IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received March 11, 2018, accepted April 16, 2018, date of publication May 15, 2018, date of current version June 19, 2018.

Digital Object Identifier 10.1109/ACCESS.2018.2833887

Energy-Efficient Resource Scheduling Within DRX Cycles for LTE-A Networks With Carrier Aggregation

LOKESH SHARMA[1], JIA-MING LIANG[1,4], AND SHIH-LIN WU[1,2,3], (Member, IEEE)
[1]Department of Computer Science and Information Engineering, Chang Gung University, Taoyuan 33302, Taiwan
[2]Department of Cardiology, Chang Gung Memorial Hospital, Taoyuan 33305, Taiwan
[3]Department of Electrical Engineering, Ming Chi University of Technology, New Taipei City 24301, Taiwan
[4]Department of General Medicine, Chang Gung Memorial Hospital, Taoyuan 33378, Taiwan

Corresponding author: Shih-Lin Wu (slwu@mail.cgu.edu.tw)

This work was supported in part by the Ministry of Science and Technology, Taiwan, under Grant 106-2221-E-182-013-MY3, Grant 105-2745-8-182-001, and Grant 106-2221-E-182-015-MY3, in part by Delta Electronics, ITRI, and in part by the Chang Gung Memorial Hospital, Taoyuan.

ABSTRACT For the future-generation wireless communications, the *carrier aggregation (CA)* of third generation partnership project (3GPP) *long-term evolution-advanced (LTE-A)* is one of the most promising technologies, which can support significant high data rates over wide frequency bandwidths for various real-time services/applications. To reduce the energy consumption, the LTE-A standard defines the *discontinuous reception (DRX)* mechanism that allows *user equipments (UEs)* to turn off radio interfaces when no data is expected to be received. However, how to allocate resource optimally within the DRX cycle for UEs with the CA technology is still an open issue. In this paper, we address the resource scheduling with CA within the DRX cycle, with an objective that maximizes the spectrum utilization while minimizes UE wake-up time. We formulate this problem and propose an energy-efficient iterative heuristic. Our scheme consists of two phases; the first phase determines the scheduling order of *component carriers (CCs)* to improve the resource efficiency, whereas the second phase minimizes UEs' unnecessary wake-up periods by optimizing their resource intervals from different CCs. Extensive simulation results show that our scheduling achieves better performance than the existing schemes.

INDEX TERMS Carrier aggregation (CA), discontinuous reception mechanism (DRX), long term evolution-advanced (LTE-A).

I. INTRODUCTION

The 3^{rd} *Generation Partnership Project (3GPP) Long Term Evolution-Advanced (LTE-A)* develops *Carrier Aggregation (CA)* technology for future-generation wireless communications, which provides a *user equipment (UE)* with peak data rate up to 3 Gbps for downlink transmission and 1.5 Gbps for uplink transmission [1], [2]. This enables various multimedia, and broadband services such as high-definition mobile TV, multi-party video conferencing, interactive 3D mobile games, and mobile virtual reality services [3], [4]. Specifically, with CA technology, UEs can subscribe and access to multiple aggregated fragmented spectra including the contiguous or non-contiguous *component carriers (CCs)* to perform multiple services at the same time. However, these services also consume UEs' energy which is constrained by the limited battery capacity [5]. On the other hand, LTE-A defines the *Discontinuous Reception (DRX)* mechanism [6] to allow UEs to turn off radio interfaces when no data needs to be received. When DRX is enabled, UEs can wake up and sleep in a periodical manner to save their energy. However, how to optimize the resources, wake up and sleep period, within DRX cycle from a system perspective is still an open issue.

In this paper, we address the resource scheduling of UEs with CA and DRX mechanism. The main objective is to maximize the spectrum utilization while minimize UE wake-up time. We formulate this problem and design an energy-efficient iterative heuristic, which includes two phases. In the first phase, we schedule UEs to maximize network throughput and, in the second phase, we decrease UEs' wake-up periods by optimizing their resources within DRX cycle. Extensive simulation results show that the proposed scheme validates our claims.

The rest of the paper is organized as follows. We present the related work and preliminaries in Section II and III, respectively. In Section IV, we develop the energy-efficient heuristic scheme to solve the problem. Simulation results and discussions regarding to the performance of our scheme are presented in Section V and VI, respectively. Finally, conclusions are presented in Section VII.

II. RELATED WORK

In the literature, [1] focuses on the structure design and framework implementation issues for CA networks. The work [7] introduces the CA technology and its feasibility to increase the peak data rates of LTE-A. Reference [8] studies the technical problem of CA, including the handover control and signaling control for mobile systems. All above studies [1], [7], [8], can significantly improve the peak data rates and network throughput but also consume UEs' energy. References [9]–[16] discuss various achieving objectives for UEs using multiple CCs. Liao *et al.* [9] focus on maximizing the system throughput while maintaining proportional fairness of radio resources allocation among all UEs. This paper considers that the scheduler can reassign CCs to each UE at each transmission time interval while maintaining modulation and coding scheme constraints. Shajaiah *et al.* [10] propose application-aware resource block scheduling with CA. The paper utilizes proportional fairness approach while guaranteeing each user a minimum *quality of service (QoS)* with priority criterion based on application. Cheng *et al.* [11] focus on resource allocation problem with multiple constraints and is solved in every time slot. This paper achieves load balancing among CCs to provide better throughput and delay fairness. The study [12] proposes strategy-proof auction approach for resource block allocation with CA in order to deliver the best configuration with carrier quality and QoS. Feng *et al.* [13] focus on throughput maximization based on channel occupancy information. However, they did not discuss the tradeoff between different parameters and neglect energy efficiency of UEs. Thus, the work [14] discusses the tradeoff between throughput and energy consumption of UEs. The study [15] proposes an UE-assisted switching mechanism to maintain a balance between power saving and latency. However, the above studies [14], [15] neglect to leverage DRX mechanism to further save UEs' energy. Reference [16] considers the energy efficiency of LTE-A devices with multiple CCs in the uplink. Authors propose a new dynamic carrier aggregation scheme to improve the energy efficiency and data rate of UEs. Recently, several studies, [17]–[21] have investigated network capacity, interference, and fairness with a number of constraints. Zhang *et al.* [17] propose a convex optimization solution to maximize network capacity with CA in a heterogeneous network environment. The study [18] considers proportional fairness optimal resource allocation with joint CA cellular networks. This paper allocates optimal aggregated rates for both high-traffic and low-traffic situation. The paper [19] suggests an adaptive DRX based approach for time domain and the best carriers with least interference for frequency domain to reduce inter-cell interference in CA. The study [21] proposes a CC selection scheme with the considering service types, channel quality, buffer size, and fairness factor to balance the frequency diversity and load among CCs in multi-user multi-service networks. However, the above studies did not discuss the energy minimization problem incurred by using CCs. References [22]–[24] consider energy minimization problem in CA due to using different CCs. Fazliu *et al.* [22] propose a distributed approach that dynamically adjusts different transmit power levels for different CCs to reduce interference as well as power consumption. Chavarria-Reyes *et al.* [23] suggest scalarization approach that chooses an optimum cell-association policy to minimize energy consumption. Chavarria-Reyes *et al.* [25] examine the performance analyses of cross-carrier aware DRX for scenarios that support CA by utilizing semi Markov model. The results show that not only the peak data rate but also the energy consumption in such scenarios are significantly improved. Zhong *et al.* [26] suggest a solution for the similar problem with CC specific DRX cycle that results in inefficient resource allocation and network utilization. However, these studies focus on the single spectrum network. Up to now, the resource scheduling within DRX cycle for multiple CCs with QoS consideration is still an open issue.

III. PRELIMINARIES

In this section, we first introduce the DRX mechanism. Then, we describe the CA network architecture. Finally, we formally define our problem.

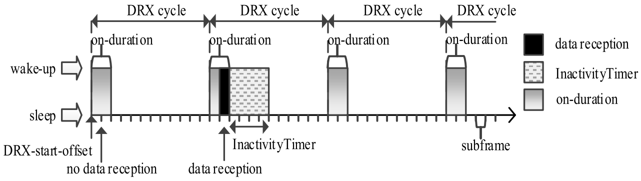


FIGURE 1. An example of DRX mechanism.

A. DRX IN LTE-A

In LTE-A, the DRX mechanism is managed by *Radio Resource Control (RRC)* [27]. The basic unit of wake-up/sleep periods is *Transmission Time Interval* (*TTI*, i.e., a subframe duration with 1 ms). The DRX mechanism supports short and long cycles. Since long cycles are the major operation for power saving, we focus on long cycles only. Four DRX parameters are defined: 1) *DRX-cycle-length*, 2) *DRX-start-offset*, 3) *on-duration*, and 4) *InactivityTimer* as shown in Fig. 1. The *DRX-cycle-length* defines the time period of each DRX cycle which is the periodic repetition of *on-duration* and sleep period. It should be shorter than the tolerable delay of data for QoS transmissions. The *DRX-start-offset* defines the beginning of a DRX cycle. At the beginning of each DRX cycle, the UE has to wake up during *on-duration* TTIs. During *on-duration period*, the UE will monitor its incoming data from the associated eNB. If any of its data is received, the UE will start an *InactivityTimer* and stay awake before the timer expires. The UE resets the value of *InactivityTimer* if it detects any of its data arriving before the timer expires. This process repeats until the UE's *InactivityTimer* expires and the UE goes to sleep and turns off its radio interface to save energy. During the sleep period, all the data of the UE will be buffered at the eNB until the *on-duration*of next DRX cycle starts. DRX configuration is directly connected to delay parameters of services that are executing at UEs [28]. This guarantees UEs with less delay and always get higher priority in the proposed algorithm.

