# Reducing power consumption in LTE data scheduling with the constraints of channel condition and QoS ☆

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ABSTRACT

3GPP has developed the Discontinuous Reception (DRX) power saving mechanism, which periodically turns off the radio interface to reduce the power consumption. However, packets cannot be received during the turn-off duration, as a result that the Quality of Services (QoS) may be violated. Therefore, optimal DRX parameters should be configured to satisfy QoS and minimize power consumption. In addition, channel condition may be unstable during the transmission, so the DRX parameters should also be dynamically adjusted. In this paper, we propose the Dynamic Scheduling with Extensible Allocation and Dispersed Offsets (DXD) scheme, which is composed of two algorithms, DRX parameters decision, to determine DRX period by considering channel condition and QoS constraints, and DRX-aware scheduling, to determine whether to extend the on duration so that QoS would not be affected by DRX. Simulation results demonstrate that the proposed DXD approach can reduce power consumption up to 96.7% compared to *No-DRX* scheme and guarantee QoS as good as *No-DRX* scheme. In addition, the power consumption can be reduced by 70.1% and 45.7% compared to the *Fixed-DRX (100 ms), start-offset* scheme and *TS* scheme in good channel condition. Our approach effectively reduces power consumption in varied channel conditions and high loading system and still achieves better delay satisfaction ratio than others.

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## 1. Introduction

Nowadays, a variety of powerful smart devices are designed to handle a wide range of traffic, such as VoIP, video streaming, and mobile gaming. In order to satisfy the growing traffic demand for wireless communications, the Third Generation Partner Project (3GPP) Long Term Evolution (LTE) has been developed to support higher transmission rate by adopting some novel technologies, such as Multi-Input Multi-Output (MIMO) and Orthogonal Frequency-Division Multiple Access (OFDMA). However, the high complexity of these new technologies may introduce large power consumption.

While the LTE transmission rate is many times faster than the 3G transmission speed, the battery, the power source of mobile devices, has not any sizeable advancement. Thus, power saving is still one of the important issues for mobile devices. To save the energy of mobile

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devices, 3GPP LTE has defined the *Discontinuous Reception* (DRX) scheme to allow devices to turn off their radio interface and go for a sleep state for a length of time, while staying connected to the network, thereby reducing the power consumption when there is no data transmission [1]. Nevertheless, if packets arrive at sleep state, these packets would pose unexpected delay, which may affect their Quality of Service (QoS) requirements. Thus, how to determine DRX parameters to reduce the power consumption and guarantee QoS simultaneously is still an open issue.

Further, channel condition should be considered when the DRX parameters are determined. The adaptive modulation and coding (AMC) in LTE offers a link adaptation method that can dynamically choose the modulation and coding scheme (MCS) according to current channel condition for each user, known as user equipment (UE). The UE uses channel quality indicator (CQI) [2] to report channel condition for the evolved Node B (eNB) to decide the MCS level. A higher MCS level (i.e., with 64 Quadrature Amplitude Modulation (64QAM) modulation) has higher transmission rate but is more prone to errors due to interference and noise. A lower MCS level (i.e., QPSK modulation) has lower rate but can tolerate a higher level of interference. When channel condition is good, AMC assigns a higher MCS, which means that the UE can transmit data with a higher transmission rate during a short period. Thus, the UE can turn off its radio interface for a long period for power saving. In contrast, when channel condition is bad, AMC assigns a lower MCS, which has a lower transmission rate. Thus, the UE needs to extend the on duration in order to meet the QoS requirements. Therefore, CQI information should be considered when determining DRX parameters.

Previous studies have investigated how to dynamically adjust the DRX parameters based on channel conditions [3,4]. A multi-threshold adaptive DRX (M-ADRX) mechanism [3] is proposed, where UEs are categorized into several groups according to their channel condition. UEs with better channel condition will be configured with lower power consumption parameters, and vice versa. In [4], DRX parameters are adjusted depending on the system load and the channel variation to improve power saving efficiency. For UEs with slow-varying channel, low-power DRX parameter is used. In order to obtain an accurate channel condition, i.e., up-to-date channel condition information, for packet scheduling and DRX parameter setting, an update period of channel condition before the actual on duration is proposed by [5]. However, this work does not consider the QoS features, such as packet delay, packet loss rate, and required data rates. A DRX-aware scheduling scheme [6] is proposed to reduce the packet loss rate due to DRX sleep, but it increases power consumption. In [7], they study the use of DRX for VoIP traffic under different scheduling strategies. Instead of proposing new adaptive DRX scheme, they only use several specific parameter settings to observe the power savings and QoS impact. In [8], the authors determine DRX parameters by considering the QoS requirements for Internet of Thing (IoT) applications, but it does not dynamically adjust the DRX parameters based on channel conditions. In addition, they propose DRX aware scheduling algorithm, but it increases power consumption too on some conditions.

