following Section, we describe and formulate the power control and allocation problem based on the involved system model.

IV. PROBLEM DEFINITION AND FORMULATION

In this work, considering the system model that is illustrated above in Section III, we are aiming to enhance the EE on the macrocell eNB urban LTE system meanwhile maximizing throughput for users with different channel quality status values. Therefore, the problem in this context is defined in two parts:

- Reduce the utilized eNB transmission power to the limit that enhances the EE.
- Distribute the allowable portion of eNB transmission power to the active subchannels in a way to maximize the SC.

Without the loss of generality, the macrocell eNB has a maximum level of transmission power, (P_{max}), that is constantly defined to (43 dBm) in LTE systems [38]. Given a determined number of N subchannels [3] in the system, P_{max} is equivalently divided among subchannels every TTI, so that, each subchannel power quota is,

$$p_{i,j}(t) = \frac{P_{max}}{N} \quad \forall i \in N \ \text{ hence,}$$
$$\sum_{i=1}^{N} p_{i,j}(t) \leqslant P_{max} \tag{3}$$

Three points can be conceived from the above scenario. Firstly, all subchannels are allocated with an equal amount of transmission power; this renders the base station performance on cell–edge UEs who report low CSI, especially when interference is assumed. As for the second point, regardless the subchannel allocation during the MAC scheduling process, all subchannels are still reserving a portion of eNB transmission power each TTI, which in turn results in an inefficient power utilization if the number of the subchannels in the system is huge. Thirdly, within each allocation iteration, the entire amount of power (P_{max}) is utilized at eNB without minding the required amount of transmission power for the scheduled UEs data; thereupon, eNB power exhausting is highly experienced when a load of data flows to be transmitted is low. From the previous observations, it can be highlighted that a severe power dissipation situation occurs as a surplus power is utilized to transmit the specific amount of bits. This consequently deteriorates the cell EE (the amount of successfully transmitted bits over joule).

The other part of the global problem is about capacity maximization and it is referred to as $R(\mathcal{F}, \mathcal{S})$. With that,

[3] In fact, in LTE–based cellular system, the number of subchannels depends on the configured bandwidth amount in the scenario, i.e. a channel bandwidth of 10 MHz provides a number of 50 subchannels available each TTI.

the SC in scheduling a data slot (value of TTI in TD) can be defined as the sum amount of successfully received bits to the selected UE and it is mathematically expressed as

$$R(\mathcal{F}, \mathcal{S}) = \sum_{i=1}^{N} \sum_{j=1}^{K} m_j(t) \cdot s_{i,j}(t) \cdot r_{i,j}(t) \tag{4}$$

where $\mathcal{F} = m_j(t) \geqslant 0 \; \forall j$ is the a positive floating value which allows eNB to impose different priorities to various UEs to ensure high performance at cell–edge UEs. This value derived from the normalized distance ratio between each UE and the base station, $m_j(t)$. We believe that by adopting this parameter in the problem objective function, subchannels that are assigned to cell–edge UEs are guaranteed, to an extent, with high level of throughput because their respective subchannels are allowed to gain more fraction of power as described in advanced sections. $\mathcal{S} = s_{i,j}(t) \geqslant 0 \; \forall i, j$ is the method of subchannel allocation to the involved flows. In this work, we consider a greedy–based method, where priority weights using QoS–driven information as in [39] are calculated for all flows in the system on the available subchannels; then flow j with the highest weight is given a priority to be assigned to a subchannel i. On the other hand, it is important to remark that the resultant value $p_{i,j}(t) \geqslant 0 \; \forall i, j$ which formulated and described at the second phase of LaPCA scheme (sub–section V-B) is applied to maximize $r_{i,j}(t)$ for each flow j mapped to subchannel i.

Therefore, given a fixed subchannel allocation values that are known for each allocated UE flow, i.e. $s_{i,j}(t)$, and the efficient allowable portion of power to the eNB that achieves the best EE (i.e, P_{EE}), the optimal subchannel power allocation scheme that maximizes SC can be obtained by solving the following objective function,

$$\max_{p} R(\mathcal{F}, \mathcal{S}) \tag{5}$$

subject to,

$$C1 : d_i(t+1) \leqslant D_{max} \quad \forall j \in K$$
$$C2 : \sum_{j=1}^{K} s_{i,j}(t) \leqslant 1 \quad \forall j \in K$$
$$C3 : s_{i,j}(t) \in \mathbb{R}^{+} \quad \forall j \in K, i \in N$$
$$C4 : \sum_{i=1}^{N} p_{i,j}(t) \leqslant P_{EE}(t) \quad \forall j \in K, i \in N$$
$$C5 : p_{i,j}(t) \geqslant 0 \quad \forall j \in K, i \in N$$
$$C6 : m_j(t) \geqslant 1 \quad \forall k \in K$$

Constraint $C1$ guarantees that the delay of all Real Time (RT) flows is always limited by the next TTI value. In $C2$, each subchannel is allowed to be assigned only to one user bearer (data flow). Besides that, the QoS coefficient weight $s_{i,j}(t)$ in $C3$ is restricted to returns a value for each UE bearer that cannot be less than zero in any case. For $C4$, it limits the total transmitted power assigned to subchannels within the power allocation method, so that it does not exceed the determined, $P_{EE}(t)$. From $C5$, the allocated amount of power to each utilized subchannel is not a negative value. And finally, $C6$ is considered to influence the subchannels power allocation process based on the UE distance from the eNB in which a subchannel is mapped to. In the following Section, we introduce the efficient power management scheme that enhance EE based on the highlighted problem above.

V. PROPOSED ENERGY–EFFICIENT LAPCA SCHEME

In this section, we comprehensively elucidate the proposed power control and allocation scheme, (LaPCA), that is generally illustrated in Figure 2. Intuitively, there always exists a proportional relationship between SC and the eNB power offered for the transmission. Therein, the system QoS performance level is usually upper–bounded by the allowed value of P_{max}. By considering eNB power control and subchannel power allocation, LaPCA is devoted to figuring out problems of eNB power dissipation and SC maximization in order to realize the main aim of enhancing the system EE in the LTE system. Basically, LaPCA comprises two phases of power management process; firstly, power control by determining an effective eNB transmission power that is a portion of the P_{max} to improve EE, and secondly, maximizing system throughput by allocating power for the utilized subchannels, such that their sum power is limited to the determined eNB power in the former phase.