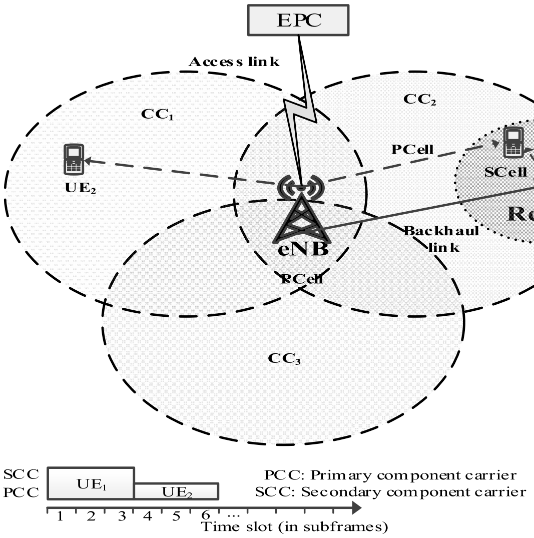
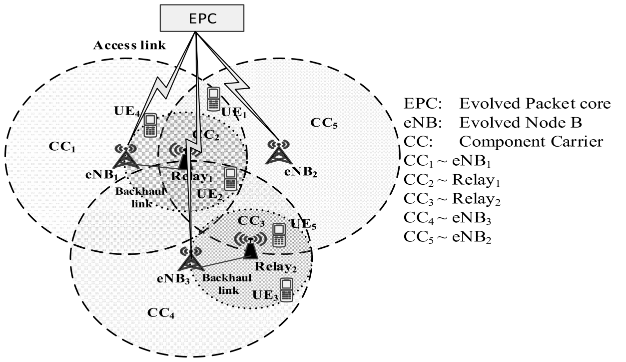


FIGURE 2. An example of CA.

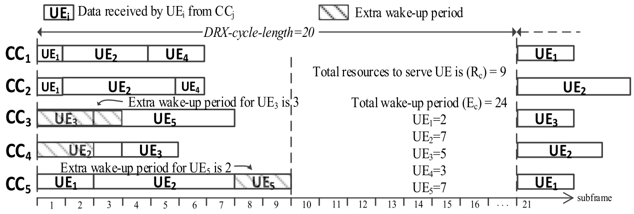
B. CA IN LTE-A

CA is an emerging technology in LTE-A networks that can make use of the fragmented spectrum and support collaborative radio technologies, as shown in Fig. 2. Each eNB is connected to *Evolved packet core* via an access link. Relay nodes coordinated with an eNB to assist handover and rapid coordination of radio resources. CA aggregates multiple CCs to increase the useable bandwidth and transmission bitrate. Each CC can have a bandwidth of 1.4, 3, 5, 10, 15 or 20 MHz. In LTE-A standard, the CA technology can aggregate up to 5 CCs where each has 20 MHz bandwidth and the maximum transmission bandwidth can achieve 100 MHz [30]. In Fig. 2, UE_1 uses two CCs: CC_2 as *Primary CC (PCC)* and CC_4 as *Secondary CC (SCC)* and UE_2 use CC_1 as PCC. UE_1 receives data from CC_2 and CC_4 at time slots $1 \sim 3$ while UE_2 receive data from CC_1 at time slots $4 \sim 6$ accordingly.

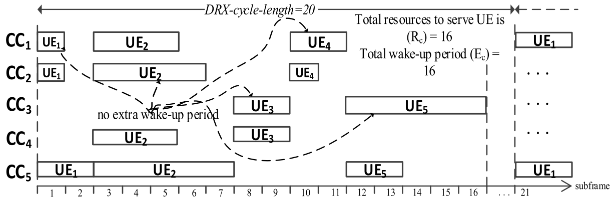
In this paper, we investigate how to adopt resource scheduling within DRX cycle with CA technology similar to [26]. Considering the DRX cycle, we define two metrics: *resource* cost (R_c) to evaluate the wasting spectrum and *energy* cost (E_c) to count wake-up time incurred by different scheduling methods on different CCs within a DRX cycle. The R_c is the total number of allocated TTIs in different CCs required to serve all UEs in the network. The E_c is the energy consumption of the total number of TTIs that the UEs need to wake-up to receive data from different CCs during a DRX cycle. The total energy consumption Ec_ji s the sum of P_s and P_d during the time Δt as shown in Eq. (1), while P_s is the constant amount of power consumption of CC j which is independent of traffic and P_d is a linear function of the radio frequency power consumption by the UEs connected to CC j which varies with traffic. The $p_{i,j}$, represents the power consumption required by CC j for UE i whereas w_j is a constant for CC j as shown in Eq. (2).



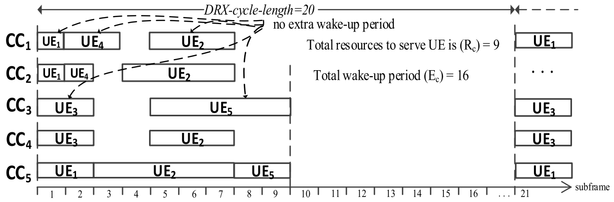
(a)



(I) High Resource utilization scheduling (HRUS)



(II) High Energy saving scheduling (HESS)



(III) Optimum scheduling

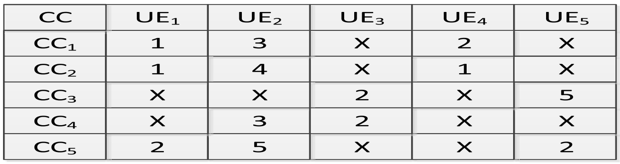
(b)

FIGURE 3. An example to illustrate our scheduling idea. (a) Network scenario. (b) Different scheduling results.

$$Ec_j = \Delta t \times (P_s(CC_j) + P_d(CC_j)), \tag{1}$$

$$P_d(CC_j) = w_j \sum_i p_{i,j}, \tag{2}$$

In Fig. 3(a), the network consists of 5 UEs ($UE_1 \sim UE_5$) and 5 CCs ($CC_1 \sim CC_5$) while CC_1, CC_2, CC_3, CC_4 and



CC	UE$_1$	UE$_2$	UE$_3$	UE$_4$	UE$_5$
CC$_1$	1	3	×	2	×
CC$_2$	1	4	×	1	×
CC$_3$	×	×	2	×	5
CC$_4$	×	3	2	×	×
CC$_5$	2	5	×	×	2

FIGURE 4. **The allocated TTIs of CCs to UEs.**

CC$_5$ are used by eNB$_1$, Relay$_1$, Relay$_2$, eNB$_3$ and eNB$_2$, respectively. Fig. 4 shows an example of the UEs subscribing to the CC number and the corresponding number of allocated TTIs. For instance, the UE$_2$ is allocated 3, 4, 3, and 5 TTIs from CC$_1$, CC$_2$, CC$_4$, and CC$_5$, respectively, to satisfy their data rates. Fig. 3(b) shows the resource allocation results of different scheduling methods under the same resource allocation in Fig. 4. In Fig. 3(b) (I), *high resource utilization scheduling (HRUS)* shows a scheduling order with low resource cost ($R_c = 9$) but high energy cost ($E_c = 24$). Contrarily in Fig. 3(b) (II), *high energy saving scheduling (HESS)* shows a scheduling order with low energy cost ($E_c = 16$) but high resource cost ($R_c = 16$). However, there exists a best schedule order with the minimum resource cost ($R_c = 9$) and the minimum energy cost ($E_c = 16$), as shown in Fig. 3(b) (III). This tells us that the scheduling order of multiple CCs in CA within DRX cycle significantly affect UEs' wake-up costs. This strongly motivates us to study the resource allocation in multiple CCs within DRX cycle.

C. RESOURCE SCHEDULING IN DRX CYCLE OPTIMIZATION PROBLEM

The primary objective of scheduling method is to maximize the utility function to achieve high cell throughput and minimize energy allocation of radio resources by different CCs to UEs as shown in Eq. (3). The scheduling is an assignment of time-frequency resources of CCs, called as resource blocks (RBs), and modulation and coding schemes (MCSs) to UEs at each TTI, that vary with time, frequency and UE's location [9]. Each UE can calculate channel quality for an RB, in order to associate with highest transmission rate MCS. We define the highest and the lowest transmission rate of the MCS as b and 1 respectively. Here $x_{i,j,u,v}(t)$ is an indicator variable to denote whether UE i can be scheduled with RB u of CC j with MCS v at TTI, t. Let i, j, u, and v be the UE, CC, RB and MCS index, respectively. Here $i \in N := \{1, \ldots, n\}$, $j \in M := \{1, \ldots, m\}$, $u \in A := \{1, \ldots, a\}$, and $v \in B := \{1, \ldots, b\}$. The scheduling problem with minimizing energy consumption is formulated in Eq. (3), subject to the constraints (4-8). The constraint in (4) verifies that an RB of any CC is allocated to one UE at time t whereas (5) ensures that a UE can use an MCS for assigned CC. The constraint in (6) restricts a UE, while not selecting an MCS index for an RB by CC, which UE cannot qualify. Here $B_{i,j,u}$ is the highest rate MCS index used by UE i on RB u of CC j. The constraint in (7) allows a UE can have at most z CCs and (8) is an indicator value selected or not.

$$\min \sum_{i=1}^{n}\sum_{j=1}^{m}\sum_{u=1}^{a}\sum_{v=1}^{b} x_{i,j,u,v} \times Ec_j, \tag{3}$$

Subject to the following constraints:

$$\sum_{i=1}^{n}\sum_{v=1}^{b} x_{i,j,u,v} \le 1, \quad i \in N,\ v \in B, \tag{4}$$

$$\sum_{v=1}^{b} \max_{u \in A} x_{i,j,u,v} \le 1, \quad i \in N,\ j \in M, \tag{5}$$

$$\sum_{v=B_{i,j,u}+1}^{b} x_{i,j,u,v} = 0, \quad i \in N,\ j \in M,\ u \in A, \tag{6}$$

$$\sum_{j=1}^{m} \max_{u \in A}\max_{v \in B} x_{i,j,u,v} \le z, \quad i \in N, \tag{7}$$

$$x_{i,j,u,v} \in \{0, 1\} \tag{8}$$

Consider an LTE-A network with eNBs serving n UEs. Assume m CCs are available for n UEs to request in the network, which means that each UE$_i$, $i = 1, \ldots, n$, can request at most m multiple CCs. We use CC$_j$, $j = 1, \ldots, m$, to represent multiple CCs of a UE that subscribes to CA. An *assembly matrix*(A) represents a matrix of m-by-n matrices. For simplicity, we use $a_{j,i}$, representing the number of allocated TTIs of CCj to UE i in Eq. (9).

$$A_{m\times n} = \begin{pmatrix} a_{11} & . & a_{1n} \\ . & . & . \\ a_{m1} & . & a_{mn} \end{pmatrix}; \qquad j \in M := \{1, \ldots, m\}; \quad i \in N := \{1, \ldots, n\} \tag{9}$$

The *multiple carrier resource scheduling (MCRS)* problem asks how to schedule n UEs in m CCs (by determining the scheduling order of UEs such that R_c and E_c metrics get reduced) within a DRX cycle (including each UEs DRX-cycle-length) such that the delay constraint of each CC is not violated and the total number of TTIs of all UE should be minimized. Table 1 summarizes the notations used in this paper.