In this study, a novel DRX scheme, called Dynamic Scheduling with Extensible Allocation and Dispersed Offsets (DXD) scheme, is proposed to meet QoS requirements, reduce power consumption, and increase system capacity in the DRX operation. The DXD scheme can be divided into two parts: (1) DRX parameters decision algorithm and (2) DRX-aware scheduling algorithm. DRX parameters decision algorithm will be executed when one of UEs needs to update its DRX parameters and it includes two parts. In the first part, period decision method determines *how much* on duration should be allocated as well as the DRX cycle to the UE so that the UE can turn off the radio circuit as long as possible to maximize the power saving without violating the QoS requirement. In the second part, the start offset decision method determines *when* the cycle starts. We need to determine the cycle start offset to disperse the on duration of UE so that each UE can fully utilize the bandwidth for resource efficiency. Furthermore, the proposed method includes a DRX-aware scheduler. It can determine whether or not to extend the on duration for QoS satisfaction. If system loading is high, extension may not improve QoS but only increases power consumption.

The rest of this paper is organized as follows. In Section 2, we firstly describe the operations of DRX in LTE systems, and review relevant literature to justify the issues. The problem statement and its notations are defined in Section 3. In Section 4, we describe the proposed DXD algorithm in detail. In Section 5, the simulation results are presented. Finally, we conclude this work in Section 6.

## 2. Background

In this section, we first introduce the operation of the DRX mechanism. Then, we describe some factors, such as channel condition, QoS, and scheduling, which should be considered in the DRX determination problem. Finally, we discuss some related work.

### 2.1. Discontinuous reception

DRX is a power saving mechanism in LTE system. When applying the DRX scheme, the UE periodically turns off the radio circuit to save power. During the period in which the radio interface is in the active state, the UE monitors Physical Downlink Control Channel (PDCCH) in order to check for incoming packets or paging signals, as shown in Fig. 1. If paging signals or packets arrive, the UE stays active until no more packets are received for a period of time, i.e., Inactivity Timer. When the Inactivity Timer expires, the UE go to DRX sleep state. The DRX behavior can be configured by the DRX parameters including On Duration, Short/Long DRX Cycle, DRX Short Cycle Timer, Inactivity Timer, and Cycle Start Offset. The DRX operation and the related parameters are illustrated in Fig. 1.

On Duration denotes the time period in which the UE wakes up and monitors PDCCH. Opportunity for DRX denotes the time period in which the UE sleeps for power saving. DRX Cycle denotes the cycle by which on duration repeats periodically. A UE can be configured by two types of DRX cycles, short DRX cycle and long DRX cycle. The
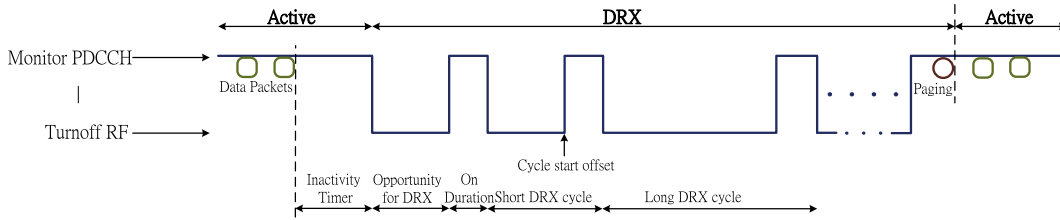
**Fig. 1.** Operation of Discontinuous Reception (DRX).

**Table 1**
4-bit CQI table.

| CQI index | Modulation | Coed rate × 1024 | Efficiency |
|---|---|---|---|
| 0 | Out of range | | |
| 1 | QPSK | 78 | 0.1523 |
| 2 | QPSK | 120 | 0.2344 |
| 3 | QPSK | 193 | 0.3770 |
| 4 | QPSK | 308 | 0.6016 |
| 5 | QPSK | 449 | 0.8770 |
| 6 | QPSK | 602 | 1.1758 |
| 7 | 16QAM | 378 | 1.4766 |
| 8 | 16QAM | 490 | 1.9141 |
| 9 | 16QAM | 616 | 2.4063 |
| 10 | 64QAM | 466 | 2.7305 |
| 11 | 64QAM | 567 | 3.3223 |
| 12 | 64QAM | 666 | 3.9023 |
| 13 | 64QAM | 772 | 4.5234 |
| 14 | 64QAM | 873 | 5.1152 |
| 15 | 64QAM | 948 | 5.5547 |

UE first adopts short DRX cycles and then changes to long DRX cycles for power saving. DRX Short Cycle Timer defines the repetition count of short cycles. Long DRX cycle follows after DRX Short Cycle Timer expires.[1] Inactivity Timer denotes the time period after the last scheduling that the UE should remain awake. If the UE does not receive any packet, this timer is decreased by one micro second. On the contrary, if the UE is scheduled, the Inactivity Timer is reset. Hence, this parameter provides means for the network to keep a UE awake beyond the On Duration when data is buffered. Cycle Start Offset denotes start time of On Duration in each cycle. DRX parameters of all UEs are determined by the eNB. The eNB uses Radio Resource Configuration (RRC) control signal to configure or update these DRX parameters. Then the UE updates its configuration after receiving the parameters from the eNB.

