Energy-Efficient DRX Scheduling for Multicast Transmissions in 3GPP LTE-Advanced Wireless Networks

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***Abstract*—The *3GPP LTE-A (Long Term Evolution-Advanced)* is the most promising technology for next-generation wireless communications. It provides high transmission rate up to 1 Gbps and supports plentiful multimedia services, especially for those bandwidth required multicast type of services, such as IPTV and Voice/Video-over-IP services. However, when users activate more services at their *user equipments (UEs)*, more energy is consumed. To save UEs' energy, the LTE-A standard defines the *Discontinuous Reception Mechanism (DRX)* to allow UEs turning off their radio interfaces and going to sleep to save energy when no data needs to be received. But, how to optimize DRX configurations for UEs is still left as an open issue. In this paper, we address the DRX optimization problem for multicast services, which asks how to guarantee the *quality of service (QoS)* of the multicast streams while minimize UEs' wake-up time. We propose an energy-efficient scheme to tackle this problem. The scheme tries to arrange the best multicast data reception orders to reduces UEs' wake-up periods while consider the resource collision avoidance. Simulation results show that the performance of the proposed scheme is effective even if the network is under saturated condition.**

***Index Terms*—Discontinuous Reception Mechanism (DRX), Multicast, Power Management, Quality of Service, Long Term Evolution-Advanced (LTE-A), Wireless Communication.**

I. INTRODUCTION

Long Term Evolution-Advanced (LTE-A) [1] is an emerging technology developed by the *3rd Generation Partnership Project (3GPP)* for next-generation wireless communications. It provides *user equipments (UEs)* with transmission rates up to 1 Gbps for low-mobility UEs and 100 Mbps for high-mobility UEs. In addition, by exploiting the *Multimedia Broadcast Multicast Service (MBMS)* technique, the LTE-A supports comprehensive multicast transmissions, such as Live *Internet Protocol Television (Live IPTV)* and *Multi-Video/Voice-over-IP (Multi-VoIP)* services [2]. Specifically, when multiple UEs request the same stream at the same time (such as watching a live TV program), the MBMS technique will collect these UEs into the same multicast group. Thus, the *Evolved Node B (eNB*) needs to transmit only one copy of the video stream data to the multicast group and all the demands of the UEs in the group are met. We also note that as the number of activated wireless transmissions increases at the UEs, the energy consumption increases. Therefore, the LTE-A specifies the *Discontinuous Reception Mechanism (DRX)* [3] to realize energy saving for UEs. Specifically, when DRX is enabled, the UEs wakes up and sleeps in a periodical manner. During the wake-up period, the UE detects whether or not there is data delivered from the eNB; if no, the UE switches to sleep at the end of the wake-up period and turns off the radio interface so as to save energy.

In the literature, the studies [4]–[6] have evaluated the performance of the DRX mechanism. They point out that enabling DRX can significantly reduce UEs' power consumption. In references [7], [8], the authors propose to dynamically adjust UEs' DRX cycle lengths according to the traffic conditions. However, it costs considerable control signaling to negotiate the adjustments. In reference [9], based on the UEs' channel qualities, an adaptive DRX is proposed to tune their wake-up periods. However, these studies [7]–[9] neglect the QoS issue of UEs, which is especially important for multimedia streams. As described above, none of work has addressed the DRX problem under the consideration of multicast streams. Therefore, this paper addresses the DRX optimization problem, which asks how to satisfy the *quality of service (QoS)* of multicast streams while minimize UEs' wake-up periods following the DRX specification. Note that the UE requesting multiple multicast streams is also under consideration. We propose an energy-efficient scheme which can reduce the wake-up period of UEs incurred by the data reception orders and DRX configurations. Simulation results show that the performance of the proposed scheme is more effective when the network is under non-saturated condition.

The rest of this paper is organized as follows. The DRX mechanism is introduced in Section II. The problem is defined in Section III. Section IV presents our scheme. Simulation results are shown in Section V. Conclusions are drawn in Section VI.