Note that *MCRS* problem is similar to the scheduling problem [30], [31], reducing inventory cost in Supply Chain Management problem [32], Tile Assembly Model problem [33], and Ant Colony Optimization problem [34]. It also can be easily reduced to Single Machine Total Tardiness (SMTT) problem [35]–[37], which is NP-complete.

IV. THE PROPOSED SCHEME

Since the MCRS problem is formulated by an integer programming which is NP-hard, finding the optimal solution is impractical for a real-time environment. Thus, we propose *Carrier Aggregation resource scheduling in DRX cycle (CADS)* scheme, which is an energy-efficient heuristic iterative scheme to tackle the problem. The scheme consists of two phases and three vector parameters. In the first phase,

TABLE 1. Summary of notations.

Variable	Explanation
R_c	total number of allocated sub-frames in different CCs
E_c	total number of sub-frames required by UEs
$x_{i,j,u,v}$	indicator variable: to denote whether UE is scheduled at sub-frame t or not where i, j, u, and v be the UEs ,CCs, RB and MCS index, respectively.
P_s	static power with no traffic
P_d	dynamic power with traffic
$P_{i,j}$	output power required by CC j for UE i
w_j	constant for CC j
$B_{i,j,u}$	highest rate MCS index used by UE i on RB u of CC j
$a_{j,i}$	element of assembly matrix (A)
S	scheduling order
λ^k	index number of UEs in scheduled order S
B^k	column vector of selected λ^k UE
B^0	null vector
ψ^k	arbitrary function of assembly matrix, A B
St and Et	start time and end time of the UE in CCs
WT	vector quantity wakeup time: largest duration of a UE to awake and receive all resource blocks from multiple CCs.
NL	vector quantity network loss: loss incurred by uneven distribution of UE resource allocation to multiple CCs
NUC	vector quantity network utilization per number of CC of UE: determine network utilization per CC

CADS exploits the minimal cost first strategy to reduce the overall resource cost of network incurred by the scheduling order of UEs on multiple CCs. In the second phase, CADS further optimizes energy cost of each UE. The details of the scheme and required parameters are described as follows.

A. PARAMETERS

1. **Wakeup time (*WT*):** The awaken duration of a UE is the period where the UE can receive all RBs from multiple CCs. Vector quantity *WT* is the largest awaken duration among UEs. This guarantees that the RBs belong to a UE from multiple CCs to meet within the awaken duration. It also ensures that the UE energy consumption is restricted to the largest duration so that there will be no extra cost in terms of energy. For the k iterations, the element wt_i^k of *WT* is calculated as shown in Eq. (10).

$$wt_i^k = \begin{cases} wt_i^k = \max\limits_j(a_{ji}); & k = 1 \\ wt_i^k = \max\limits_j(a_{ji}) - wt_i^{k-1}; & k \geq 2 \end{cases} \tag{10}$$

2. **Network Loss (*NL*):** It is the loss incurred by uneven distribution of a UE resource allocation to multiple CCs, which compromises the throughput of the network. This guarantees that the network will achieve maximum utilization of resources within the same wake-up time. Vector quantity *NL* for k^{th} step consists of i eligible UEs. In order to maximize throughput, we first select that UE which provides the minimum value for *NL*. The nl_i^k of *NL* is the ratio of unutilized TTIs to the total TTIs by the network as shown in Eq. (11).

$$nl_i^k = (m \times \max_j(a_{ji}) - \sum_j a_{ji})/(m \times \max_j(a_{ji})) \tag{11}$$

3. **Network Utilization per number of CC of UE (*NUC*):** Vector quantity *NUC* qualifies when two or more UEs allocated TTIs by multiple CCs are equal, but with different combinations of CCs. This guarantees the network fairness while considering that UE first which is considering more number of CCs with the same *NL*. In Eq. (12), the element nuc_i^k of *NUC* determines the network utilization per CC. The scheme first selects the UE which has a minimum value of *NUC*, so that the network will be more stable and less vulnerable.

$$nuc_i^k = \sum_j a_{ji}/(m \times \max_j(a_{ji}) \times \underset{j}{count}(a_{ji})) \tag{12}$$

For example in Fig. 5, UE$_2$ in 1st iteration is allocated to CC$_1$, CC$_2$, CC$_4$, and CC$_5$, has 3, 4, 3 and 5 allocated TTIs, respectively. The CC$_5$ has 5 TTI which is the maximum required wake-up time required by UE$_2$, so $wt_2^1 = 5$. For remaining WT^1 = [**2**, 5, **2**, **2**, 5]. The nl_2^1 for UE$_2$(5*5-sum (3, 4, 3, 5)) / (5*5) is 0.4. Similarly for NL^1 = [**0.6**, 0.4, **0.6**, 0.7, 0.72]. The nuc_2^1 for UE$_2$ for 1st iteration sum (3, 4, 3, 5)/ (5*5*4) is 0.15. Similarly for NUC^1 = [**0.13**, 0.15, 0.2, 0.15, 0.14].

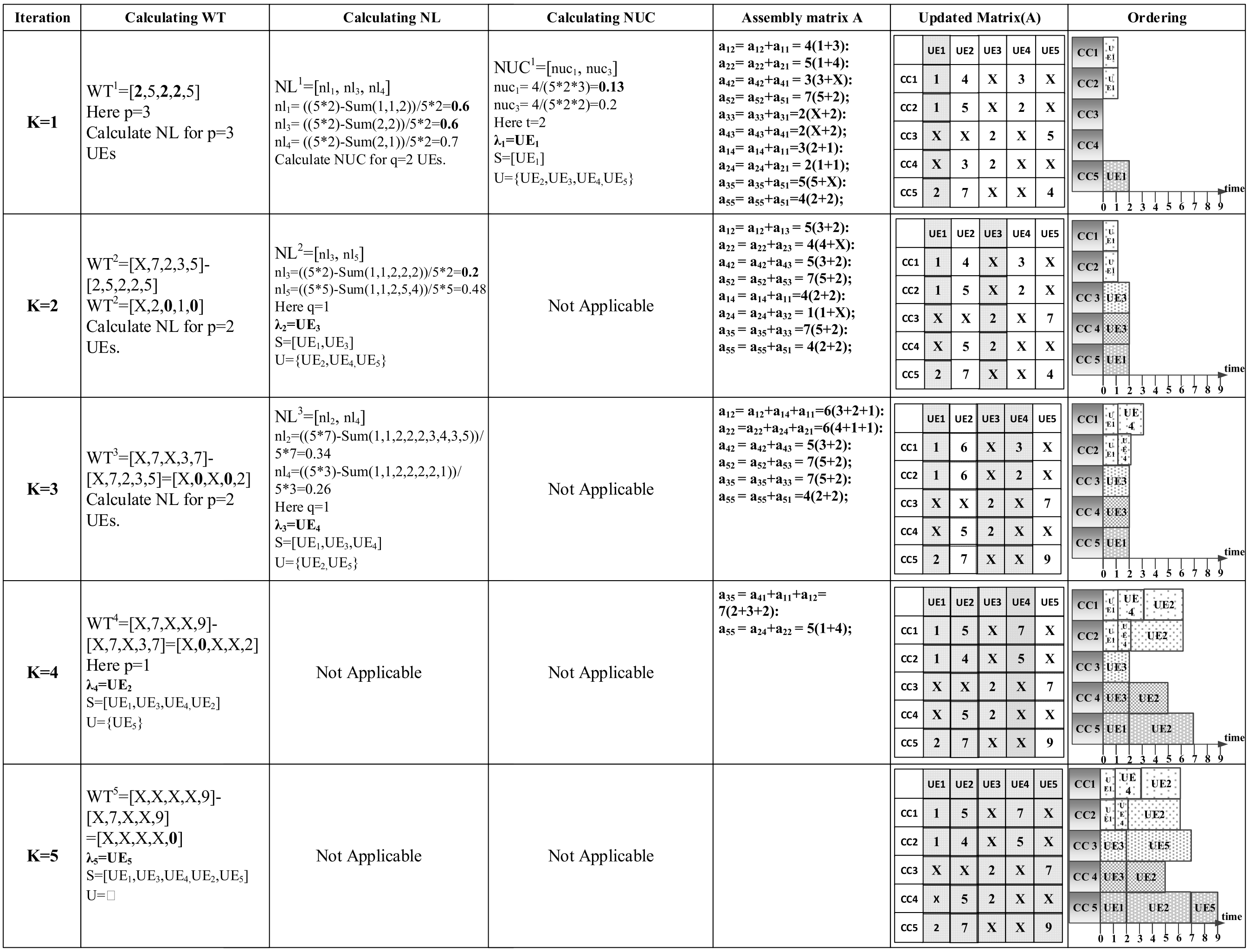
B. FIRST PHASE: OPTIMIZE SCHEDULING ORDER