### 2.2. Channel condition

Channel condition changes rapidly in wireless networks. Since the channel condition affects the network capacity, we should take it into consideration when designing the scheduling algorithm or determining the DRX parameters. The UE uses CQI reporting [2] to report channel condition to the eNB, which can decide the adaptive MCS level. The CQI index is between 1 and 15 as shown in Table 1. Each CQI index corresponds to a MCS,

including modulation, code rate, and efficiency. The modulation order is determined by the number of the different symbols that can be transmitted using it. The higher modulation means, e.g., 64-QAM, a symbol can carry more information. In addition, in order to protect data, data will be coded before transmission. To recover from transmission errors, the parity bits are added. Coding rate is diverse in different coding, and it is the ratio of the number of information bits to the number of total bits. The higher the code rate is, the less the number of parity bits is. Efficiency is the number of information bits that can be carried within a symbol. It can be calculated using modulation order and code rate (efficiency = modulation order × code rate). So a higher MCS level has a higher transmission bit rate but is more prone to errors due to interference and noise. A lower MCS level has a lower bit rate but can tolerate higher levels of interference.

### 2.3. QoS Class Identifier (QCI)

As the wireless communication prevails, the traffic, such as VoIP, video streaming, becomes more abundant and complicated. In order to meet all the requirements of all kinds of traffic, LTE specifically defines the QCI metric, which grades the QoS in nine classes as shown in Table 2. Each class contains quadruple, i.e., resource type, priority, packet delay budget, and packet error loss rate. Resource type denotes whether the traffic needs guaranteed bit rate (GBR) and its value if any. For priority, the smaller the number is, the higher priority the traffic owns. Packet delay budget puts the constraint on the transmission delay of each packet, and packet error loss rate claims on the acceptable error rate of traffic. Different QCI configuration could be adopted to an evolved packet system (EPS) bearer depending on what quality the application needs. An EPS bearer is the tunnel for transporting traffic between the UE and the external network.

### 2.4. Scheduling

When the UE wants to upload or download packets, packets will be buffered in a RLC (Radio Link Control) buffer and wait for scheduling. Each RLC buffer corresponds to a bearer. LTE do the scheduling process according to a 10 ms radio frame structure which consists of 10 subframes. Each subframe is divided into 2 slots, and each slot is 0.5 ms. Each slot is further divided into multiple resource blocks (RBs) in frequency domain. A group of RBs are combined into one resource block group (RBG). The basic unit

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[1] In 3GPP specification [1], short DRX cycle is optional. Hence, we only consider long DRX cycle in this study.

**Table 2**
Standardized QCI characteristics.

| QCI | Resource type | Priority | Packet delay budget (ms) | Packet error loss rate | Example services |
|---|---|---|---|---|---|
| 1 | GBR | 2 | 100 | $10^{-2}$ | Conversational voice |
| 2 | | 4 | 150 | $10^{-3}$ | Conversational video (live streaming) |
| 3 | | 3 | 50 | $10^{-3}$ | Real time gaming |
| 4 | | 5 | 300 | $10^{-6}$ | Non-conversational video (buffered streaming) |
| 5 | Non-GBR | 1 | 100 | $10^{-6}$ | IMS Signaling |
| 6 | | 6 | 150 | $10^{-6}$ | Video (buffered streaming), TCP-based (e.g., www, e-mail, chat, ftp, p2p file sharing, progressive video, etc.) |
| 7 | | 7 | 50 | $10^{-3}$ | Voice, video (live streaming), interactive gaming |
| 8 | | 8 | 300 | $10^{-6}$ | Video (buffered streaming) |
| 9 | | 9 | | | TCP-based (e.g., www, e-mail, chat, ftp, p2p file sharing, progressive video, etc.) |

of scheduling is RB or RBG. The scheduling priority can be calculated based on different factors (e.g. CQI, QCI). In addition, it determines how many RBs are allocated. The resource allocation information will be carried in PDCCH to indicate the PDSCH attributes: (1) where are the resource blocks and (2) which MCS scheme should be used in the resource block. Both scheduler and DRX are implemented in the eNB, but they operate independently. If the scheduler considers the DRX parameters, system performance can be further improved.