II. DISCONTINUOUS RECEPTION MECHANISM (DRX)

In the LTE standard, the DRX mechanism is managed by the *Radio Resource Control (RRC)* [3]. When DRX is enabled, the UE wakes up and sleeps in a cycle periodically, as shown in Fig. 1. The basic unit of wake-up and sleep durations is a

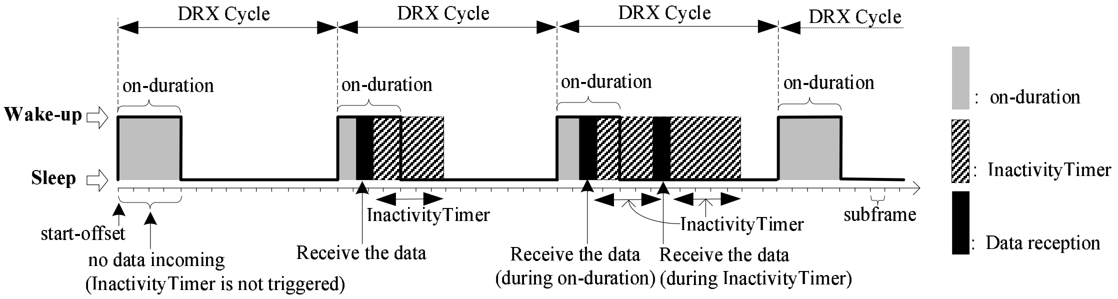

Fig. 1. An overview of the DRX mechanism.

subframe (which is with the length of 1 ms). The DRX mechanism supports two kinds of cycles; one is the short cycle; the other is the long cycle. The short cycle is used for real-time streams and the long cycle is used for non-real-time streams. Since multicast streams are real-time streams, we focus only on the operation of the short cycle. Thus, the term "cycle" used in this paper means the "short cycle" unless otherwise stated. When the DRX mechanism is activated, there are four parameters need to be specified for each UE. These parameters are 1) cycle length, 2) on-duration, 3) start-offset, and 4) InactivityTimer. The cycle length (in subframes) is composed of a wake-up and a sleep periods. Usually, the cycle length should be shorter than the allowable delay of real-time streams for QoS purposes. The on-duration is a necessary period (in subframes) in a cycle that the UE has to awake. During the wake-up period, the UE will monitor whether or not the eNB delivers data to it. The start-offset is the initial subframe that the UE starts DRX operations. The InactivityTimer is used for extending UEs' wake-up periods. Specifically, the UE starts the InactivityTimer when it monitors any of its data delivered from the eNB. Before the InactivityTimer expires, if the UE receives data from the eNB, the InactivityTimer restarts to count down. Once the InactivityTimer expires, the UE will go to sleep and turn off the radio interface to save energy. During the UE's sleep period, all the data for the UE will be buffered at the eNB until the UE's next on-duration arrives.