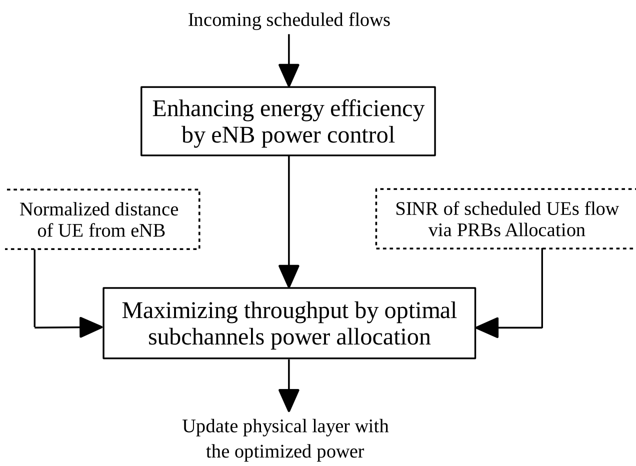


FIGURE 2. Proposed power control and allocation framework.

Basically, the procedures and the functionalities of LaPCA are manipulated complying with the PRBs allocation process that is handled in MAC layer. However, to keep the discussion in this context aligned with the scope of the work, we assume that the PRBs allocation process to the selected flows is already performed as a prior phase to the power allocation process where our proposed scheme is manipulated. For simplicity purpose, in this work, the PRBs allocation process is performed by assuming a model of greedy–based allocation each TTI as in [8]. Wherein, all involved flows are allocated to the available PRBs throughout priority weight that is determined using a QoS–based rule in [39]. In the following context, we present the details of the first phase in LaPCA, which enhanced energy throughout controlling eNB transmission power.

A. ENB POWER CONTROL FOR ENERGY EFFICIENCY

In this phase, the objective is to enhance the system EE so that, the amount of transmitted bits over the joule unit is increased against the offered network load. Complying with the first part of the defined problem, it is important to control the eNB transmission power; so that, the utilized transmission power each TTI is not always equivalent to P_{max} to mitigate the dissipated power.

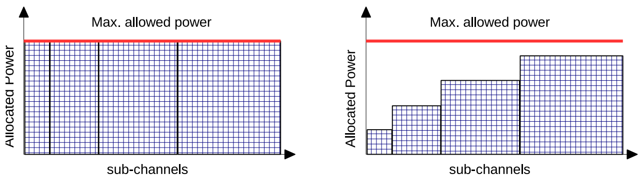


FIGURE 3. Left side, power–unaware allocation; right side, power–aware allocation.

Figure 3 demonstrates an example of power efficiency for two concepts. For the left side power allocation concept, the consumed power is always equal to the maximum allowed power to eNB regardless the number of allocated subchannels. Such a concept is not aware of the required power for each amount of subchannels though. Therefore, system power dissipation is highly experienced in this case. It is noteworthy that no matter the amount of granted additive power to the subchannels over their required power is, the system throughput harvests the same level. This is because each allocated subchannel at this level has already been mapped with the proper MCS that has a limited maximum amount of bits that can be transmitted in a subchannel. So, in case of a small flow size with good channel quality, high MCS (i.e. 64 QAM) that allows transmitting a higher order of maximum bits is possibly selected and thereby, spectral efficiency on that subchannel is increased. Adhere, any extra value of power assigned to the subchannel has no effect on the throughput. On the other hand, for a flow with relatively bigger size and belongs to a UE with a low channel quality, a certain additive value of power over the required subchannel power might be beneficial for guaranteeing the delivery of the flow's payload. Nevertheless, it should be understood that the decision of scheduling flows with different CQI is highly restricted to the process of PRBs allocation, where UE channel status is a major considered parameter. Furthermore, the right side power allocation in Figure 3 implies an example of a promising concept for saving eNB power, hence the power is scaled proportionally with the increased amount of allocated subchannels.

According to the explanation above, we propose a method that imposes a similar power allocation pattern as in the right side of Figure 3. For more obvious understanding,

Algorithm 1 eNB Power Control for EE

Initialization:
  Define P_{max} of eNB;
  Set $p_{req,i,j}(t) \leftarrow P_{max}/N \quad \forall i \in N$;
  set $TTI \leftarrow 0$;
Event *On TTI* **do**
  for $i \leftarrow 1$ **to** M **do**
    for $j \leftarrow 1$ **to** L **do**
      compute $P_{req,M,L}(t)$ based on Equation 6;
    end
  end
  if $0 < P_{req,M,L}(t) < P_{max}$ **then**
    compute $P_{EE}(t)$ based on Equation 7;
  else if $(P_{max} - P_{req,M,L}(t) < 1)$ **then**
    update $P_{EE}(t) \leftarrow P_{req,M,L}(t)$;
  end
  else
    update $P_{EE}(t) \leftarrow P_{max}$;
  end
  update eNB physical layer with $P_{EE}(t)$;
  update $TTI \leftarrow TTI + 1$;
end

Algorithm 1 illustrates the steps of the proposed energy-efficient method. Initially, the required transmission power for each available subchannel i on UE bearer j in the system, $p_{req,i,j}(t)$, is defined equivalent to Equation 3, i.e $p_{req,i,j}(t) \equiv p_{i,j}(t)$ on a given N and P_{max}.

$p_{req,i,j}(t)$ is considered as the minimum transmission power value that each active subchannel can be assigned with. After which, we determine the amount of sum power that is resulted from the allocated subchannels. In a specific TTI, if the there are M subchannels that have been utilized during the PRBs allocation process to schedule a number of L UE bearers, such that $M, L \leqslant N, K$, respectively, then the required sum power for M subchannels on L bearers, $P_{req,M,L}(t)$, can be calculated as,

$$P_{req,M,L}(t) = \sum_{i=1}^{M} \sum_{j=1}^{L} p_{req,i,j}(t) \tag{6}$$

It is important to note that since $M, L \leqslant N, K$, respectively, then $P_{req,M,L}(t)$ is always $\leqslant P_{max}$. This guarantees that the dissipated power is always kept proportional to the required power by the utilized subchannels each TTI. However, our goal is also to ensure that eNB is able to allow an additional portion of power in order to maximize the throughput for both cell–edge and cell–center UEs that have huge data flows to be transmitted. This is actually beneficial to maintain a high level of system EE while still providing a good performance on UEs. For that, the efficient amount of power that eNB can be assigned to enhance EE, $P_{EE}(t)$, is formalized as,

$$P_{EE}(t) = P_{req,M,L}(t) + \ln(P_{max} - P_{req,M,L}(t)) \tag{7}$$

In Equation 7, the additive power $[\ln(P_{max} - P_{req,M,L}(t))]$ is determined so that, when $P_{req,M,L}(t)$ is relatively low at a specific TTI, the additive power is increased in a logarithmic behavior which is bounded by $\ln(P_{max})$ as depicted in Figure 4. Whereby, with the proportional low amount of $P_{req,M,L}(t)$, a high value of the remained power is available to reach the peak eNB power value, P_{max}. Based on the notion that the system capacity limit is upper–bounded hence any increase in the assigned power will have no effect to the performance, the goal in this phase to use the minimum amount of additional power that enables achieving the maximum SC and thus enhance the EE. This eventually leads us to the point that permitting a marginal fraction of the eNB power $(P_{max} - P_{req,M,L}(t))$ is beneficial to significantly improve the EE level. This indeed grants an adequate power which can be employed for throughput maximization handled by the second phase, and adhere, increasing the ratio of throughput to utilized power.