### 2.5. Related work

Previous studies have investigated how to dynamically adjust the DRX parameters, e.g., inactivity timer and on duration timer, based on channel conditions [3,4]. A multi-threshold adaptive DRX (M-ADRX) mechanism [3] is proposed, where UEs are divided into several groups according to their CQI values. UEs with a higher CQI will be configured with shorter DRX inactivity timer, and vice versa. In [4], the on duration timer and inactivity timer would be adjusted depending on the system load and the channel variation to improve power saving efficiency. For UEs with a slow-varying channel, shorter DRX inactivity timer is used. Furthermore, in order to obtain the accurate channel condition, i.e., up-to-date CQI information for packet scheduling and DRX parameter settings, the CQI preamble period is proposed before the actual on-duration [5].

In [9,10], the work considers the QoS requirements with multiple traffics when determining the DRX parameters. However, the channel condition is not taken into consideration. In [9], DRX parameters are configured based on delay requirement and power saving constraint. The proposed algorithm optimizes one of these two performance metrics while satisfying a pre-defined level of performance guarantee for the other. In addition, the proposed algorithm only focuses on the DRX inactivity timer and DRX cycles with fixed on duration. A traffic-based DRX cycles adjustment (TDCA) [10] scheme is proposed to improve power saving. It employs the partially observable Markov decision process (POMDP) to conjecture the present traffic status for DRX parameters selection while the packet delay constraint can still be satisfied.

When designing the scheduling algorithm, DRX operations should be also taken into consideration [6,7].

It means that DRX parameters are introduced into the scheduling determinants, so as to reduce packet loss or packet delay caused by the sleeping process during DRX. A DRX-aware scheduling scheme [6] is proposed to reduce the packet loss rate due to DRX sleep. The scheduler takes inactivity timer into consideration. If inactivity timer is smaller, the UE would be given a higher priority in order to meet delay requirements. In [7], the impact on the QoS requirements of VoIP is analyzed with dynamic and semi-persistent packet scheduling schemes. In [8], the Three-Stage (TS) scheme determines DRX parameters by considering the QoS requirements for Internet of Thing (IoT) applications. In addition, they also propose DRX-aware scheduling algorithm. However, there are some differences between TS and our work. First, they only consider the application with the strictest QCI to determine on duration even though the UE has to serve multiple services. Second, they use static DRX configurations which based on the worst CQI report. We summarize the related work in terms of issues in Table 3.

### 3. Problem statement

In this paper, we consider the LTE network of an evolved Node B, $eNB$, that serves $N$ user equipments, $UEs$. Each $UE_i$, $i = 1, \ldots, N$, has $M_i$ application services, which are denoted as $S_{i,k}$, $k = 1, \ldots, M_i$. Each $S_{i,k}$ is assigned to a QoS class identifier (QCI), $QCI_{i,k}$, including Packet Delay Budget $L_{i,k}$ (ms) and Guaranteed Bit Rate $R_{i,k}$ (bps). Each $UE_i$ is configured with a set of DRX parameters $D_i$, including On Duration Timer $TOD_i$ (ms), DRX Cycle $CLD_i$ (ms), Inactivity Timer $TIA_i$ (ms), and Cycle Start Offset $CSO_i$ (ms). Furthermore, the channel quality indicator and power consumption in mW for each $UE_i$ are denoted as $CQI_i$ and $P_i$, respectively. The notations are summarized in Table 4.

The DRX parameters determination problem is described as follows. Given an $eNB$, a set of user equipments $\mathbf{UE} = \{UE_i, 1 \leqslant i \leqslant N\}$, which have a set of application services, $\mathbf{S} = \{S_{i,k}, 1 \leqslant i \leqslant N, 1 \leqslant k \leqslant M_i\}$ with it corresponding QoS class identifier (QCI), $\mathbf{QCI} = \{QCI_{i,k}, 1 \leqslant i \leqslant N, 1 \leqslant k \leqslant M_i\}$, and channel quality indicator, $\mathbf{CQI} = \{CQI_i, 1 \leqslant i \leqslant N\}$. The objective is to design an approach to allocate the resource blocks and determine the DRX parameters $D_i$ for each $UE_i$, including $TOD_i, CLD_i$,

**Table 3**
Comparisons of related work.

| Work | Power saving | Channel condition | QoS | Scheduling |
|------|--------------|-------------------|-----|------------|
| Gao et al. [3] | Inactivity timer | Single/multiple CQI thresholds | X | X |
| Lin et al. [4] | On duration, inactivity timer | Number and velocity of connected UEs are considered | X | X |
| Aho et al. [5] | Fixed DRX | CQI preamble period are introduced | X | X |
| Jha et al. [9] | Inactivity timer and DRX cycle | X | Delay requirement | X |
| Yu et al. [10] | DRX cycle | X | Delay requirement | X |
| Bo et al. [6] | Fixed DRX | X | X | DRX parameters are introduced into the scheduling |
| Polignano et al. [7] | Fixed DRX | X | VoIP | Dynamic and semi persistent scheduling |
| TS [8] | Inactivity timer, on duration, DRX cycle, start offset | Static (based on worst CQI) | QCI | DRX parameters are introduced into the scheduling |
| DXD | On duration, DRX cycle, start offset adjustment | Dynamic | QCI | DRX, CQI, and QCI are introduced into the scheduling |