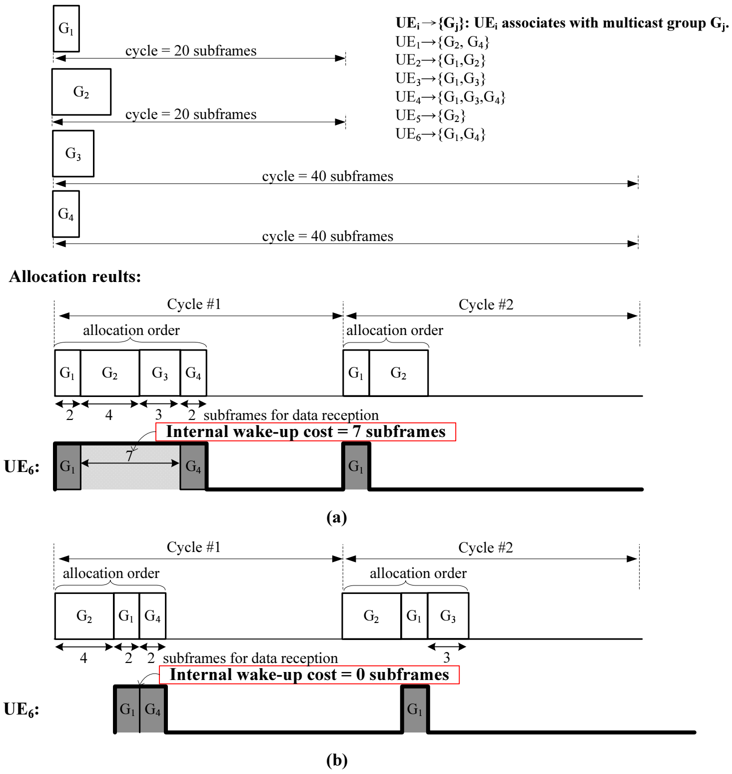

Fig. 2. Effects of multicast allocation orders on the internal wake-up cost of the UE.

To minimize the total energy consumption of UEs, we have to reduce the total amount of UEs' wake-up time. During a wake-up period of a UE, busy subframes are necessary cost which associated with one or more multicast groups, while the idle subframes are the extra cost. This extra cost can be further divided into two categories. One is the *internal cost*, which are the idle listening subframes between two groups of busy subframes; the other is the *external cost*, which are the idle listening subframes before a UE goes to sleep. Note that for any burst of internal cost, the number of consecutive idle listening subframes must be less than the UE's DRX InactivityTimer, or the UE will go to sleep because the DRX InactivityTimer expires. We give two examples in Fig. 2. They show that different multicast group allocation orders result in different internal costs for a UE. Consider that there are six UEs (i.e., $UE_1 \sim UE_6$) and four multicast streams in the network, which forms four multicast groups, i.e., $G_1 \sim G_4$, where $\{G_1, G_2\}$ and $\{G_3, G_4\}$ are with cycle lengths of 20 and 40 subframes due to the streams' delay requirements, respectively. Each multicast stream requires some subframe space to serve the data arriving during a cycle, e.g., 2, 4, 3, and 2 subframes for G_1, G_2, G_3, and G_4 in the example, respectively. Each UE may subscribe to some multicast groups, e.g., UE_6 subscribes to groups G_1 and G_4 (we use $UE_6 \rightarrow \{G_1, G_4\}$ for representation). In Fig. 2(a), the example shows a poor allocation order (i.e., [G_1, G_2, G_3, G_4] in cycle 1 and [G_1, G_2] in cycle 2), which makes UE_6 awake to receive data not only for G_1 and G_4 (it subscribes to) but also for G_2 and G_3 (it does not subscribe to). Similarly, UE_1, UE_3, UE_4, and UE_5 also awake for some groups which are not subscribed by them. The total internal cost incurred by this allocation order is 19 subframes. Contrarily, Fig. 2(b) shows a better allocation order. This order (i.e., [G_2, G_1, G_4] in cycle 1 and [G_2, G_1, G_3] in cycle 2) makes UE_6 wake up only for G_1 and G_4 without any internal cost because these two groups are allocated adjacently in the allocation lists. Similar results also

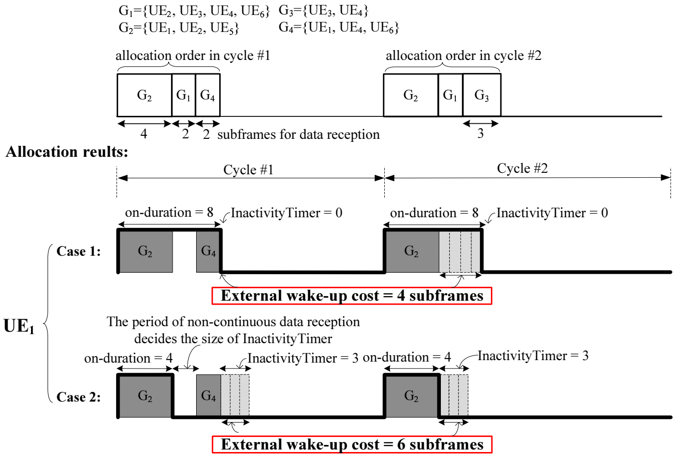

Fig. 3. Effects of on-duration and InactivityTimer of the UE on the external wake-up cost.

apply for UE$_2$, UE$_3$, and UE$_4$. The total internal cost incurred by the allocation order is only 2 subframes. Since each UE awakes only one period in a cycle, a good allocation order can reduce the amount of internal cost for UEs. However, finding an optimal allocation order to make all groups be ordered adjacently for all UEs is difficult (this will be discussed later in the next section).