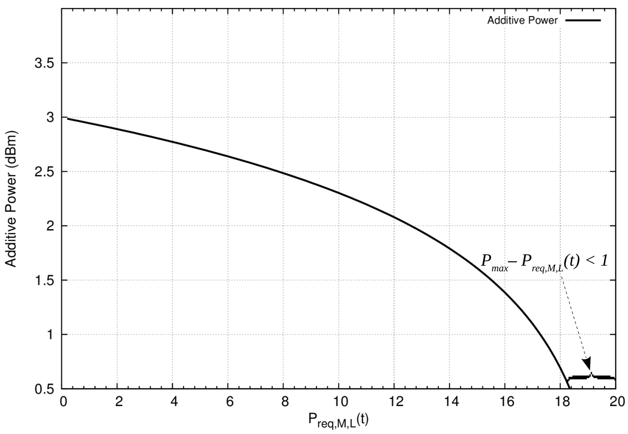


FIGURE 4. Additive power for EE in eNB.

B. SUBCHANNEL POWER OPTIMIZATION FOR SC MAXIMIZATION

Now, that the efficient power $P_{EE}(t)$ is allocated to eNB by the previous phase, the procedures within this phase are performed complying with the obtained $P_{EE}(t)$ value. The objective of this phase is to maximize throughput of the urban LTE system model using power optimization method. This method distributes the eNB power, $P_{EE}(t)$, among the active subchannels which eventually leads to fulfilling the main aim of LaPCA on enhancing EE. For that, we concentrate on the second part of the defined problem in Section IV and solve the objective function in Equation 5. It is noteworthy that the optimization problem in Equation 5 is not concave with $p_{i,j}(t)$, such that it is defined as non–convex problem. Besides, it is also considered as a combinatorial optimization problem that is raised from the constraint of the user bearer weight. To solve this problem, the objective function is simplified by using a nonlinear fractional programming method.

1) TRANSFORMATION OF THE OBJECTIVE FUNCTION

Now, we utilize a theorem belongs to nonlinear fractional programming [40] to transform the objective function. Therein, the maximum system throughput is obtained if and only if

$$P_{EE}(t) - \max_{\mathcal{F},\mathcal{S}} \left(\vartheta . R(\mathcal{F}, \mathcal{S})\right) = 0 \tag{8}$$

such that,

$$P_{EE}(t) \geqslant 0, \quad R(\mathcal{F}, \mathcal{S}) > 0.$$

where ϑ is defined as the optimization coefficient that achieves the highest throughput on the considered system. It is clear that Equation 8 above provides the essential condition for the optimal resource allocation method. Particularly, for an optimization problem with a fractional objective function, it is arbitrarily common to form optimization problem in a subtractive manner e.g., $P_{EE}(t) - \vartheta . R(\mathcal{F}, \mathcal{S})$ on the referred case, hence both problem formulations defiantly lead to the same optimal resource allocation method.

2) DUAL PROBLEM FORMULATION BY NONCONVEX OPTIMIZATION

According to the duality theory of nonconvex optimization investigated in [41] and [42], it can be understood that in multicarrier systems, a nonconvex optimization problem gains a zero duality gap (near–optimality) when the time–sharing condition is fulfilled. This means that regardless the implication for relaxing the value of user selection in $C3$ of Equation 5 which returns a near–optimal solution, this solution still converges to zero when the number of subchannels, $|N|$, is sufficiently large.

Adhere; we can solve Equation 5 by manipulating the Lagrange dual decomposition optimization method stated in [43]. So, the Lagrangian function of Equation 4 is expressed as,

$$\begin{aligned}\mathscr{L}(p, \vartheta) &= \sum_{i=1}^{M}\sum_{j=1}^{L}(m_j(t) \cdot s_{i,j}(t) \cdot r_{i,j}(t)) \\ &\quad + \vartheta \cdot \left(P_{EE}(t) - \sum_{i=1}^{M}\sum_{j=1}^{L}(m_j(t) \cdot s_{i,j}(t) \cdot r_{i,j}(t))\right) \\ &= \sum_{i=1}^{M}\sum_{j=1}^{L}\Big(m_j(t) \cdot s_{i,j}(t) \cdot r_{i,j}(t) \\ &\quad - \vartheta \cdot m_j(t) \cdot s_{i,j}(t) \cdot r_{i,j}(t)\Big) + (\vartheta \cdot P_{EE}(t))\end{aligned} \tag{9}$$

hence ϑ is a non–negative value and is defined as the Lagrange multiplier that is corresponding to the constraint $C4$ of Equation 5. Accordingly, the Lagrangian dual function of the problem in Equation 5 is formulated as,

$$\mathcal{D}(\vartheta) = \max_{p} \mathscr{L}(p, \vartheta) \tag{10}$$

Let us define Equation 5 as the primal optimization problem. Based on that, the dual optimization problem is expressed as,

$$\min_{\vartheta} \mathcal{D}(\vartheta) \qquad s.t, \vartheta \geqslant 0 \tag{11}$$

Theorem 1: Under time–sharing condition, the duality gap between Equations 5 and 11 is near to zero when the number of subchannels is adequately large.

Proof: Refer to Appendex A. □

3) LAGRANGE DUAL DECOMPOSITION

Based on Theorem 1, it is evident that Equation 11 expresses a convex problem on ϑ; thus convex optimization techniques can be applied as a solution. Without the loss of generality, the solution of the dual optimization problem in Equation 11 exhibits the upper bound solution of our primal problem in Equation 5. This means that a situation of non–zero duality gap may occur when there is a variation between the optimal values obtained from Equation 5 and Equation 11. Notwithstanding, according to the time–sharing theorem explained above, it is possible to obtain a zero duality gap in this optimization problem when the number of subchannels is sufficiently large. Therein, solving Equation 11 is approximated to the existed solution of Equation 5. For that, by defining the UE bearer j that is assigned to the subchannel i as $j(i)$. The Lagrangian function from Equation 9 can be expressed as,

$$\mathscr{L}(\mathbf{p}, \vartheta) = \sum_{i=1}^{M}\sum_{j=1}^{L} m_j(t) \cdot s_{i,j}(t) \cdot r_{i,j}(t) \cdot \log_2 \cdot \left(1 + \frac{p_{i,j}(t) \cdot g_{j(i),i}(t)}{I_{j(i),i}(t) + N_0}\right) + \vartheta \cdot \left(P_{EE}(t) - \sum_{i=1}^{M}\sum_{j=1}^{L} p_{i,j}(t)\right) \tag{12}$$

By exploiting the Krush–Kuhn–Tucker (KKT) conditions in [43], we can determine the utilized transmission power on each active subchannel i that is assigned to a particular UE bearer j by the formula,

$$p_{i,j}(t) = \left[\frac{m_j(t).s_{j(i)}(t).b_i}{\vartheta.\ln 2} - \frac{p_{i,j}(t).g_{j(i),i}(t)}{I_{j(i),i}(t) + N_0}\right]^+ \quad \forall\, i \in M,\ j \in L \tag{13}$$

whereby, $[x]^+$ refers to $\max(0, x)$. To the best of our knowledge, the second term of Equation 13 can be estimated by the periodically reported UE's CQI feedbacks in the LTE system model and the power allocation from the previous TTI.