The goal of this phase is to determine the scheduling order of multiple CCs and UEs in terms of TTIs, such that the overall resource cost of UEs can be minimized. In the following algorithm, we first select a UE with the minimum *WT* time to satisfy as many UEs as possible. This can help UEs to reduce their wake-up time and minimize *energy cost*. Second, select a UE with minimum *NL* to maximize the *network throughput*. Finally, we use *NUC* to maintain *fairness* based on required conditions for each CCs and then determine each UE scheduling order based on these results. We generalize CADS solution similar to the linear stationary iterative method in Eq. (14). Initially, A^0, is our input assembly matrix and B^0 is a null vector. B^k is the column vector of selected λ^k UE. The $addColumnVector(A^{k-1}, B^{k-1})$ function adds the column vector B^{k-1} to each column of the matrix of A^{k-1} as shown in Eq. (13). Here ψ^1, ψ^2, ..., and ψ^k are the arbitrary functions of A, B, and λ. For k^{th} iteration, ψ^k is a linear function of λ^1, λ^2, ..., λ^{k-1}. Thus, the linear iterative method ψ $(\lambda^k; A, B)$ has the form for different k as shown in Eq. (14).

$$A^k = addColumnVector(A^{k-1}, B^{k-1}) \tag{13}$$

$$\lambda^k = \begin{cases} \psi^1(A^0, B^0); & k = 1 \\ \psi^k(\lambda^1, \lambda^2, \ldots, \lambda^{k-1}, A^{k-1}, B^{k-1}); & k \geq 2 \end{cases} \tag{14}$$

The purpose of Algorithm 1 is to schedule the resource allocation of UEs while minimizing resource cost of the



Iteration	Calculating WT	Calculating NL	Calculating NUC	Assembly matrix A	Updated Matrix(A)	Ordering
K=1	WT^1=[**2**,5,**2**,**2**,5] Here p=3 Calculate NL for p=3 UEs	NL^1=[nl_1, nl_3, nl_4] nl_1= ((5*2)-Sum(1,1,2))/5*2=**0.6** nl_3= ((5*2)-Sum(2,2))/5*2=**0.6** nl_4= ((5*2)-Sum(2,1))/5*2=0.7 Calculate NUC for q=2 UEs.	NUC^1=[nuc_1, nuc_3] nuc_1= 4/(5*2*3)=**0.13** nuc_3= 4/(5*2*2)=0.2 Here t=2 **λ_1=UE$_1$** S=[UE$_1$] U={UE$_2$,UE$_3$,UE$_4$,UE$_5$}	$a_{12}= a_{12}+a_{11} = 4(1+3)$: $a_{22}= a_{22}+a_{21} = 5(1+4)$: $a_{42}= a_{42}+a_{41} = 3(3+X)$: $a_{52}= a_{52}+a_{51} = 7(5+2)$; $a_{33}= a_{33}+a_{31}=2(X+2)$: $a_{43}= a_{43}+a_{41}=2(X+2)$; $a_{14}= a_{14}+a_{11}=3(2+1)$: $a_{24}= a_{24}+a_{21} = 2(1+1)$; $a_{35}= a_{35}+a_{51}=5(5+X)$: $a_{55}= a_{55}+a_{51}=4(2+2)$;	UE1 UE2 UE3 UE4 UE5 CC1 1 4 X 3 X CC2 1 5 X 2 X CC3 X X 2 X 5 CC4 X 3 2 X X CC5 2 7 X X 4	CC1 UE1 CC2 UE1 CC3 CC4 CC5 UE1 time 0 1 2 3 4 5 6 7 8 9
K=2	WT^2=[X,7,2,3,5]-[2,5,2,2,5] WT^2=[X,2,**0**,1,**0**] Calculate NL for p=2 UEs.	NL^2=[nl_3, nl_5] nl_3=((5*2)-Sum(1,1,2,2,2))/5*2=**0.2** nl_5=((5*5)-Sum(1,1,2,5,4))/5*5=0.48 Here q=1 **λ_2=UE$_3$** S=[UE$_1$,UE$_3$] U={UE$_2$,UE$_4$,UE$_5$}	Not Applicable	$a_{12}= a_{12}+a_{13} = 5(3+2)$: $a_{22} = a_{22}+a_{23} = 4(4+X)$: $a_{42} = a_{42}+a_{43} = 5(3+2)$: $a_{52} = a_{52}+a_{53} = 7(5+2)$; $a_{14} = a_{14}+a_{11}=4(2+2)$: $a_{24} = a_{24}+a_{32} = 1(1+X)$; $a_{35} = a_{35}+a_{33} =7(5+2)$: $a_{55} = a_{55}+a_{51} = 4(2+2)$;	UE1 UE2 UE3 UE4 UE5 CC1 1 4 X 3 X CC2 1 5 X 2 X CC3 X X 2 X 7 CC4 X 5 2 X X CC5 2 7 X X 4	CC1 UE1 CC2 UE1 CC 3 UE3 CC 4 UE3 CC 5 UE1 time 0 1 2 3 4 5 6 7 8 9
K=3	WT^3=[X,7,X,3,7]-[X,7,2,3,5]=[X,**0**,X,**0**,2] Calculate NL for p=2 UEs.	NL^3=[nl_2, nl_4] nl_2=((5*7)-Sum(1,1,2,2,2,3,4,3,5))/5*7=0.34 nl_4=((5*3)-Sum(1,1,2,2,2,2,1))/5*3=0.26 Here q=1 **λ_3=UE$_4$** S=[UE$_1$,UE$_3$,UE$_4$] U={UE$_2$,UE$_5$}	Not Applicable	$a_{12}= a_{12}+a_{14}+a_{11}=6(3+2+1)$: $a_{22} =a_{22}+a_{24}+a_{21}=6(4+1+1)$: $a_{42} = a_{42}+a_{43} = 5(3+2)$: $a_{52} = a_{52}+a_{53} = 7(5+2)$; $a_{35} = a_{35}+a_{33} = 7(5+2)$: $a_{55} = a_{55}+a_{51} =4(2+2)$;	UE1 UE2 UE3 UE4 UE5 CC1 1 6 X 3 X CC2 1 6 X 2 X CC3 X X 2 X 7 CC4 X 5 2 X X CC5 2 7 X X 9	CC1 UE1 UE 4 CC2 UE1 UE4 CC 3 UE3 CC 4 UE3 CC 5 UE1 time 0 1 2 3 4 5 6 7 8 9
K=4	WT^4=[X,7,X,X,9]-[X,7,X,3,7]=[X,**0**,X,X,2] Here p=1 **λ_4=UE$_2$** S=[UE$_1$,UE$_3$,UE$_4$,UE$_2$] U={UE$_5$}	Not Applicable	Not Applicable	$a_{35}= a_{41}+a_{11}+a_{12}=$ $7(2+3+2)$: $a_{55}= a_{24}+a_{22}= 5(1+4)$;	UE1 UE2 UE3 UE4 UE5 CC1 1 5 X 7 X CC2 1 4 X 5 X CC3 X X 2 X 7 CC4 X 5 2 X X CC5 2 7 X X 9	CC1 UE1 UE 4 UE2 CC2 UE1 UE4 UE2 CC 3 UE3 CC 4 UE3 UE2 CC 5 UE1 UE2 time 0 1 2 3 4 5 6 7 8 9
K=5	WT^5=[X,X,X,X,9]-[X,7,X,X,9]=[X,X,X,X,**0**] **λ_5=UE$_5$** S=[UE$_1$,UE$_3$,UE$_4$,UE$_2$,UE$_5$] U=□	Not Applicable	Not Applicable		UE1 UE2 UE3 UE4 UE5 CC1 1 5 X 7 X CC2 1 4 X 5 X CC3 X X 2 X 7 CC4 x 5 2 X X CC5 2 7 X X 9	CC1 UE1 UE 4 UE2 CC2 UE1 UE4 UE2 CC 3 UE3 UE5 CC 4 UE3 UE2 CC 5 UE1 UE2 UE5 time 0 1 2 3 4 5 6 7 8 9

FIGURE 5. Examples to schedule UEs according to algorithm 1.

network. Line 1, assigns $S = \emptyset$ initially whereas U is the set contained all unscheduled UEs. Line 2, sort all UEs according to their corresponding service delay so that the UE with less delay will get higher priority. Line 3-4, initialize A and A^0 for initial processing. Line 5-31, for loop, calculates scheduling order for n UEs. Line 6-7, 12-13, and 18-19 calculates WT, NL, and NUC respectively. The number of occurrences of minimum element of WT, NL, and NUC are calculated by p, q, and t respectively. If there is no resource competition among UEs, the minimum selected one will be the next scheduled UE. Otherwise, UEs have to follow the subsequent algorithm. Line 29-30, calculate resource allocation of the network according to scheduling order. Finally, line 32 will provide UE scheduling order. Below, we give an example in Fig. 5 to show the complete operation of algorithm 1, where $n = 5$, $m = 5$. In the example, we assume the resource allocation for each UE with multiple CCs as shown in Fig. 4. After executing algorithm 1, the $R_c = 9$ and $E_c = 18$.

C. SECOND PHASE: MINIMIZE ENERGY COST

The goal of this phase is to reduce the energy cost of previous scheduling order S by reducing the total wake-up time of a UE. By this, the UE can access a bunch of data in a reduced number of TTIs and save UE's energy. The detailed operations are given in algorithm 2.