On the other hand, Fig. 3 shows that different DRX configurations (i.e., InactivityTimer and on-duration) of the UE lead to different *external* costs. We use the allocation results from Fig. 2(b) and take UE$_1$ as the example. Consider the two cases in Fig. 3, where the first case shows that if UE$_1$ adopts a larger on-duration (8 subframes in this case), it can use a shorter InactivityTimer (at least 0 subframe) to receive its data. This incurs an external cost of 4 subframes for UE$_1$ every two DRX cycles. Next, the second case shows that if UE$_1$ adopts a shorter on-duration (in this case, it is 4 subframes), it may need a larger InactivityTimer (3 subframes in this case) to cover the idle period incurred by the middle group G$_1$ to avoid the expiration of InactivityTimer so as to receive the arrival data of G$_4$. This example incurs the external cost of $3 \times 2 = 6$ subframes every two DRX cycles because UE$_1$ has to awake until the expiration of the InactivityTimer.

From the examples shown in Fig. 2 and Fig. 3, they point out that the multicast group allocation order and the configuration of DRX parameters will significantly affect the wake-up costs of UEs. This strongly motivates us to study the DRX problem.

III. THE DRX OPTIMIZATION PROBLEM

We consider an LTE-A network with an eNB serving N UEs. Assume that M multicast streams are requested in the network, which means that there are M multicast groups[1], and each UE$_i, i = 1..N$, can request at most M different multicast streams at the same time. For each multicast stream $j, j = 1..M$, it is with a delay constraint D_j (subframes) and a data rate R_j (bits/subframe) to ensure its QoS. The transmission rate from the eNB to UE$_i$ is C_i (bits/subframe), which depends on UEs' *modulation and coding scheme (MCS)* defined in Table I. Our problem asks how to determine the schedule of M multicast groups and the DRX configurations for each UE$_i, i = 1..N$, including 1) the cycle length L_i, 2) start-offset S_i, 3) on-duration O_i, and 4) InactivityTimer I_i (all in subframes), to satisfy the QoS of each multicast stream $j, j = 1..M$, where the QoS parameters include the stream's delay constraint D_j and the data rate R_j, while minimizes the overall wake-up costs of UEs for energy conservation.

TABLE I
THE MODULATION AND CODING SCHEMES SUPPORTED BY THE LTE-A STANDARD [10], WHERE THE BANDWIDTH IS 10 MHZ.

Channel Quality Identifier	Modulation	Code rate × 1024	Rate (bits/subframe)
1	QPSK	78	1279.2
2	QPSK	120	1969.0
3	QPSK	193	3166.8
4	QPSK	308	5153.4
5	QPSK	449	7366.8
6	QPSK	602	9876.6
7	16QAM	378	12403.4
8	16QAM	490	16078.4
9	16QAM	616	20212.8
10	64QAM	466	22936.2
11	64QAM	567	27907.4
12	64QAM	666	32779.4
13	64QAM	772	37997.0
14	64QAM	873	42968.6
15	64QAM	948	46659.4

Our problem can be reduced from the *Hyper-graph Optimal Linear Arrangement (HOLA)* problem [11], which is known to be NP-complete. Consider the case of M multicast groups, where their delay constraints are identical, i.e., $D_j = D_1, j = 2..M$ and thus the cycle-lengths of all streams are the same and the best InactivityTimers I_i of each UE$_i$ is 0. Note that we also consider that each multicast group G$_j, j = 1..M$, requests $T_j = 1$ subframe to serve its arrival data in a cycle to meet QoS. Thus, the UE set can be mapped to the hyper-edge set of a hyper-graph and the multicast group set can be mapped to the vertex set of the hyper-graph. Then, if our problem has a solution of the total wake-up periods λ and thus the HOLA problem has a solution of the total hyper-edge lengths $\lambda - N$. This shows that our problem is NP-complete.