4) ITERATIVE METHOD FOR SC MAXIMIZATION AND EE ENHANCEMENT

From Equation 13, the following relation should hold to comply with KKT conditions,

$$\vartheta.\left(P_{EE}(t) - \sum_{i=1}^{M}\sum_{j=1}^{L} p_{i,j}(t)\right) = 0 \tag{14}$$

It is evident from Equation 14, that ϑ returns a non–zero for any possible power allocation solution that satisfies the constraint $C4$; this conceives the follwoing relation,

$$P_{EE}(t) = \sum_{i=1}^{M}\sum_{j=1}^{L} p_{i,j}(t) \tag{15}$$

Therefore, the solution of the dual optimization problem in Equation 11 is obtained by solving Equation 10 which consequently leads to the optimal power allocation solution for the defined problem in Equation 5. For that, we utilize a multi–dimensional binary search mechanism [44] which is presented in Algorithm 2 to iteratively allocate the optimal power values over the active subchannels. It is necessary to remark that the procedures of this iterative algorithm are performed complying with the amount of $P_{EE}(t)$ that is obtained by the prior phase (sub–section V-A). Based on Algorithm 2, it is noteworthy that the subchannels power allocation is influenced by the channel gain which is the second part of Equation 13, such that, a bearer j that belongs to UE with a presumably good CQI is allowed to be mapped with a subchannel i that is allocated with high power value. Nonetheless, the subchannel power allocation decision is also impacted by environment–based and information–based parameters, that are $m_j(t)$ and $s_{j(i)}(t)$, respectively. In details, by considering $m_j(t)$ that is defined based on Constraint $C6$ of the power allocation problem, subchannels that are mapped cell–edge UEs' bearers are ensured to have higher power values to possibly transmit all their payload with good achievable data rates. Besides, adopting $s_{j(i)}(t)$ imposes the power allocation procedure to satisfy the QoS–awareness feature. Basically, $s_{j(i)}(t)$ is represented as the inverse of the

Algorithm 2 Iterative Subchannel Power Allocation Method for EE and SC Maximization

Define σ as the positive small coefficient value for ϑ;
Initialize $a1_\vartheta \leftarrow 0$ and $a2_\vartheta \leftarrow [X]^+$: X is a huge number;
repeat
  Compute ϑ as a mean value of $a1_\vartheta$ and $a2_\vartheta$.;
  for $i \leftarrow 1$ **to** M **do**
    for $j \leftarrow 1$ **to** L **do**
      Solve the problem in 5 for a given ϑ to determine $p_{i,j}(t)$;
    end
  end
  if $|P_{EE,M,L}(t) - \sum_{i=1}^{M}\sum_{j=1}^{L} p_{i,j}(t)| < \sigma$ **then**
    break;
  else
    if $P_{EE,M,L}(t) > \sum_{i=1}^{M}\sum_{j=1}^{L} p_{i,j}(t)$ **then**
      $a2_\vartheta \leftarrow \vartheta$;
    else
      $a1_\vartheta \leftarrow \vartheta$;
    end
  end
until *ϑ and p converge*;

scheduling priority weight [4] for each the UE flow. Hence, small $s_{j(i)}(t)$ value indicates that the scheduling priority weight is high, and thus, more transmission power is assigned to the respective subchannel of the bearer over the iterations.

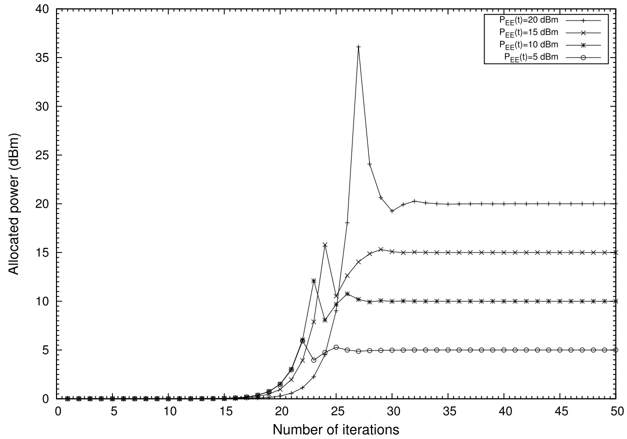


FIGURE 5. Convergence of allocated power on different $P_{EE}(t)$ values.

From the iterative method described in Algorithm 2, ϑ plays an important role in both of the resultant power allocation process and the algorithm complexity. As shown in Figure 5, the power allocation problem converges to the effectively assigned eNB transmission power with less than 35 iterations over different obtained $P_{EE}(t)$ values. This rapid convergence occurs due to the tight control of ϑ values, and moreover, the obtained value of KKT formula in Equation 13 that is influenced by $C2$, $C3$ and $C6$ of the objective function. At the beginning of the algorithm search process, $a1_\vartheta$ is always zero. Thereafter, ϑ is derived by a given two boundaries as expressed in line 4 of Algorithm 2 using the iteratively updated value of $a2_\vartheta$ until $\sum_{i \in M} \sum_{j \in L} p_{i,j}(t)$ is greater than $P_{EE}(t)$ for all i and j. At this point, the other bound, $a1_\vartheta$, is updated with ϑ to narrow down the range between the two bounds which leads to the convergence state of both ϑ, and $p_{i,j}(t)$. With the obtained value of ϑ, SC is maximized up to the level that returned the most enhanced value of EE for the system. To this end, it is observed that the complexity of Algorithm 2 is only restricted to $\mathcal{O}(C \,.\, \log(M \,.L))$, where C is the number of iterations required to reach the convergence states to the power optimization.

VI. PERFORMANCE EVALUATION

The proposed power allocation scheme is evaluated using system level simulations. For that, a common and open–source simulation tool named LTE–Sim [8] that is developed in C++ language is utilized to carry out the experiments. In fact, LTE–Sim is an appropriate and detailed framework tool that models the entire LTE protocol stack with comprehensive layer–based functions, especially on MAC and Physical layers. LTE–Sim supports both TD and FD resources allocation to offer a wide range of performance testing. To be aligned with the main objective of the proposed work, throughout the performance evaluation, we mainly focus on the ability of the power scheme to enhance the system EE, meanwhile maintaining a good level of other QoS metrics such as spectrum efficiency, throughput, delay, and data loss.