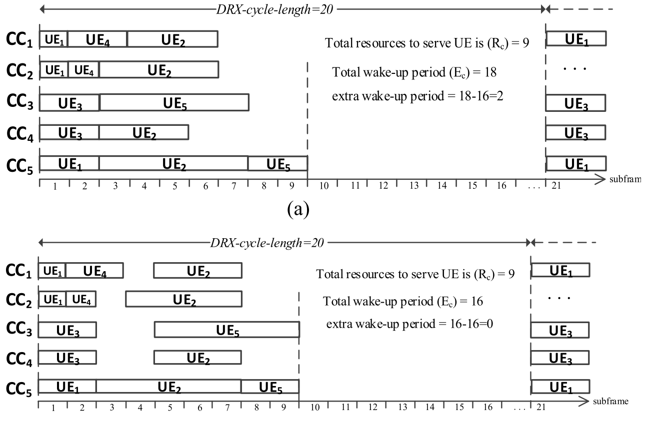
Let start time (St) and end time (Et) be two m-by-n matrices of m CCs and n UEs based on scheduling sequence S of the first phase. We assume the start time of first scheduled UE (λ^1) i.e., $St_{j,\lambda^1} = 0$ and the end time Et_{j,λ^1}, is the sum of $A^0_{j,i}$ to CCs regarding to λ^1 as shown in line 3-4. Line 6, calculates the St for other scheduled UEs which is the Et of last scheduled UE. The Et is the sum of St time of λ^k UE and A^0_{j,λ^k}. Line 9-17, this time k iteration starts from n to 1, which means the last scheduled UE in S. Line 10-12, will fix the Et time of λ^k to the maximum value among all CCs. The St will be the subtracted value of A^0_{j,λ^k} from E_{j,λ^k} time. For rest of the scheduled UEs, Et will be the minimum of St time of succeeding scheduled UE or maximum of current UE as

Algorithm 1 First Phase: Optimize Scheduling Order

```
1:  Assign: $S = \emptyset$, $U = \{UE_i$, for $i = 1, 2, \ldots, n;\}$/* $S$ is
    the set of Scheduled UE, $U$ is the set of Unscheduled
    UEs */
2:  Sort all $UE_i$ by delay constraints ($D$) in an increasing
    order. Without loss of generality $D_1 \leq D_2 \leq \ldots \leq D_i$
3:  $A_{m*n} = \{a_{j,i}$, for $j = 1, 2, \ldots, m$, $i = 1, 2, \ldots, n\}$;
4:  Set: $A^0_{j,i} = A_{m*n}$
5:  for $k \leftarrow 1$ to $n$ iterations do
6:      Calculate $WT^k$ of $a_{j,i}$; $i \epsilon$U;
7:      $p = count(\min_i(WT^k))$;
8:      if $p = 1$ then
9:          $\lambda^k$ = UE having least value in $WT$;
10:         $S = S \cup \{\lambda^k\}$ & $U = UE_i - S$
11:     else
12:         Calculate $NL^k$ of $a_{j,i}$; $UE_i \epsilon U$;
13:         $q = count(\min_i(NL^k))$;
14:         if $q = 1$ then
15:             $\lambda^k$ = UE having least value in $NL$;
16:             $S = S \cup \{\lambda^k\}$ & $U = UE_i - S$;
17:         else
18:             Calculate $NUC^k$ of $a_{j,i}$; $i \epsilon U$;
19:             $t = count(\min_i(NUC^k))$ ;
20:             if $t = 1$ then
21:                 $\lambda^k$ = UE having least value in $NUC$
                    $S = S \cup \{\lambda^k\}$ & $U = UE_i - S$;
22:             else
23:                 $\lambda^k$ = first UE from $NUC$;
24:                 $S = S \cup \{\lambda^k\}$ & $U = UE_i - S$
25:             end if
26:         end if
27:     end if
28:     Calculate $A^k$;
29:     $a^k_{j,i} = a^{k-1}_{j,i} + a^0_{j,\lambda^k}$; $i \epsilon U$;
30: end for
31: Finally $S = [\lambda^1, \lambda^2, \ldots, \lambda^k]$
```

Algorithm 2 Second Phase: Minimize Energy Cost

```
1:  Assign: $St_{j,i} = 0$; $Et_{j,i} = 0$
2:  for $k \leftarrow 1$ to n iterations do
3:      if $k = 1$ then
4:          $St_{j,\lambda^k} = 0$ and $Et_{j,\lambda^k} = A^0_{j,\lambda^k}$
5:      else
6:          $St_{j,\lambda^k} = Et_{j,\lambda^{k-1}}$ and $Et_{j,\lambda^k} = St_{j,\lambda^k} + A^0_{j,\lambda^k}$
7:      end if
8:  end for
9:  for $k \leftarrow n$ to 1 iterations do
10:     if $k = n$ then
11:         $Et_{j,\lambda^k} = \max_j(Et_{j,\lambda^k})$;
12:         $St_{j,\lambda^k} = Et_{j,\lambda^k} - A^0_{j,\lambda^k}$
13:     else
14:         $Et_{j,\lambda^k} = \min_j(St_{j,\lambda^{k+1}}, \max_j(Et_{j,\lambda^k}))$;
15:         $St_{j,\lambda^k} = Et_{j,\lambda^k} - A^0_{j,\lambda^k}$
16:     end if
17: end for
18: $Ec = \sum_i (\max_j(Et_{j,i}) - \min_j(St_{j,i}))$
```



(a)

(b)

FIGURE 6. (a) Algorithm 1, resource block allocation according to scheduled order S with extra wake-up period 2 TTIs. (b) Algorithm 2, resource block allocation according to scheduled order S with no extra wake-up period.

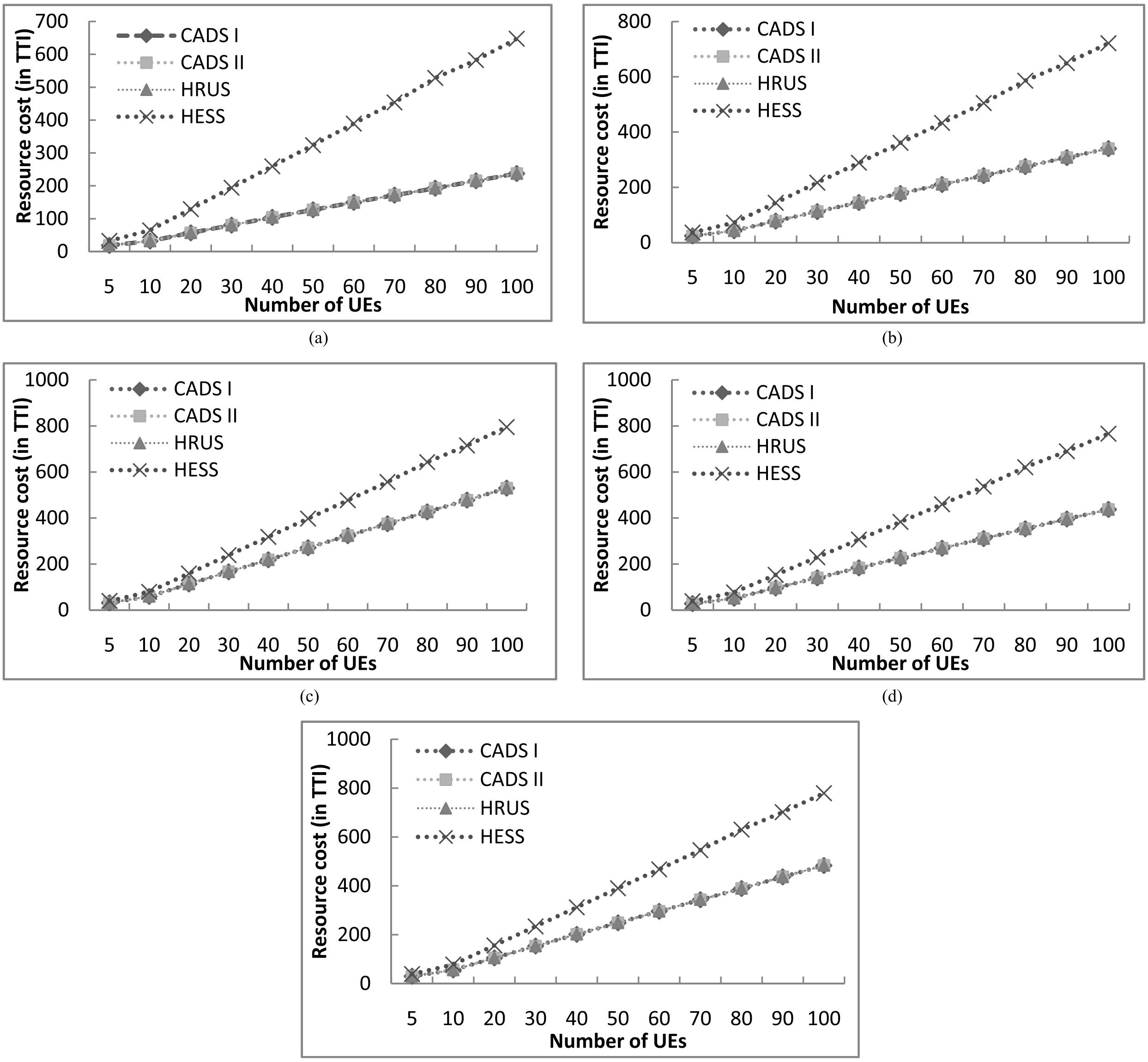
shown in line 14. Line 18 calculates the Ec of all UEs within the time frame.

Considering the same example with S=[UE$_1$, UE$_3$, UE$_4$, UE$_2$, UE$_5$] as shown in Fig. 6. The R_c and E_c are 9 and 16, respectively.