IV. THE PROPOSED SCHEME

In this section, we present an energy-efficient heuristic. The main idea of the scheme is to assign all UEs the same cycle-length to eliminate the external cost and exploits the "*minimal cost first*" strategy to reduce the overall internal costs of UEs incurred by the allocation order. In the following, we first determine the cycle length and start-offset for each multicast group and then determine those of UEs based on above results. The detailed steps are depicted as follows.

Step 1: Let $\widehat{L}_j$ be the cycle length of G$_j, j = 1..M$. We set the cycle length $\widehat{L}_j$ for multicast group G$_j, j = 1..M$ by

$$\widehat{L}_j = \min_{j=1..M}\{D_j\}. \tag{1}$$

By Eq. (1), it can ensure to meet the delay constraint of stream j because of $\widehat{L}_j \leq D_j, j = 1..M$. Eq. (1) also implies that the allocation results will repeat every $\widehat{L}_1$ subframes.

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[1] Note that we may use multicast group $G_j, j = 1..M$, to represent the multicast stream j later in the paper for ease of presentation.

Step 2: Let $T_j, j = 1..M$, be the number of subframes to serve stream j's arrival data during the cycle length $\widehat{L}_j$, where

$$T_j = \left\lceil \frac{R_j \times \widehat{L}_j}{\min\{C_i | UE_i \in G_j\}} \right\rceil . \tag{2}$$

In Eq. (2), the numerator part is the amount of the arrival data (in bits) of stream j during $\widehat{L}_j$ subframes and the denominator part is the transmission rate (bits/subframe) of group G_j, which is restricted by the lowest transmission rate that the UE adopts in group G_j. Thus, by reserving T_j subframes for group G_j during a cycle, it can guarantee all the UEs in group G_j to receive the arrival data of stream j, even if the UE has the lowest transmission rate.

Step 3: Next, let S be the first available subframe in the cycle. Initially, we set $S = 0$. Then, let $\widehat{G}$ be the unallocated-group set; initially, set $\widehat{G} = \{G_1, G_2, .., G_M\}$. In addition, let $\hat{S}_j$ be the group G_j's start-offset in the cycle. We set $\hat{S}_j = 0$ initially.

Then, we define the *potential internal cost function* $\hat{E}_j$ for each group G_j in the cycle, to represent the overall potential increased internal costs when group G_j is allocated into the allocation list $\hat{A}$, i.e.,

$$\hat{E}_j = |K_j| \times T_j, \tag{3}$$

where K_j is the subset of the UEs disappearing in G_j but appearing in both the allocation list and unallocated groups which would increase the overall internal cost, i.e.,

$$K_j = \{UE_i | UE_i \notin G_j, UE_i \in \varphi, UE_i \in \hat{\varphi}\}, \tag{4}$$

where φ is the UEs in the groups of the allocation list $\hat{A}$ and $\hat{\varphi} = \{UE_i | UE_i \in \widehat{G}\}$ is the subset of the UEs contained in the groups that have not been allocated. Thus, the potential cost function can evaluate the internal wake-up cost potentially incurred by the UEs whose groups do not ordered adjacently in the allocation list.

Based on above cost function, we design two procedures to select groups into the allocation list. The first procedure is used to select the first group for the allocation list. The second strategy is used to select the middle group for the allocation list. We note that the first strategy is a special case of the second strategy and both of them use the potential cost as the metric. Thus, if $\hat{A} = \phi$, we adopt **procedure 1** for the first group selection. Otherwise, we use **procedure 2** to choose the middle group for the allocation list. These group selections are terminated until $\widehat{G} = \phi$. The details of the procedures are described as follows.