**Table 4**
Summary of parameters/notations.

| Notation | Definition |
|----------|------------|
| $eNB$ | A evolved Node B in LTE system |
| **UE** | A set of user equipments $\mathbf{UE} = \{UE_i,\ 1 \leqslant i \leqslant N\}$ |
| $M_i$ | Number of application services in $UE_i$ |
| **S** | A set of application services $\mathbf{S} = \{S_{i,k},\ 1 \leqslant i \leqslant N,\ 1 \leqslant k \leqslant M_i\}$ |
| **QCI** | A set of QoS class identifier $\mathbf{QCI} = \{QCI_{i,k},\ 1 \leqslant i \leqslant N,\ 1 \leqslant k \leqslant M_i\}$, where $QCI_{i,k} = (L_{i,k}, R_{i,k})$ |
| **L** | A set of Packet Delay Budget $\mathbf{L} = \{L_{i,k},\ 1 \leqslant i \leqslant N,\ 1 \leqslant k \leqslant M_i\}$ |
| **R** | A set of Guaranteed Bit Rate $\mathbf{R} = \{R_{i,k},\ 1 \leqslant i \leqslant N,\ 1 \leqslant k \leqslant M_i\}$ |
| **CQI** | A set of channel quality indicator $\mathbf{CQI} = \{CQI_i,\ 1 \leqslant i \leqslant N\}$ |
| **D** | A set of DRX parameters $\mathbf{D} = \{D_i,\ 1 \leqslant i \leqslant N\}$, where $D_i = (TOD_i, TIA_i, CLD_i, CSO_i)$ |
| $TOD_i$ | On Duration timer for $UE_i$ |
| $TIA_i$ | Inactivity timer for $UE_i$ |
| $CLD_i$ | DRX Cycle for $UE_i$ |
| $CSO_i$ | Cycle Start Offset for $UE_i$ |
| **P** | A set of power consumption $\mathbf{P} = \{P_i,\ 1 \leqslant i \leqslant N\}$ |

and $CSO_i$ depending on the channel condition $CQI_i$, such that all QoS requirement $QCI_i$ can be satisfied as like as in the DRX-disabled settings. In the meantime, the power consumption $P_i$ for each $UE_i$ should be less as much as possible.

## 4. Dynamic scheduling with extensible allocation and dispersed offsets scheme

To save the power of mobile devices, 3GPP LTE has defined the DRX scheme to allow devices to turn off their radio interface and go for a sleep state when there is no data transmission. However, if packets arrive at sleep state, these packet would pose unexpected delay, which may affect their QoS requirement. Thus, we need to determine a set of DRX parameters to reduce the power consumption and guarantee QoS simultaneously.

We observed that the DRX parameter settings, QoS requirements, and channel conditions of a UE are tightly coupled with each other. For example, the UE with good channel quality can use the higher MCS which means that the UE can transmit data with a higher transmission rate to finish the data transmission within a short on duration. Thus, the UE can turn off its radio interface for a longer period for power saving. In contrast, when channel condition is bad, a lower MCS, which has a lower transmission rate, is assigned to the UE. Thus, the UE needs a longer on duration with higher power consumption in order to meet the QoS requirements. In addition, if UEs are active/scheduled at the same time, the bandwidth would be shared among UEs, thereby prolonging the transmission time due to the limited resource. Thus, the eNB should disperse the on durations for all UEs as possible. Furthermore, the on duration may still overlap with each other due to limited resources, which affecting the delay requirement. Extending the on duration achieves better QoS but incurs more power consumption. However, if the extended on duration could not be used to serve the UE when the channel condition is bad or system load is high, it still consumes more power. Thus, if we want to extend the on duration to increase the QoS satisfaction ratio, we must consider the system load and the channel quality. If the network does not have enough sufficient radio resources to allocate to the UE in UEs extended on duration, the proposed scheme does not extend the on duration.

### 4.1. Overview about DXD scheme

In this study, a novel scheme, called Dynamic Scheduling with Extensible Allocation and Dispersed Offsets (DXD), is proposed with the objectives of satisfying the QoS requirements, reducing the power consumption, and increasing the system capacity with DRX operations. As illustrated in Fig. 2, the DXD scheme can be divided into two parts: (1) DRX parameters decision algorithm and (2) DRX-aware scheduling algorithm.