The CADS algorithm is an efficient way to schedule UEs where resources and wake-up time are the critical parameters for the network. CADS can find the best sequence and optimizes both the parameters. Based on the execution sequence of parameters, CADS can be classified in two ways CADS I and II. In CADS I, the sequence is the same as mentioned in the above algorithm, whereas in CADS II, the execution sequence of parameters starts with *NL* then *WT* and finally *NUC*. The pros and cons of above-categorized algorithms CADS I and II are explained in the discussion section.

V. SIMULATION RESULTS

In this section, we develop a simulator in C++ language to verify the effectiveness of the proposed scheme. The parameters used in simulations are shown in Table 2. The number of UEs is n = 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100. The total number of multiple CCs available for the UEs to subscribe is m = 1, 2, 3, 4, and 5. Each CA scenario is formulated with 2 CCs, 3 CCs, 4 CCs, 5 CCs and random CCs. The number of TTIs in one cycle is 100 and 1 TTI is equal to 1ms. We randomly allocate TTIs (maximum 10 ms) to the number of CCs of UEs. In the simulation, we compare our CADS scheme, CADS I, and CADS II with HRUS and HESS schemes. The HRUS scheme can determine the



(a)

(b)

(c)

(d)

(e)

FIGURE 7. **(a) Resource Allocation for 2 CCs. (b) Resource Allocation for 3 CCs. (c) Resource Allocation for 4 CCs. (d) Resource Allocation for 5 CCs. (e) Resource Allocation for random CCs.**

best scheduling order to reduce resource cost but it neglects the optimization of UEs' energy saving. The HESS scheme always adopts the best scheduling order to optimize energy saving of UEs. Thus, it incurs high resource cost.

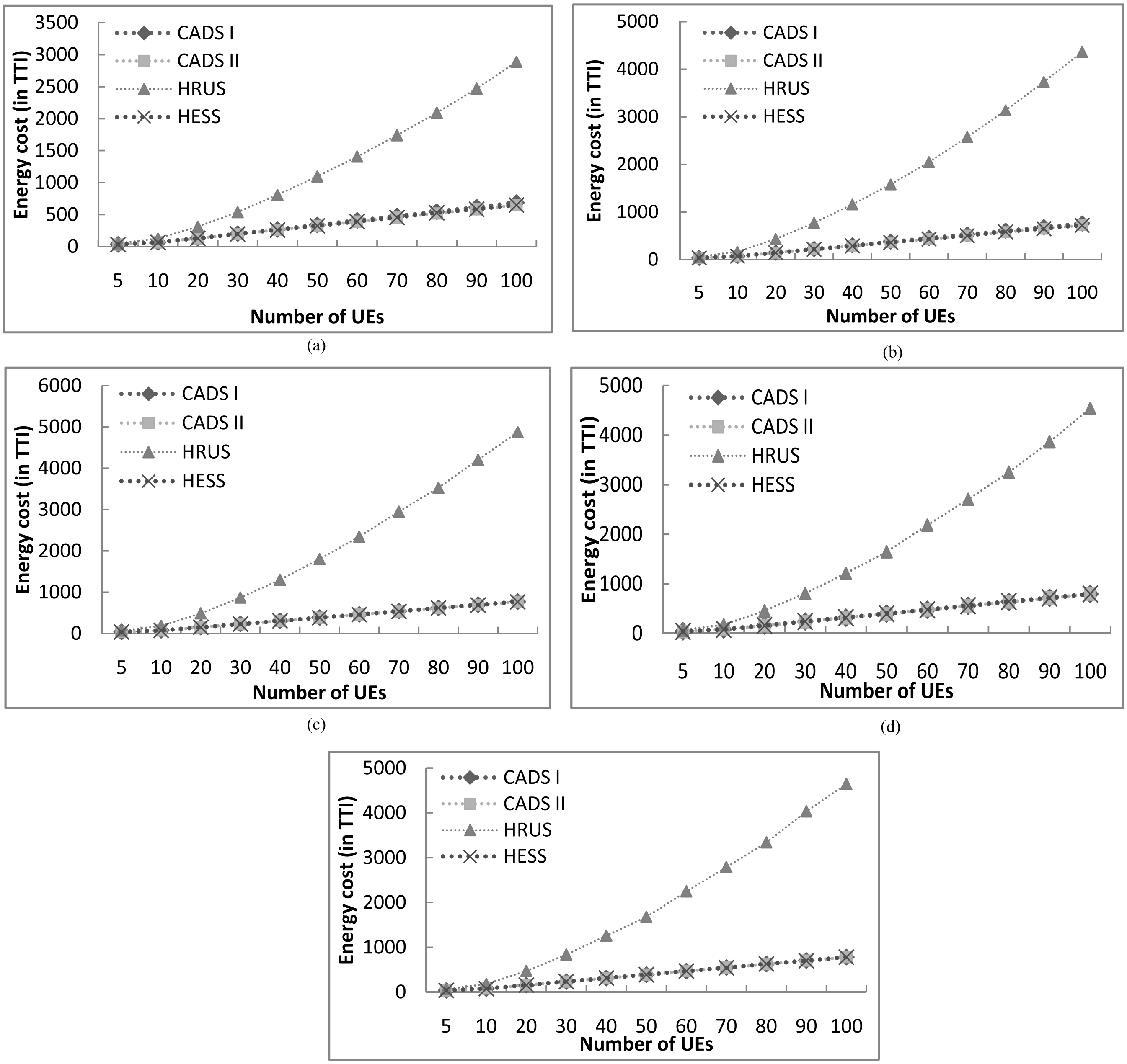
To evaluate the performance of our proposed scheme we consider four performance metrics: (i) *Resource cost*: (ii) *Energy cost*: (iii) *Number of served UEs*: number of UEs served in one DRX cycle i.e., 100 ms; (iv) *Carrier utilization:* Average wake-up time in different carrier utilization. Note that each simulation result is averaged by 2000 experiments.

A. RESOURCE COST

When more CCs can be subscribed by UEs (maximum 5CCs in CA), the resource allocation of the network will also increase as shown in Fig. 7. The HESS scheme incurs the highest resource cost because it neglects the optimization of allocated resources to the network. The HRUS scheme is better than HESS because it reduces the resource cost; however, the energy cost did not change. Note that proposed

TABLE 2. **Simulation parameters.**

Parameter	Values
Number of UEs	5, 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100
Number of CCs	5
CCs bandwidth	1.4, 3, 5, 10, 15, 20 MHz.
1 cycle	100 ms.
Carrier aggregation with number of CCs	2 CCs, 3 CCs, 4 CCs, 5 CCs.
1 TTI (subframe)	1 ms.



(a)

(b)

(c)

(d)

(e)

FIGURE 8. (a) Wake-up time for 2 CCs. (b) Wake-up time for 3 CCs. (c) Wake-up time for 4 CCs. (d) Wake-up time for 5 CCs. (e) Wake-up time for random CCs.

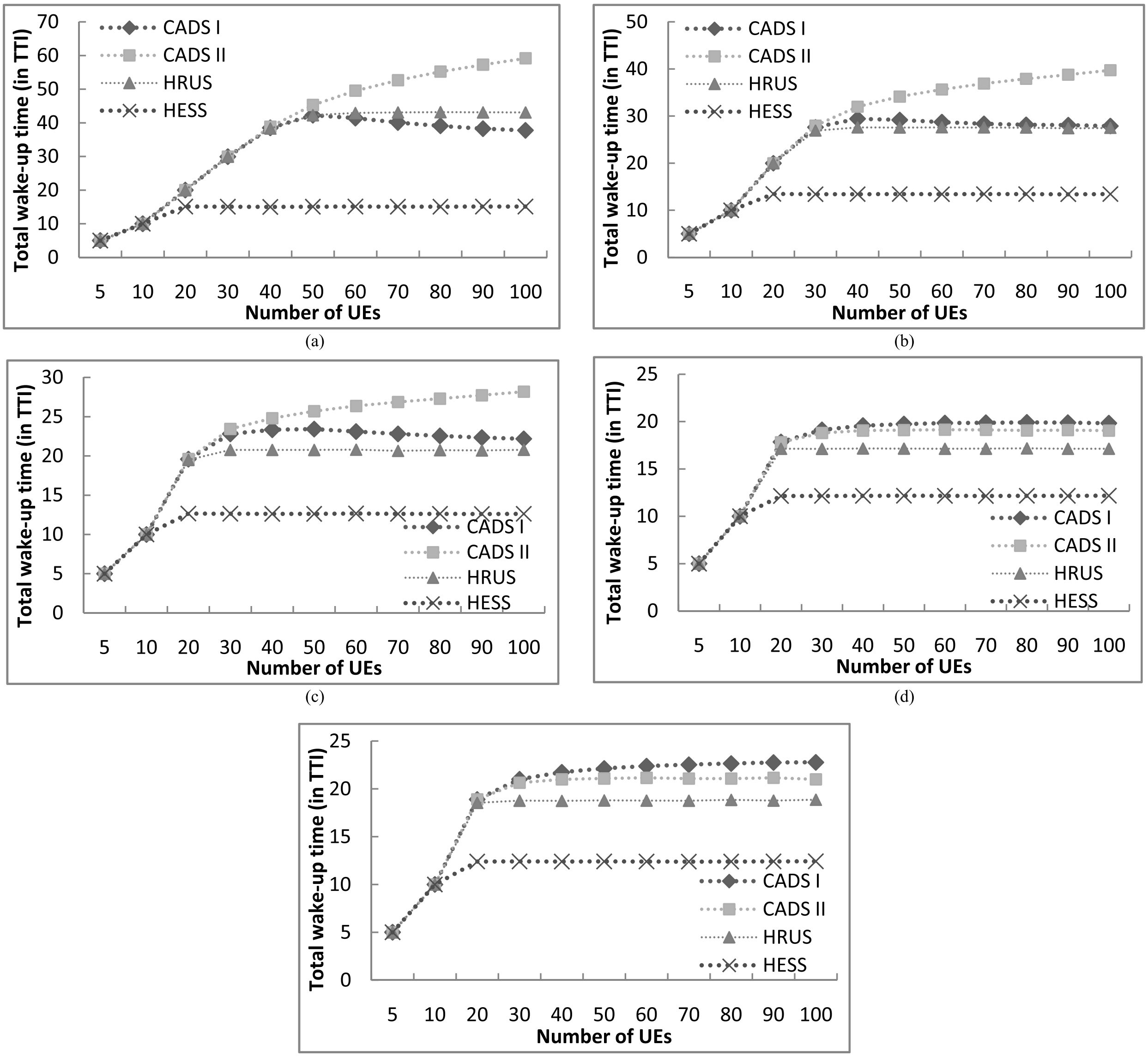
CADS I and CADS II try to reduce both the resource and energy cost by optimizing the scheduling order through the phases 1 and 2. Thus, the unnecessary wake-up periods of UEs are significantly reduced.