- **Procedure 1: The First Group Selection**
  Set $\varphi = \hat{\varphi}$ and find the group G_{j*}, which has the maximal potential cost in the cycle, i.e.,

  $$\hat{E}_{j*} = \max_{j=1..M} \{\hat{E}_j\}. \tag{5}$$

  Note that the initial value of $\varphi = \hat{\varphi}$ is used to illustrate the increased cost if group G_j stays in the middle of the allocation list. Then, we add the group G_{j*} as the first group of the allocation list $\hat{A}$. Next, set the offset of G_{j*} by $\hat{S}_{j*} = 0$, and update the next available offset of the cycle by $S = T_{j*}$. Then, update $\widehat{G}, \varphi$, and $\hat{\varphi}$ by $\widehat{G} = \widehat{G} - G_{j*}, \varphi = \{UE_i | UE_i \in G_{j*}\}$, and $\hat{\varphi} = \{UE_i | UE_i \in \widehat{G}\}$.
  With the strategy, we can avoid the group to put into the middle of the allocation list which incurs the maximal internal wake-up cost for the system.

- **Procedure 2: The Middle Group Selection**
  This strategy finds the best group G_{j*} which incurs the minimal potential cost $\hat{E}_{j^*}$ as the next group in $\hat{A}$, i.e.,

  $$\hat{E}_{j^*} = \min_{G_j \in \hat{G}} \{\hat{E}_j\}. \tag{6}$$

  Here, if more than one group G_{j*} matches, choose the one with the smaller index for representation. Then, after adding G_{j*} to the allocation list $\hat{A}$, we update the offset of G_{j*} by $\hat{S}_{j^*} = S$ and update the next available start-offset of the cycle by $S = S + T_{j*}$. Then, update $\varphi = \varphi \cup \{UE_i | UE_i \in G_{j^*}\}$. Next, update $\widehat{G}$ and $\hat{\varphi}$ by $\widehat{G} = \widehat{G} - G_{j^*}$ and $\hat{\varphi} = \{UE_i | UE_i \in \widehat{G}\}$, respectively. Then, check if $\widehat{G} = \phi$. If yes, terminate the step.

With the procedures 1 and 2, we can effectively reduce the potential internal wake-up costs of the UEs.

Step 4: Finally, calculate the start-offset of each UE_i by the minimal start-offset of group G_j that UE_i subscribes to, i.e.,

$$S_i = \min_{j=1..M} \{\hat{S}_j | UE_i \in G_j\}. \tag{7}$$

Then, the cycle length of UE_i is set by $L_i = \widehat{L}_1, i = 1..N$.

Step 5: Set $I_i = 0$ and $O_i = EPO_i - SP_i$, where EPO_i is the farthest end point of the last group, that UE_i subscribes to, and SP_i is the closest start point (in subframe) of the first group, that UE_i subscribes to, in the cycle, i.e.,

$$\begin{aligned} EPO_i &= \max_{j=1..M} \{\hat{S}_j + T_j | UE_i \in G_j\}, \\ SP_i &= \min_{j=1..M} \{\hat{S}_j | UE_i \in G_j\}. \end{aligned} \tag{8}$$

By Eq. (8), we can see when InactivityTimer is set by $I_i = 0$, the on-duration O_i should cover all the data receiving period which starts from the point of the first group and ends at the end point of the latest group, that UE_i subscribes to.

With the scheme, we can determine the cycle length, start-offset, InactivityTimer, and on-duration for each UE_i through the allocated results. Meanwhile, it can also ensure to serve the amount of multicast data during their cycle lengths and meet their delay constraints. Most important of all, with the "minimum cost first" strategy, the proposed scheme can reduce unnecessary internal wake-up costs incurred by the allocation orders. In addition, the external costs of UEs are also eliminated by uniforming the cycle length of all multicast streams.

We give an example in Fig. 4 to show the calculation of the potential cost, where $N = 5, M = 4$ and all the groups are with the same cycle length. In this example, we assume that G_1 and G_2 have been allocated in the allocation list $\hat{A}$ but G_3 and G_4 have not been allocated. Thus, if adding G_3 as