A. SIMULATION EXPERIMENT SCENARIO

The simulation scenario in this work is defined by considering the system model shown in Figure 1. Whereby, an outdoor communication system of a single–cell in an urban area is assumed. An eNB is deployed and located at the central area of the cell. The eNB is directly communicating with a number of users that are uniformly distributed within the transmission area of the eNB. In addition, UEs are moving inside the eNB radius in a pedestrian speed of 3 km/h and their mobility is modeled using random direction model.

During the simulation scenario, three traffic types (RT Video, RT VoIP, and NRT application) are involved. The load of these traffic sources is imposed to the network in such a way that 40% of UEs are using RT Variable Bit Rate (VBR) Video application, 40% of UEs are using RT VoIP application, and the rest of 20% are using NRT application. Further description of other important simulation parameters is depicted in Table 1. It is important to remark that the QoS parameters of the radio bearers are implemented following the default configuration of *QoSParameters* object in the simulator.

TABLE 1. Description of simulation parameters.

Parameter	Description
Bandwidth	10 MHz (50 PRBs per TTI)
eNBs in cell	1 eNB
Simulation time	120000 ms
Max delay bound	100 ms
Frame structure	FDD
eNB radius	1 km
PRBs allocation time	1 ms
UEs applications rates	242 kbps video, 9 kbps VoIP, and 20 kbps NRT
MCSs	QPSK, 16QAM, 64QAM
Path Loss model	Urban outdoor propagation model [45]
Shadowing	Log–Normal
Channel fading model	Rayleigh
RLC ARQ of UEs	Activated with max 5 retransmissions
Number of UEs	10–100 with period of 10 UEs

On the other hand, the physical layer at the downlink channel is modeled using carrier frequency band of 2.1 GHz, which contains a number of sub–carriers with 15 kHz spacing for each. The maximum transmission power P_{max} at eNB is configured to 43 dBm. By default, the propagation loss model in LTE operates by combining four different models (multi–path, shadowing, path loss, and penetration). Adhere, in this work, propagation loss at the channel is implemented

[4]This weight is determined by invoking a certain scheduling rule for all UE bearers on the available subchannels within the PRBs allocation process in MAC scheduler. In this work, the scheduling priority weight is determined according to the rule in [39], in which a straightforward QoS–awareness can be imposed.

using a macrocell urban area model according to [38], hence path loss is calculated based on the formula

$$\rho_L = 128.1 + 37.6 \log d \quad (16)$$

where d refers to the distance in meters between eNB and UE. Multi–path is reckoned such that Rayleigh fast fading is implemented using Jakes' model [46], and a number of multiple paths is uniformly selected from the set $\{6, 8, 10, 12\}$. In addition, the penetration loss is set to 10 dB, and shadowing is modeled by log–normal distribution according to [8] (standard deviation = 8dB, with mean of 0dB).

B. TRAFFIC MODELS

The RT VBR Video application is implemented using a trace–based generator. It sends packets based on realistic trace files of a traffic model that is available in [47]. Video data sequences are encoded using H.264 standard at the average VBR coding of 242 Kbps. On the other hand, VoIP application is a RT and light–weight traffic which generates packets using voice type of G.729 and is defined as an ITU standard model [48]. this application is modeled by ON/OFF Markov chain. The ON period is exponentially distributed with a mean value of 4 sec, whereas the OFF period has an abbreviated exponential Probability Density Function (PDF) with an upper boundary of 6.9 sec with an average value of 3 sec model [49]. During the ON period, the application source transmits packets with 20 bytes size every 20 ms. While for the OFF period, no transmission occurs assuming the presence of voice activity detector. Finally, for NRT application (i.e. buffered video streams), traffic flows are generated with a constant bit rate; where packet size and their inter–arrival time are fixed to return a data rate of 20 Kbps. It is necessary to highlight that results of handled within the performance evaluations are demonstrated based on simulation outputs of RT (VoIP and VBR video), and NRT traffic. This classification allows conceiving a high–level QoS evaluation of the power management schemes on multimedia applications within the LTE system.

C. NUMERICAL RESULTS AND DISCUSSIONS

For comparison purpose, the discussion of LaPCA performance is demonstrated with respect to recent power allocation schemes such as [4], [7], and [8]. Within the comparison, we mainly emphasize on discussing QoS in terms of energy efficiency and consumed power against the network load. However, other QoS parameters such as system throughput with relatively low latency should be maintained in a relatively good level.

The results of system energy efficiency versus the number of UEs connected to the cell are demonstrated in Figure 6. At the beginning state of the network load, LaPCA induces eNB to make the most effective use of the additive power determined in $P_{EE}(t)$ in order to achieve the maximum throughput as seen in Figure 9. This enables EE to be enhanced by the minimal power usage complying with

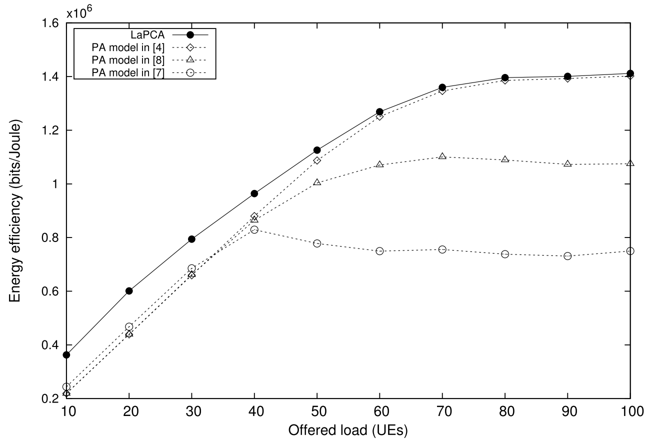


FIGURE 6. Average system energy efficiency.

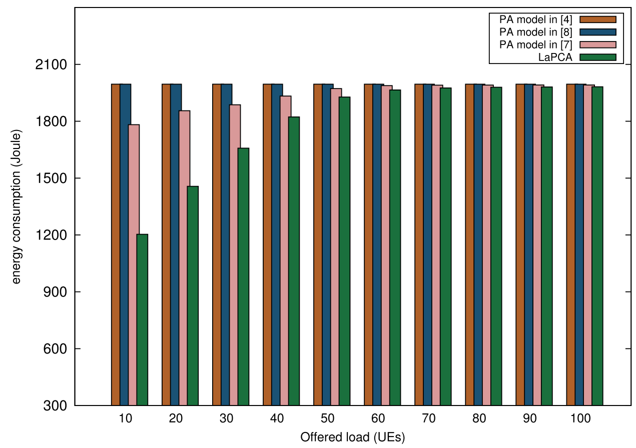


FIGURE 7. Average system energy consumption.