B. ENERGY COST

We then investigate the effects of a number of UE and CCs on the wakeup time, i.e., energy conserved in TTIs of all schemes. As shown in Fig. 8, when the number of CCs and UEs increases, the energy to the process of all schemes increases. This is because the conserved energy of UEs is directly proportional to wake-up periods. The HRUS scheme saves the least energy and the HESS scheme is better than HRUS scheme because HRUS neglects to determine the best optimization of allocated resources to the network. Note that the performance of our CADS schemes is close to HESS because they significantly reduce the wake-up costs incurred by the resource and energy costs.

C. NUMBER OF SERVED UEs

Next, we investigate the effects of resource and energy metrics on the number of served UEs in 100 ms (i.e., 1 cycle)



(a) (b) (c) (d) (e)

FIGURE 9. **(a) Number of UE served for 2 CCs. (b) Number of UE served for 3 CCs. (c) Number of UE served for 4 CCs. (d) Number of UE served for 5 CCs. (e) Number of UE served for random CCs.**

by the network. As shown in Fig. 9, when the number of UEs and CCs are increased, our CADS schemes outperform other schemes. This is because they consider resource and energy cost simultaneously. Specifically, CADS II shows good results when the network is not much congested such as 2 CCs, 3 CCs, and 4 CCs, but with 5CCs the results are not good since it executes NL first. CADS I scheme executes WT first, so the UEs with a minimum resource allocation will be scheduled first. Thus, the UEs served in maximum CCs by CADS I is higher than other schemes.

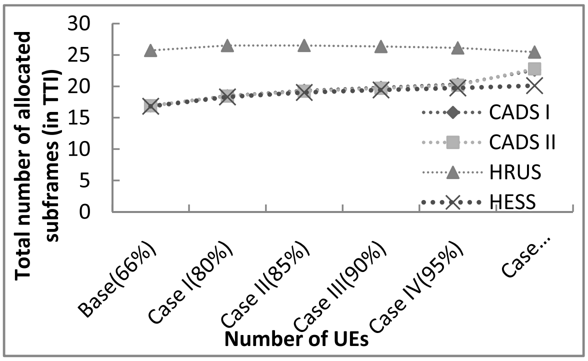
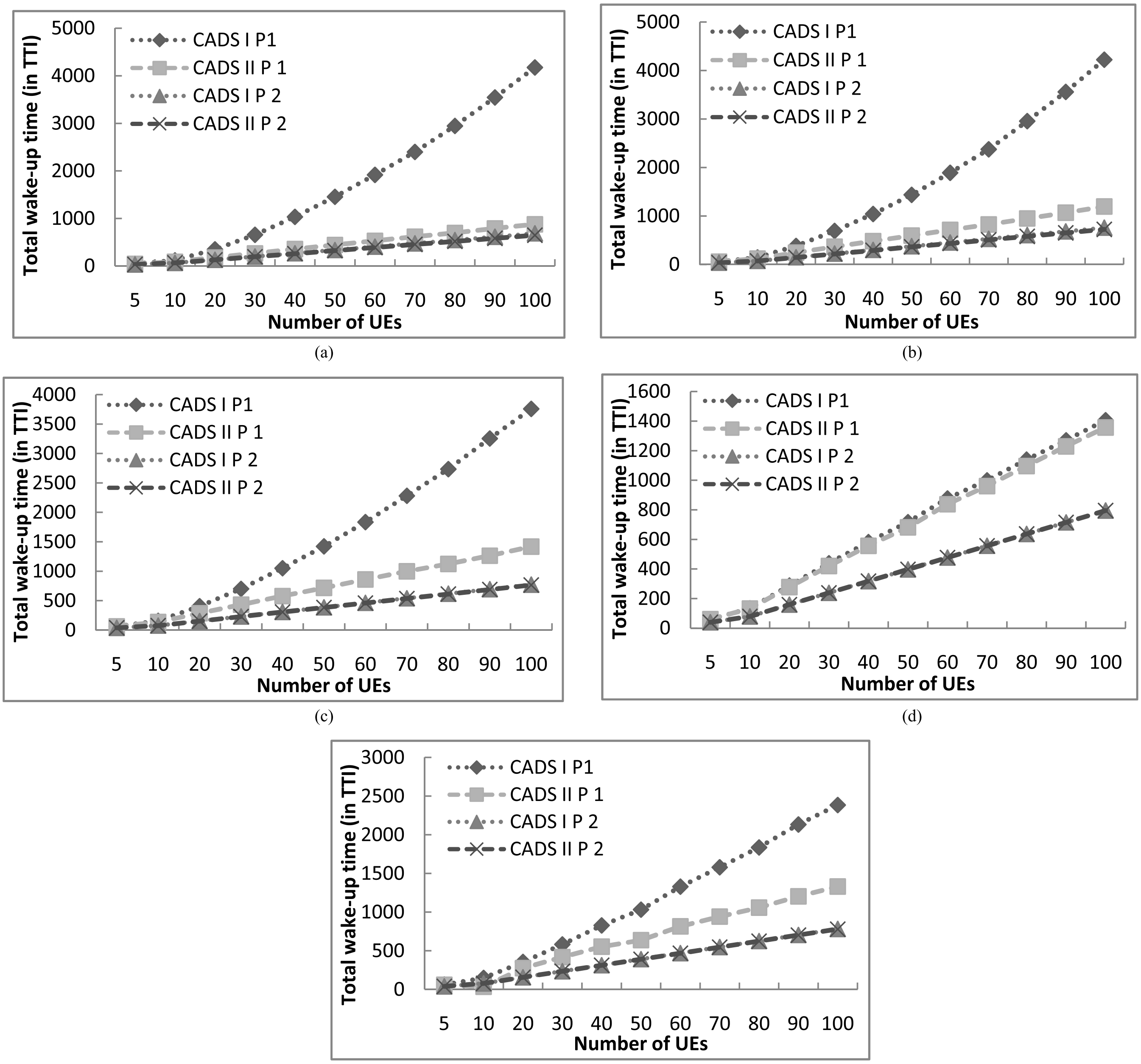


FIGURE 10. **Number of allocated subframes in different cases with 5 UEs.**

D. CARRIER UTILIZATION

Next, we investigate the carrier utilization of the network as shown in Fig. 10, which is the ratio of allocated TTIs to total available TTIs for all UEs in the network. We formulate six cases with 5 UEs connected to 5 CCs with different percentage of carrier utilization. For example, the base case carrier utilization is 66% ((33×100)/50), where 33 is total resources allocated


(a)

(b)

(c)

(d)

(e)

FIGURE 11. **(a) Number of wake-up subframes for 2 CCs. (b) Number of wake-up subframes for 3 CCs. (c) Number of UE served for 4 CCs. (d) Number of UEs served for 5 CCs. (e) Number of UE served for random CCs.**

with the maximum TTIs 50 in the network. Note that CADS I and II have a similar result. They show bad results in Case V only when all CCs allocated with their maximum value because there is no available space for adjustment. Thus, they show an increase in energy cost whenever resource allocation rate to multiple CCs is high.

VI. DISCUSSIONS

Based on the results, we express our discussions. In Fig. 7, it shows that CADS and HRUS schemes successfully minimize the resources. While increasing the number of CCs in CA, then there is a resource to satisfy UEs with more number of CCs as shown in Fig. 7 (c) and (d). Whereas in Fig. 8, CADS and HESS show a similar number of wake-up time while increasing the number of CCs in CA. Since we randomly allocate the resources (maximum 10 TTI) to a UE by a CC. Due to this, a UE can require the maximum 10 TTI wake-up time to receive all the resources with different number of CCs in CA. That is why it shows a constant behavior among Fig. 8 (a-e). In Fig 9 (a), when the number of CC is 2, CADS II has served a high number of UEs since NL is the first parameter that maximizes the throughput but with

5 number of CCs, CADS II cannot handle the same situation. CADS I maximizes the number of UEs as it considers the UE first which has minimum WT time to satisfy as many UEs as possible. From this, we can consider CADS II whenever the network has registered UEs with less number CC in CA and we can consider CADS I in a high number of CCs in CA. We can also witness the significance of NUC in CADS since it maintains fairness among different CCs. While increasing the number of CCs, the wake-up time is reduced and the system is much fairer if we do compare with 2 CCs.

While comparing CADS I and CADS II, we have investigated each with their phases, phase 1 (P1) and phase 2 (P2) as shown in Fig. 11. CADS I (P1) and CADS II (P1) show a substantial difference in 2 CCs, 3 CCs, and 4 CCs; however, with 5 CCs, it is reduced due to high carrier utilization. CADS I (P2) and CADS II (P2) show a similar course since the P2 optimizes the differences of P1. Thus, CADS I and CADS II show an almost similar pattern.