First, we determine the DRX period by considering channel condition, i.e., CQI, and QoS constraints, i.e., QCI,
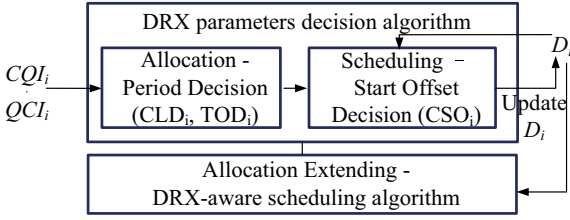
**Fig. 2.** Dynamic Scheduling with Extensible Allocation and Dispersed Offsets (DXD) scheme.

under the assumption that the UE can fully utilize the network resource. Thus, the buffered packets can be transmitted within the on duration without violating their QoS requirements. Since the network resources are shared by multiple UEs, we need to disperse the on duration of UEs to let the UE fully utilize the bandwidth during its on duration and finish its transmission as soon as possible to go to sleep for more time. In addition, we design a DRX-aware scheduling, which cooperates with the DRX parameters decision algorithm to dynamically extend the on duration. The detailed operations of DXD are described as follows.

### 4.2. DRX parameters decision algorithm

DRX parameters decision algorithm will be executed when one of UEs $UE_i$ needs to update its DRX parameters $D_i$. DRX parameters decision algorithm includes two parts. In the first part, period decision method determines *how much* the on duration $TOD_i$ should be allocated as well as the DRX cycle $CLD_i$ to the UE so that the UE can turn off the radio circuit as long as possible to reduce the power saving without violating the QoS requirement. In the second part, the start offset decision method determines *when* the DRX cycle starts. We need to determine the cycle start offset $CSO_i$ to disperse the on durations of UEs. The reason is that when the on durations of UEs are not overlapped, UEs in theirs on durations could fully utilized the network resource. Once finishing the data reception, the UE can turn off the radio interface immediately to save power. Otherwise, the UE would share the network resource with other UEs who are also in the on duration simultaneously. Consequently, it takes more time to finish the data reception and consume more power. Thus, the on durations of UEs should be separated as possible.

#### 4.2.1. Allocation – period decision

When the $UE_i$ attaches to the *eNB* or detects the change of channel condition, period decision method need to update its DRX cycle $CLD_i$ and on duration $TOD_i$. To reduce the power saving and meet the strictest delay budget, DRX cycle is set as the minimum delay budget among all application services for $UE_i$ as

$$CLD_i = \min_{1 \leqslant k \leqslant M_i} \{L_{i,k}\}. \tag{1}$$

In order to save power, $UE_i$ should turn off the circuit immediately after its all packets are transmitted. Therefore, on duration $TOD_i$ is set as the expected transmission time according to its channel quality indicator $CQI_i$ as

$$TOD_i = \left\lceil CLD_i \times \min \left\{ \frac{\sum_{1 \leqslant k \leqslant M_i} R_{i,k}}{B(CQI_i) \cdot N_{RB}/0.0005}, 1 \right\} \right\rceil. \tag{2}$$

$TOD_i$ is obtained from multiplying the DRX cycle $CLD_i$ by the ratio of the sum of guaranteed bit rate $R_{i,k}$ for all application services in $UE_i$ to the available transmission rate. The available transmission rate is obtained based on current channel condition, thus we use $B(CQI_x)$ as a function to obtain the number of bits could be carried in one resource block (RB) by looking up the CQI table. Let $N_{RB}$ denote the number of RBs per slot, which length is 0.5 ms. $N_{RB}$ depends on the channel bandwidth. For example, the channel bandwidth is 10 MHz, thus we have $N_{RB} = 50$ RBs in each slot. If the required data rate is larger than the available transmission rate, we set the on duration $TOD_i$ as the DRX cycle $CLD_i$.

#### 4.2.2. Scheduling – start offset decision

In order to improve radio resource efficiency in the on duration, we disperse the on duration of each UE by assigning different cycle start offsets. Thus, the UE can fully utilize the bandwidth during its on duration if the on duration does not overlap with other UEs. Otherwise, the UE would share the network resource with other UEs who are also in the on duration simultaneously. Consequently, the UE takes more time to finish the data reception and consume more power.

For the purpose, we maintain $NA = \{NA_j, 1 \leqslant j \leqslant CLCM\}$, in which $NA_j$ is the number of UEs which stays in the on duration at subframe $j$. Let $CLCM$ denote the least common multiple (LCM) of all DRX cycles $CLD_i$, i.e., $CLCM = lcm(CLD_1, CLD_2, \ldots, CLD_N)$. Since the DRX cycle $CLD_i$ repeats multiple times within the $CLCM$ time period, so we introduce $NRP_i = \{NRP_{i,k}, 1 \leqslant k \leqslant CLD_i\}$ in unit of DRX cycle $CLD_i$ to simplify the algorithm. $NRP_{i,k}$ indicates the number of UEs which active at the same offset $k$ in every cycle $CLD_i$ within the whole $CLCM$. So, we have $NRP_i$ as

$$NRP_{i,k} = \sum_{j \bmod CLD_i = k, \forall j} NA_j, \quad 1 \leqslant j \leqslant CLCM. \tag{3}$$