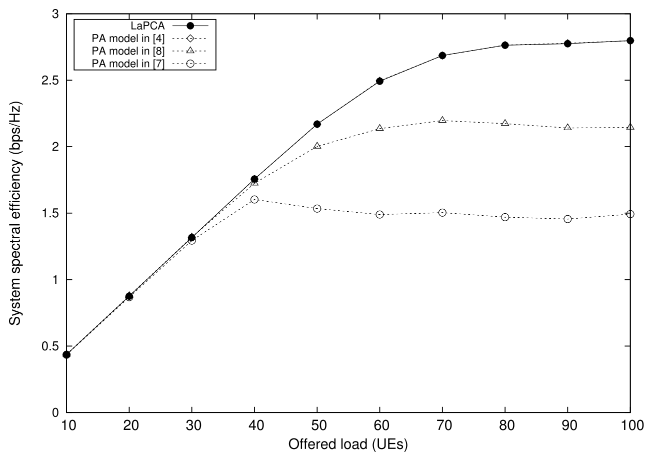


FIGURE 8. Average system spectral efficiency.

$P_{EE}(t)$ such that $(P_{EE}(t) < Pmax)$ for all the utilized sub-channels. In addition, in order to effectively benefit from eNB transmission power, LaPCA considers a QoS–based weight of the scheduled flow $(s_{j(i)}(t))$ throughout PRBs allocation

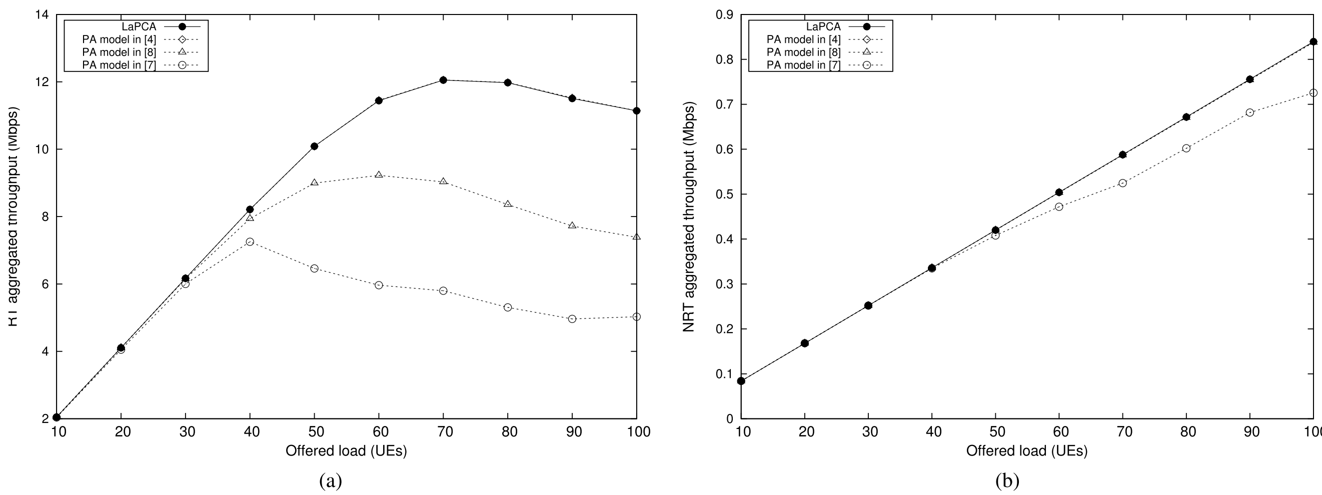


FIGURE 9. **Average aggregated throughput for (a) RT, (b) NRT flows.**

process, [5] as well as the UE–to–eNB distance parameter ($m_j(t)$) to allocate more power to the subchannels. This in fact enables cell–edge UEs to contribute to the system EE by improving the SC as shown in Figure 8.

The power scheme in [7] focuses on improving EE by reducing the portion of allowable power up to the limit of $Pmax$. At the initial state of network load, the scheme maintains a good level of EE by only keeping a low level of energy consumption as noticed in Figure 7 while SC is not actually considered. As the offered amount of UEs grows up in the system (perhaps greater than 40 UEs), the aggregated channel transmission rate is expected to increase due to multiuser diversity. This makes the scheme allocating low power values to subchannels since the iteratively increased energy efficiency factor forces the sum value of the allocated power to remain small in order to reach the convergence state. Besides, the subchannels' power formula at the scheme adopts a flat bearer priority weight for all UEs flows which compromises their QoS requirements though. Therefore, in a simulation scenario where variable multi–traffic applications are involved, EE indeed is not guaranteed to an adequate level since bearers with high QoS weights are transmitted by subchannels with low power.

For the power scheme in [4], EE is ensured by maximizing SC whereby the entire amount of $Pmax$ is utilized regardless the offered load to the network. This however leads to a situation of a high dissipated power which can be obviously noticed when a load of 10-50 UEs is introduced to the eNB. On the other hand, the power scheme in [8] follows the rule of blind equal subchannel power allocation. EE in this case has no guarantee to be improved, nonetheless, the decent level of allocated power (compared with [7]) allows the system to maintain an average performance level.

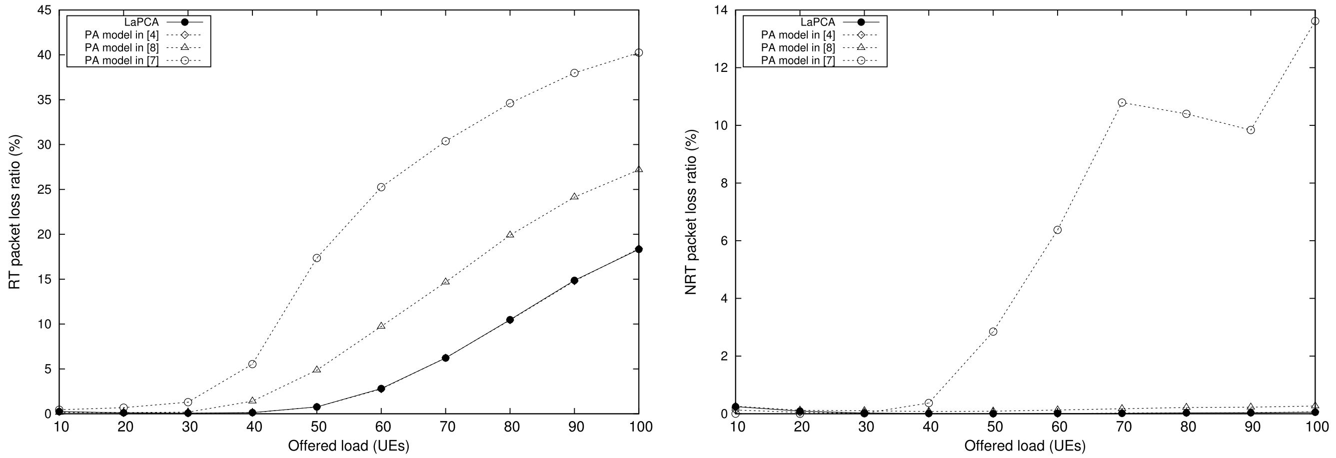
[5] This process is a MAC scheduler procedure that takes place in prior to the power allocation function (LaPCA), wherein flows are assigned with PRBs based on a determined QoS–based priority weight.