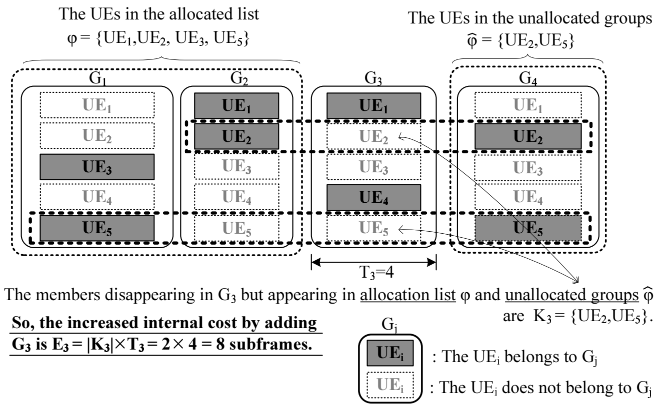

Fig. 4. An example of calculating the potential cost.

the next group of the allocation list $\hat{A}$, it will increase the idle period of the UEs (i.e., $K_3 = \{UE_2, UE_5\}$) because these UEs do not subscribe to stream 3 but subscribe to the streams allocated before and after stream 3 in the allocation list, i.e., $UE_2 \to \{G_2, G_4\}$ and $UE_5 \to \{G_1, G_4\}$. Thus, the internal cost incurred by adding G$_3$ is $|K_3| \times T_3 = 2 \times 4 = 8$ subframes.

V. SIMULATION RESULTS

In this section, we develop a simulator in C++ language to verify the effectiveness of the proposed scheme. The system parameters of the simulator are listed below. The frequency bandwidth is 10 MHz. The total number of the multicast streams is up to $M = 7$. The number of UEs is $N = 150$. Each UE can request $1 \sim 5$ multicast streams at the same time. Each multicast stream j has the admitted data rate $R_j = 100 \sim 1900$ bits/ms [12] and the delay constraint $D_j = 50 \sim 300$ subframes [13]. The transmission rate of each UE is generated according to [10]. In the simulation, we compare our minimal-cost scheme (**MC**) to the optimal scheme (**OPT**). The OPT scheme can find the optimal allocation order, InactivityTimer, and on-duration for UEs by a brute force manner. Thus, it incurs high computational cost.

We consider three performance metrics: (i) *wake-up ratio*: the ratio of wake-up subframes over the DRX execution time, (ii) *successful-to-schedule probability*: the probability to succeed determining UEs' DRX configurations to meet the QoS of their requested multicast streams, and (iii) *computational complexity*: the average computational time to successfully determine DRX configurations for all UEs in each round. Note that each experiment is averaged by at least 2000 simulation results.

A. Wake-up Ratio

We first investigate the effects of number of multicast streams on the wake-up ratio of all schemes. As shown in Fig. 5, as the number of streams increases, the wake-up ratio of all schemes increases. The reason is that more streams are able to be subscribed by UEs, a longer period UEs have to awake. Note that the performance of our scheme is close to that of the **OPT** scheme, because our scheme can reduce the unnecessary wake-up periods caused by allocation orders and DRX parameters.

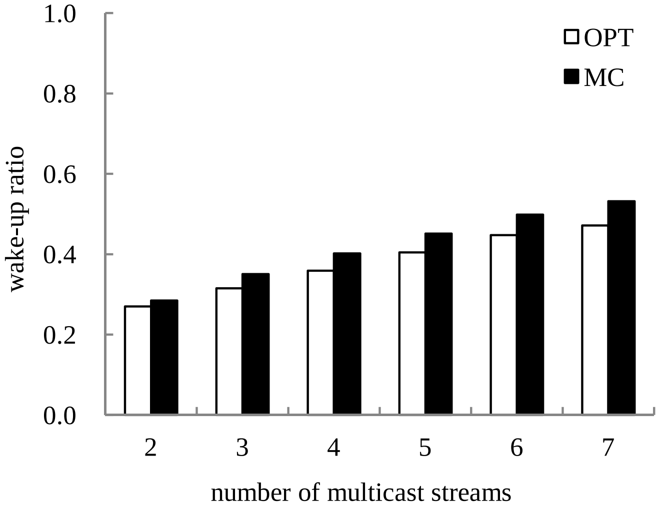

Fig. 5. Comparison on the wake-up ratio of all schemes under $M = 2 \sim 7$ multicast streams.