Since $NRP_{i,k}$ indicate the number of other UEs which active at the same offset $k$ in every cycle $CLD_i$ within the whole $CLCM$, it also represents that if the on duration of $UE_i$ is also at subframe $k$, there are *total* $NRP_{i,k}$ UEs turning on theirs radio at subframe $k, k + CLD_i, k + 2 \times CLD_i, \ldots$ which would compete the network resource with $UE_i$. Thus, we must find out the minimal non-overlapped period and let the on duration of $UE_i$ be scheduled within such period. So, the cycle start offset $CSO_i$ can be found by

$$CSO_i = \arg \min_{1 \leqslant k \leqslant CLD_i} \sum_{j=k}^{k+TOD_i-1} NRP_{i,j \bmod CLD_i}. \tag{4}$$

Eq. (4) means that during the on duration of $UE_i$, the number of UEs which also stay in the on duration is minimal within the whole $CLCM$ time period. It means that if the on duration of $UE_i$ does not overlap with the on duration of other UEs, $UE_i$ can fully utilize the bandwidth during the on duration, finish its transmission as soon as possible, and go to sleep for more time.

However, we observe that the value of $NRP_i$ may not be sufficient to grasp the impact come from other UEs. Take Fig. 3 as an simplified example. Here, there are three UEs with different DRX cycles and UEs may active at the same time (case 1) or active at different time (case 2). According to the definition of $NRP_i$, the value of $NRP_i$ in both cases are the same (i.e., $NRP_{i,1} = 3$ and $NRP_{i,j} = 0$, if $j \neq 1$). However, the impact from other UEs in case 1 is more than that in case 2 because all other UEs are active at the same time in case 1. If $UE_i$ is also active at the same time, the network resource would be shared with other three UEs. On the other hand, UEs are active at the different time period in case 2; thus $UE_i$ only competes with one UE.

So we consider a weighted version of $NA$ as $NA' = \{NA'_j = (NA_j)^2, \ 1 \leqslant j \leqslant CLCM\}$ in order to differentiate the degree of dispersion of UEs' on durations. A subframe with more active users has more impact on the start offset decision. Then, we have the new $NRP'_i$ as

$$NRP'_{i,k} = \sum_{j \bmod CLD_i = k, \forall j} NA'_j, \quad 1 \leqslant j \leqslant CLCM. \tag{5}$$

Then, the optimal cycle start offset $CSO_i$ can be found by

$$CSO_i = \arg \min_{1 \leqslant k \leqslant CLD_i} \sum_{j=k}^{k+TOD_i-1} NRP'_{i,j \bmod CLD_i}. \tag{6}$$

### 4.3. Allocation extending – DRX-aware scheduling algorithm

After we obtain (1) the DRX cycle $CLD_i$ and the on duration $TOD_i$ from the Period Decision algorithm in Section 4.2.1 and (2) the cycle start offset $CSO_i$ from the Start Offset Decision algorithm in Section 4.2.2, the on duration of UE may still overlap with each other. Therefore, the delay requirement may not be satisfied due to the limited network resource. The DRX aware scheduling proposed in [8] is a possible solution which can dynamically extend the on duration in order to increase the satisfaction ratio on delay budget. As we known, DRX inactivity timer will be reset if the UE is scheduled. With this feature, the UE that will go for sleep at the next subframe is scheduled one RB to extend the inactivity timer if RLC buffer is not empty. However, frequent extending the on duration will significantly increase power consumption especially in the case of poor channel condition or high system load. The reason is that the system may not have sufficient radio resources to allocate to the UE in UE's extended on duration. Therefore, our proposal DRX-aware Scheduling algorithm does not extend the on duration of the UE if the system is unable to serve the UE in the extended on duration. It means that if we want to extend the on duration to increase the satisfaction ratio on the delay budget, we must consider the system load and the channel quality. If the network does not have enough sufficient radio resources to allocate to the UE in UE's extended on duration, the proposed algorithm does not extend the on duration. Our scheme can integrated with other scheduling algorithms. We just propose a new scheduling priority function $p_i(t)$ by considering the DRX parameters and system loads as

$$p_i(t) = \begin{cases} p_i^*(t) + \alpha, & \text{if } TOD_i \leqslant 1, TIA_i \leqslant 1, \text{ and } \rho_i < \delta_i \\ p_i^*(t), & \text{otherwise} \end{cases} \tag{7}$$

$$\rho_i = \sum_{p_j^*(t) > p_i^*(t), \forall j} \frac{R_j(t)}{r_j(t)}, \quad \delta_i = \frac{CLD_i - TOD_i}{CLD_i}, \tag{8}$$