Based on the above demonstrated results of EE, we believe that the long–term EE enhancement can be realized by emphasizing on the behavior of both energy consumption as in Figure 7 and the SC that is reflected by the measured spectral efficiency and the aggregated throughput in Figures 8 and 9, respectively. Unlike the referenced power allocation schemes, LaPCA emphasizes on assigning power to eNB according to the number of utilized subchannels. Therefore, with the link adaptive feature in LaPCA, energy consumption is observed to be reduced to the average of 16.2% when the cell is involved with a range of 10–60 UEs. This enable LaPCA to enhance the EE up to 27.4%, 22.9%, and 37.22% with respect to reference power allocation methods in [4], [7], and [8] respectively.

In addition, the illustrated results of LaPCA in Figures 8 and 9 reveal that a high SC can be guaranteed with a low amount of eNB dissipated power. Hence, as discussed in the above context, the SC is upper bounded as the harvested energy efficiency reaches the maximum value. Therefore, the long–term EE is ensured in LaPCA by effectively controlling eNB transmission power and maximizing the system throughput under the limited eNB power.

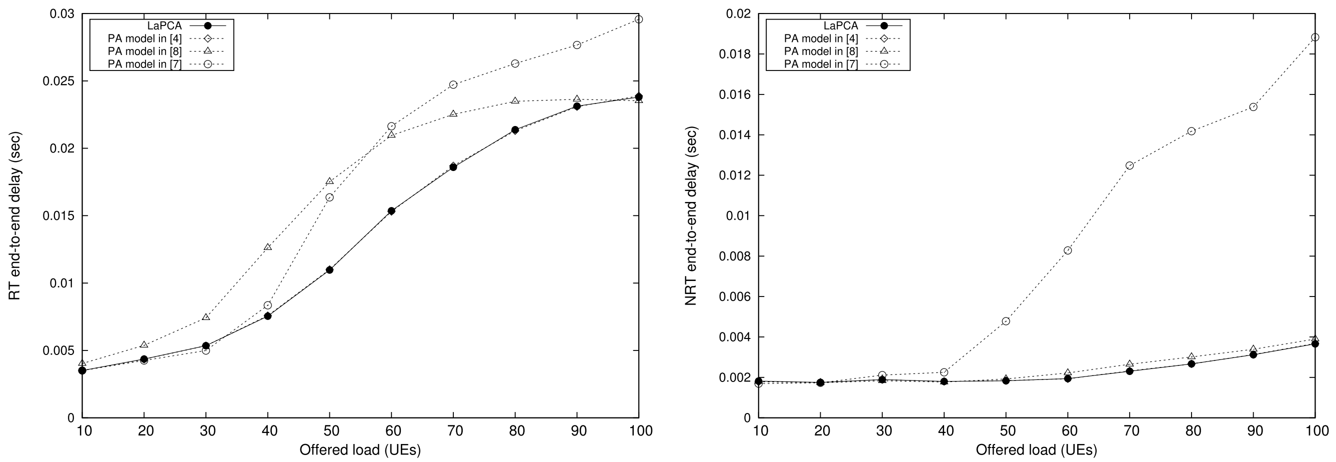
To deliver a comprehensive performance evaluation of the proposed power allocation scheme, we further demonstrate the results of other QoS indices. The measured PLR against the in offered network load is depicted in Figure 10. For RT traffic, LaPCA plots a similar PLR behavior to the power allocation scheme in [4]. However, it presents a reduced pattern that is kept as low as 43.4% comparing with the other scheme in [8]. On NRT flows, LaPCA maintained a low PLR level that is persistent against the increased load. This in turn enables guarantying the QoS of such traffic type as long as the data rate is maintained high [50]. With that, when the number of UEs at the cell is more than 70, LaPCA succeeds to reduce PLR to 13.9% comparing with the power scheme in [4].

Furthermore, the exhibited results of the average end–to–end delay in Figure 11 indicate that by using the optimization



(a) (b)

FIGURE 10. PLR for (a) RT, (b) NRT flows.



(a) (b)

FIGURE 11. Average end–to–end delay for (a) RT, (b) NRT flows.

method in phase 2 of LaPCA, more power is allocated to the available subchannels each TTI and complied with the level of maximum energy efficiency. Flows of cell–edge UEs are adhere ensured to be transmitted on time as they are mapped to subchannels that have a high portion of eNB transmission power (complying with $C6$ of the power allocation problem). The power model in [4] maintains low delay from excessive power allocation to subchannels that leads to high energy consumption though. Besides, the power model in [8] follows a simpler distribution principle than the latter, hence all subchannels gain an equal amount of transmission power. This retards some UEs (particularly, which high data volumes or weak CQI) from transmitting their data with low delay and at high data rates. The power model in [7] is showing a steadily low end–to–end delay at the initial network load states. Nevertheless, as the offered amount of UEs increases, the allocated power to the subchannels is inadequate to transmit the entire flow payload. This eventually causes more retransmissions and thereby high experienced delay.

VII. CONCLUSION

In this work, we have examined the issue of power control and allocation in LTE urban macrocell system. It is found that in most of the common existing power allocation schemes, eNB is starving from a high volume of dissipated power. This power wastage severely degrades the energy efficiency at the LTE system no matter the achieved SC. To figure out this dilemma, a novel power management scheme (LaPCA) has been presented whereby mechanisms for both eNB power control and subchannel power allocation were thoroughly described over macrocell with multiuser urban system model. By dynamically determining the allowable power on eNB using a geometric formula at the power control mechanism, energy saving is guaranteed. Moreover, maximizing SC is realized by subchannel power allocation using nonlinear fractional programming mechanism. A joint model of these two mechanisms enable harvesting a high EE over long–term network states. The output results of the simulation experiments conceived that LaPCA imposes a proportional pattern on the consumed energy and maintains a maximum level of achieved system capacity. This leads to a significant enhancement of EE up to 29.17% with respect to the involved reference schemes, and furthermore, distinguishes LaPCA as a possible power management scheme with a cost–effective solution for real urban LTE systems under green networks.

APPENDIX

For the purpose of presentation simplicity, we omit the time index t from $p_{i,j}$; and furthermore, we define

$$H_{i,j}(p_{i,j}) = s_{i,j}.\log_2\left(1 + \frac{p_{i,j}.\tau_{i,j}}{I_{i,j} + N_0}\right) \tag{17}$$

In addition, we define $s_{i,j}(p_{i,j}) = p_{i,j}$. Therefore, Equation 5 can be rewritten as,

$$\max_p \sum_{i=1}^{N} H_{i,j}(p_{i,j}) \quad \text{subject to} \sum_{i=1}^{N} p_{i,j} \leqslant \mathcal{U} \tag{18}$$

hence, $H_{i,j}(.) : \mathbb{R} \to \mathbb{R}, p \in \mathbb{R}^{|N|}$. By mapping between Equation 5 and Equation 17, it can be inferred that $\mathcal{U} = P_{EE}$. In order ro prove that the duality gap of the problem is zero, it is necessary to formalize the time–sharing condition.