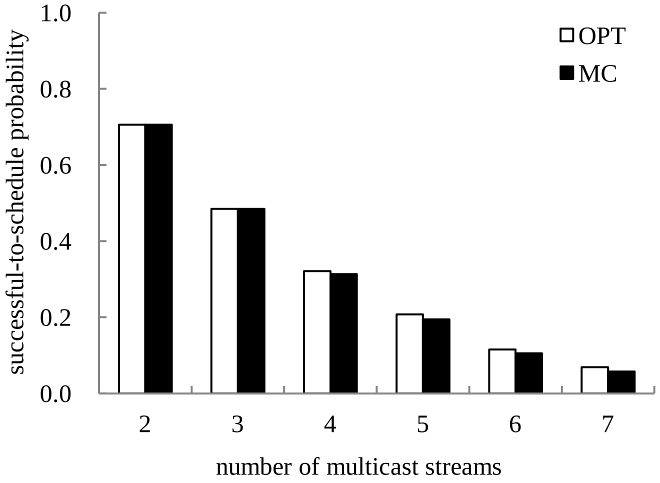

Fig. 6. Comparison on the successful-to-schedule probability of all schemes under $M = 2 \sim 7$ multicast streams.

B. Successful-to-Schedule Probability

Next, we investigate the effects of number of multicast streams on successful-to-schedule probability of all schemes. As shown in Fig. 6, as the number of streams increases, the probability of all schemes decreases. The reason is that the total frame space is getting insufficient when more multicast streams are subscribed by UEs. Similarly, the successful-to-schedule probability of our scheme is close to the **OPT** scheme, because our scheme can well utilize the frame space by reducing the necessary wake-up subframes for each UE.

C. Computational Complexity

Finally, we investigate the effects of number of multicast streams on computational time of all schemes. Here, the computation time is measured by the platform of DELL Optiplex 745 with Intel Core 2 Duo E6400 2.13 GHz and DDR2 SDRAM 2 GB. As shown in Fig. 7, the computing time of the **OPT** scheme increases exponentially as the number of streams grows (note that the y-axis is drawn with exponential

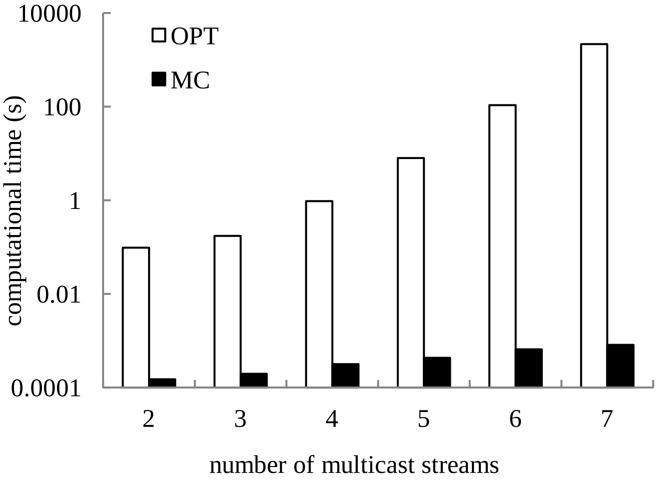

Fig. 7. Comparison on computational complexity of all schemes under $M = 2 \sim 7$ multicast streams.

scales). This is because it takes more combinations to find the optimum allocation list and corresponding DRX parameters for UEs when the number of streams increases. Contrarily, our scheme takes less computational time because our scheme sequentially determines the group allocation orders by the proposed minimal cost strategy. Thus, the time complexity of our scheme is reduced significantly.

VI. CONCLUSIONS

In this paper, we have addressed the DRX optimization problem with the consideration of the QoS for multicast streams and the energy conservation for UEs. We have developed an energy-efficient scheme. The scheme uses the minimal cost strategy to reduce internal costs of UEs and uniforms the cycle lengths of all multicast streams for UEs to eliminate the external cost. Simulation results have verified the effectiveness of our scheme and shown that our scheme can significantly decrease the wake-up ratios of UEs with higher successful-to-schedule probability.

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