VII. CONCLUSION

In this paper, we have addressed the MCRS problem under the consideration of network resources and UE energy consumption. We developed an energy-efficient heuristic iterative methods. The proposed CADS schemes provide a unique scheduling algorithm which is a tradeoff between network resources and UEs' energy consumption. Our CADS schemes consist of two phases. The first phase reduces network resources and schedules the transmission order of UEs. The second phase reduces the energy consumption of UEs by minimizing wake-up time. Extensive simulation results have verified the effectiveness of our schemes and shown that our schemes can well utilize the spectrum resource and decrease the energy consumption of UEs.

REFERENCES

[1] M. Iwamura, K. Etemad, M. H. Fong, R. Love, and R. Nory, "Carrier aggregation framework in 3GPP LTE-Advanced," *IEEE Commun. Mag.*, vol. 48, no. 8, pp. 60–67, Aug. 2010.

[2] J. Wannstrom. *3GPP the Mobile Broadband Standard LTE-Advanced*. Accessed: Mar. 1, 2018. [Online]. Available: http://www.3gpp.org/technologies/keywords-acronyms/97-lte-advanced

[3] B. Arendse, A. Adedeji, M. Mhlungu, G. Thomas, S. Bakhshi, and S. Malik, "Broadband as a platform for video delivery: What to expect from platforms and applications," in *Broadband as a Video Platform*. Cham, Switzerland: Springer, 2014, pp. 81–93.

[4] M. A. M. Albreem, "5G wireless communication systems: Vision and challenges," in *Proc. Int. Conf. Comput., Commun., Control Technol. (I4CT)*, Apr. 2015, pp. 493–497.

[5] A. Elnashar and M. A. El-Saidny, "Extending the battery life of smartphones and tablets: A practical approach to optimizing the LTE network," *IEEE Veh. Technol. Mag.*, vol. 9, no. 2, pp. 38–49, Jun. 2014.

[6] *Evolved Universal Terrestrial Radio Access (E-UTRA); Medium Access Control (MAC) Protocol Specification*, document 3GPP TS36.321, v8.0.0 (Release 8), 2012.

[7] R. Ratasuk, D. Tolli, and A. Ghosh, "Carrier aggregation in LTE-Advanced," in *Proc. IEEE 71st Veh. Technol. Conf.*, May 2010, pp. 1–5.

[8] G. Yuan, X. Zhang, W. Wang, and Y. Yang, "Carrier aggregation for LTE-advanced mobile communication systems," *IEEE Commun. Mag.*, vol. 48, no. 2, pp. 88–93, Feb. 2010.

[9] H.-S. Liao, P.-Y. Chen, and W.-T. Chen, "An efficient downlink radio resource allocation with carrier aggregation in LTE-advanced networks," *IEEE Trans. Mobile Comput.*, vol. 13, no. 10, pp. 2229–2239, Oct. 2014.

[10] H. Shajaiah, A. Abdelhadi, and T. C. Clancy, "Towards an application-aware resource scheduling with carrier aggregation in cellular systems," *IEEE Commun. Lett.*, vol. 20, no. 1, pp. 129–132, Jan. 2016.

[11] X. Cheng, G. Gupta, and P. Mohapatra, "Joint carrier aggregation and packet scheduling in LTE-Advanced networks," in *Proc. IEEE Int. Conf. Sens., Commun. Netw. (SECON)*, Jun. 2013, pp. 469–477.

[12] C.-Y. Wang, H.-Y. Wei, and W.-T. Chen, "Resource block allocation with carrier-aggregation: A strategy-proof auction design," *IEEE Trans. Mobile Comput.*, vol. 15, no. 12, pp. 3142–3155, Dec. 2016.

[13] K.-T. Feng, P.-R. Li, and J.-H. Chu, "Novel design of optimal spectrum sharing for cognitive radio-enabled LTE-A multi-cell networks," *IEEE Trans. Mobile Comput.*, vol. 15, no. 10, pp. 2507–2521, Oct. 2016.

[14] M. Lauridsen, H. Wang, and P. Mogensen, "LTE UE energy saving by applying carrier aggregation in a HetNet scenario," in *Proc. IEEE 77th Veh. Technol. Conf. (VTC Spring)*, Jun. 2013, pp. 1–5.

[15] A. T. Koc, S. C. Jha, R. Vannithamby, and M. Torlak, "Device power saving and latency optimization in LTE-A networks through DRX configuration," *IEEE Trans. Wireless Commun.*, vol. 13, no. 5, pp. 2614–2625, May 2014.

[16] F. Liu, K. Zheng, W. Xiang, and H. Zhao, "Design and performance analysis of an energy-efficient uplink carrier aggregation scheme," *IEEE J. Sel. Areas Commun.*, vol. 32, no. 2, pp. 197–207, Feb. 2014.

[17] J. Zhang, L. Meng, and H. Ji, "Joint cell association and user scheduling in carrier aggregated heterogeneous networks," *Information*, vol. 9, no. 1, p. 9, Jan. 2018.

[18] H. Shajaiah, A. Abdelhadi, and C. Clancy, "Robust resource allocation with joint carrier aggregation in multi-carrier cellular networks," *IEEE Trans. Cognit. Commun. Netw.*, vol. 4, no. 1, pp. 53–65, Mar. 2018.

[19] I. Baig, S. Chaudhuri, and D. Das, "Downlink interference control through adaptive DRX in a carrier aggregation enabled LTE-Advanced heterogeneous networks," in *Proc. IEEE Int. Conf. Adv. Netw. Telecommun. Syst. (ANTS)*, Nov. 2016, pp. 1–6.

[20] A. James and A. S. Madhukumar, "Enhanced coverage through relay assisted carrier aggregation for cellular networks," *Digit. Signal Process.*, vol. 65, pp. 52–62, Jun. 2017.

[21] Q. Wang, Q. Zhang, Y. Sun, Z. Wei, and Z. Feng, "A QoS-guaranteed radio resource scheduling in multi-user multi-service LTE-A systems with carrier aggregation," in *Proc. 2nd IEEE Int. Conf. Comput. Commun. (ICCC)*, Oct. 2016, pp. 2927–2932.

[22] Z. L. Fazliu, C.-F. Chiasserini, G. M. Dell'Aera, and E. Hamiti, "Distributed downlink power control for dense networks with carrier aggregation," *IEEE Trans. Wireless Commun.*, vol. 16, no. 11, pp. 7052–7065, Nov. 2017.

[23] E. Chavarria-Reyes, I. F. Akyildiz, and E. Fadel, "Energy-efficient multi-stream carrier aggregation for heterogeneous networks in 5G wireless systems," *IEEE Trans. Wireless Commun.*, vol. 15, no. 11, pp. 7432–7443, Nov. 2016.

[24] S. Chaudhuri, I. Baig, and D. Das, "QoS aware downlink scheduler for a carrier aggregation LTE-Advance network with efficient carrier power control," in *Proc. IEEE Annu. India Conf. (INDICON)*, Dec. 2016, pp. 1–6.

[25] E. Chavarria-Reyes, E. Fadel, S. Almasri, and M. G. A. Malik, "Reducing the energy consumption at the user equipment through multi-stream cross-carrier-aware discontinuous reception (DRX) in LTE-Advanced systems," *J. Netw. Comput. Appl.*, vol. 64, pp. 43–61, Apr. 2016.

[26] C. Zhong, T. Yang, L. Zhang, and J. Wang, "A new discontinuous reception (DRX) scheme for LTE-advanced carrier aggregation systems with multiple services," in *Proc. IEEE Veh. Technol. Conf. (VTC Fall)*, Sep. 2011, pp. 1–5.

[27] *Evolved Universal Terrestrial Radio Access (E-UTRA); Radio Resource Coutrol (RRC); Protocol Specification*, document 3GPP TS 36.331, v13.0.0 (Release 13), 2016.

[28] J.-M. Liang, J.-J. Chen, P.-C. Hsieh, and Y.-C. Tseng, "Two-phase multicast DRX scheduling for 3GPP LTE-Advanced networks," *IEEE Trans. Mobile Comput.*, vol. 15, no. 7, pp. 1839–1849, Jul. 2016.

[29] *E-UTRA; Carrier Aggregation Enhancements; User Equipment and Base Station Radio Transmission and Reception*, document 3GPP TR 36.823, v11.0.1 (Release 11), 2013.

[30] E. Yucesan and S. Jacobson, "On the intractability of verifying structural properties of discrete event simulation models," INSEAD, Boulevard Constance, Fontainebleau, France, Dept. Oper. Res., Weatherhead School Manage., Case Western Reserve Univ., Cleveland, OH, USA, Tech. Rep., 1992.

[31] J. D. Ullman, "*NP*-complete scheduling problems," *J. Comput. Syst. Sci.*, vol. 10, no. 3, pp. 384–393, Jun. 1975.

[32] S. H. Jacobson and E. Yücesan, "On the complexity of verifying structural properties of discrete event simulation models," *Oper. Res.*, vol. 47, no. 3, pp. 476–481, Jun. 1999.

[33] Y. Brun, "Solving NP-complete problems in the tile assembly model," *Theor. Comput. Sci.*, vol. 395, no. 1, pp. 31–46, Apr. 2008.

[34] M. Dorigo, "An investigation of some properties of an ant algorithm," in *Proc. Parallel Problem Solving Nat. Conf.*, Brussels, Belgium, 1992, pp. 509-520.

[35] A. A. Lazarev and E. R. Gafarov, "Special case of the single machine total tardiness problem is NP-hard," *IFAC Proc. Vol.*, vol. 39, no. 3, pp. 155–157, 2006.

[36] A. Bauer, B. Bullnheimer, R. F. Hartl, and C. Strauss, "An ant colony optimization approach for the single machine total tardiness problem," in *Proc. Congr. Evol. Comput. (CEC)*, 1999, pp. 1445–1450.

[37] J. Du and J. Y.-T. Leung, "Minimizing total tardiness on one machine is NP-hard," *Math. Oper. Res.*, vol. 15, no. 3, pp. 483–495, 1990.