Definition 1: Assume that, p_1^*, p_2^* are the optimal solutions Equation 18, implying that $\mathcal{U} = P_{EE1}$ and $\mathcal{U} = P_{EE2}$, respectively. The optimization problem in Equation 18 is declared to satisfy the time–sharing condition, if and only if there exists a possible solution p_3^* for φ of a value $0 \leqslant \varphi \leqslant 1$ that satisfies the following relation,

$$\sum_{i=1}^{N} s_{i,j}(\mathbf{p}_{i,j,3}^*) \leqslant \varphi \cdot P_{EE1} + (1-\varphi) \cdot P_{EE2}$$

and

$$\sum_{i=1}^{N} H_{i,j}(\mathbf{p}_{i,j,3}^*) \leqslant \varphi \cdot \sum_{i=1}^{N} H_{i,j}(\mathbf{p}_{i,j,1}^*) + (1-\varphi) \cdot \sum_{i=1}^{N} H_{i,j}(\mathbf{p}_{i,j,2}^*)$$

Initially, we prove $\sum_{i=1}^{N} H_{i,j}(p_{i,j}^*)$ is a concave function over $\mathcal{U}$, that is related to Definition 1. Consider that $(p_{i,j,3}^*)$ is the optimal solution to Equation 18, given that, $P_{EE3} = \varphi.P_{EE1} + (1-\varphi).P_{EE2}$, $\forall\ 0 \leqslant \varphi \leqslant 1$. Adhere, the time–sharing condition states that there is a possible solution P_{EE3}, wherein,

$$\sum_{i=1}^{N} s_{i,j}(p_{i,j,3}^*) \leqslant P_{EE3} = \varphi \cdot P_{EE1} + (1-\varphi) \cdot P_{EE2}$$

and

$$\sum_{i=1}^{N} H_{i,j}(p_{i,j,3}) \leqslant \varphi \cdot \sum_{i=1}^{N} H_{i,j}(p_{i,j,1}^*) + (1-\varphi) \cdot \sum_{i=1}^{N} H_{i,j}(p_{i,j,2}^*)$$

Furthermore, it indicates that

$$\sum_{i=1}^{N} s_{i,j}(p_{i,j,3}^*) \leqslant \sum_{i=1}^{N} s_{i,j}(p_{i,j,3}) \leqslant \varphi \cdot \sum_{i=1}^{N} H_{i,j}(p_{i,j,1}^*) + (1-\varphi) \cdot \sum_{i=1}^{N} H_{i,j}(p_{i,j,2}^*)$$

From on the above analysis, $\sum_{i=1}^{N} H_{i,j}(p_{i,j})$ is shown to be a concave function of $\mathcal{U}$. Consequently, it is exhibited that the formulated time–sharing condition is satisfied in LTE/LTE–A as an example of multi–carrier systems, as long as the number of subchannels is sufficiently large. If p_1^* and p_2^* are found to be the two solution for the power allocation problem, then a percentage of φ from the total number of subchannels N is allocated to p_1^*, while the rest of the percentage $(1-\varphi)$ of the N subchannels are assigned to p_2^*. This indicates that, $\sum_{i=1}^{N} H_{i,j}$ is approximately linear for the combination $\sum_{i=1}^{N} \big(H_{i,j}\varphi.H_{i,j}(p_{i,j,1}^*) + (1-\varphi).H_{i,j}(p_{i,j,2}^*)\big)$. Therefore, this approximation is rigorous when $|N| \to \infty$ under the time–sharing condition. Adhere; it is clearly evident that as the number of subchannels N is sufficiently large the duality gap in time–sharing condition becomes zero in order to obtain the optimal solution.

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NADIM K. M. MADI received the B.Sc. degree in information technology majoring in computer networks from University Utara Malaysia in 2010, and the M.Sc. degree (Hons.) in computer science majoring in distributed computing from Universiti Putra Malaysia, in 2012, where he is currently pursuing the Ph.D. degree in radio resource management and QoS enhancements in 4GG LTE mobile networks. His research experience started in the early of 2011. His research themes include radio resource management in mobile networks, network QoS measurement and traffic analysis, simulation modeling techniques, and algorithm analysis in LTE/LTE-A mobile networks. Up to 2018 he has publications in LTE resources allocation, DiffServ packet scheduling, and cloud computing security.

ZURINA BINTI MOHD HANAPI received the B.Sc. degree in computer and electronic system engineering from Strathclyde University in 1999, the M.Sc. degree in computer and communication systems engineering from Universiti Putra Malaysia (UPM) in 2004, and the Ph.D. degree in electrical, electronic, and system engineering from Universiti kebangsaan Malaysia in 2011. She is currently a Lecturer with UPM. Her research interests in routing, wireless sensor network, wireless communication, distributed computing, network security, crpytography, and intelligent systems. She was a recipient of an Excellence Teaching Awards in 2005, 2006, and 2012, respectively. She was also a recipient of the silver medal in 2004 and bronze medal in 2012. She is a leader of some research projects and she has published many conference and journal papers.

MOHAMED OTHMAN received the Ph.D. degree (Hons.) from the National University of Malaysia. Prior to that he was a Deputy Director of the Information Development and Communication Center, where he was incharge for Universiti Putra Malaysia (UMP)Net network campus, uSport Wireless Communication project, and UPM DataCenter. He is currently a Professor in computer science and the Deputy Dean of the Faculty of Computer Science and Information Technology, UPM, where he is also an Associate Researcher and a Coordinator of the High Speed Machine with the Laboratory of Computational Science and Informatics, Institute of Mathematical Science. He has authored over 150 National and International journals and over 200 proceeding papers. His main research interests are in the fields of parallel and distributed algorithms, high-speed networking, and network design and management. He is a member of the IEEE Computer Society, Malaysian National Computer Confederation, and Malaysian Mathematical Society. He was a recipient of the Best Ph.D. Thesis in 2000 awarded by Sime Darby Malaysia and Malaysian Mathematical Science Society. From 2002 to 2010, he was also a recipient of many gold and silver medal awards for University Research and Development Exhibitions and Malaysia Technologies Exhibition which is at the national level.

SHAMALA SUBRAMANIAM received the B.S. degree in computer science and the M.S. and Ph.D. degrees from University Putra Malaysia, in 1996, 1999, and 2002, respectively. Her research interests are computer networks, simulation and modeling, scheduling, and real time system.