where $p_i^*(t)$ denotes priority determined by the original scheduling which can be any scheduling scheme, such as [11], at subframe $t$ for $UE_i$. Let $\rho_i$ denote the total loading of active UEs whose priorities are higher than $UE_i$, and it is calculated by $R_j(t)$ and $r_j(t)$ which are average data rate and achievable data rate depending on $CQI_j$ at subframe $t$, respectively. Let $\delta_i$ denote the ratio of idle period, i.e., $CLD_i - TOD_i$ to DRX cycle $CLD_i$. So $\rho_i \geqslant \delta_i$ means that system loading is too high to serve $UE_i$ during the rest of time in its DRX cycle. Therefore, when $UE_i$ will turn off its radio interface at the next subframe (i.e., $TOD_i \leqslant 1$, and $TIA_i \leqslant 1$) and the system load is less than the free resource from off duration (i.e., $\rho_x < \delta_x$), the priority of UE will be increased by $\alpha$. Here, we let $\alpha > \max_{\forall j}\{p_j^*(t)\}$ to ensure that the $UE_i$ could has the highest priority to be scheduled.

### 4.4. System overhead analysis

Here, we discuss signaling overhead of DRX parameters configuration. Since our approach only configure one UE at a time and does not affect settings of other UEs, when there are $N$ UEs attaching the network one by one, the signal overheads will be $O(N)$. Three-Stage (TS) algorithm proposed in [8], which is similar to our work, need to recalculate parameters of all UEs when one particular the UE needs to configure DRX parameters, so the signal overhead is $1 + 2 + 3 + \cdots + N = ((1 + N)N)/2 = O(N^2)$.

## 5. Performance evaluations

In this section, we present our simulation results to verify the effectiveness of the proposed scheme. We developed the proposed DXD scheme in NS-3 simulator [12]. The system parameters of the simulator are listed below. The channel bandwidth bandwidth is 5 MHz which has 12 RB at each subframes. Fifteen channel qualities are adopted in the simulation, as shown in Table 1. Two types of application services are considered in the simulations. One is G.711 VoIP traffic, which has data rate as 64 Kbps with 160 bytes payload, the other is MPEG video streaming with peak and mean data rate as 2.1 Mbps and 0.1 Mbps respectively. The requested QCI values set for VoIP and video streaming are 1 and 4 respectively. In addition, the
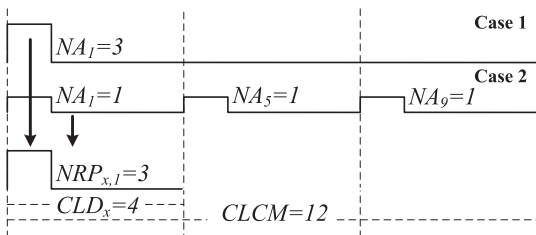


**Fig. 3.** The impact of other UEs for $UE_i$ with $CLD_i = 4$ and $CLCM = 12$.

scheduler used in our simulation is Proportional Fair (PF) scheduler [13]. If DRX scheme is enabled and use a set of fixed settings, which we refer as *Fixed-DRX* scheme, the default DRX parameters listed in Table 5 are used. Otherwise, the DRX parameters are obtained from the proposed DXD approach. The power consumption model [14,15] as shown in Fig. 4 is a general reference model for use in 3GPP which is generic enough to capture the basics of the hardware and is used to obtain the power consumption of UE in this work. This power model includes four states which are deep sleep, light sleep, active with no data rx, and active with data rx. The UE has different power consumption in each state and during the transitions. Deep sleep and light sleep correspond to long DRX cycle and short DRX cycle, respectively.

We consider three scenarios: (1) adaptability to channel conditions, (2) multiple services handling, and (3) system capacity problem with different types of traffic and settings to verify the effectiveness of our proposed DXD scheme. We compare our scheme against the Three-Stage (TS) algorithm [8], which is the most relative scheme to the topic of this paper. In addition, we also compared with the DRX-disabled scheme, which called as *No-DRX* scheme. The performance metrics are delay satisfaction ratio, which indicates the percentage of packets that satisfy the delay budget, and power consumption.

## 5.1. Adaptability to channel conditions

In order to observe the adaptability to channel conditions, we investigate the relationship between CQI and delay satisfaction ratio in Fig. 5. A scheme has higher adaptability to channel condition means that it achieves high delay satisfactory ratio regardless of the channel conditions.

In Fig. 5, No-DRX label represents the case where DRX is not enabled. No-DRX scenario has the highest adaptability to channel condition but also has the highest power consumption as shown in Fig. 6. We also observe the results of Fixed-DRX scheme with different lengths of DRX cycles. Fixed-DRX scheme with longer DRX cycles has lower power consumption. Nevertheless, delay cannot be satisfied if the DRX cycle is longer than the delay budget of the services even in the best channel condition. In addition, the results for the Fixed-DRX scheme with 100 ms DRX cycle duration show that when CQI decreases, i.e., worst channel condition and lower transmission rate, delay satisfaction ratio also decreases significantly. The reason is that when CQI decreases, the UE needs more radio resources to
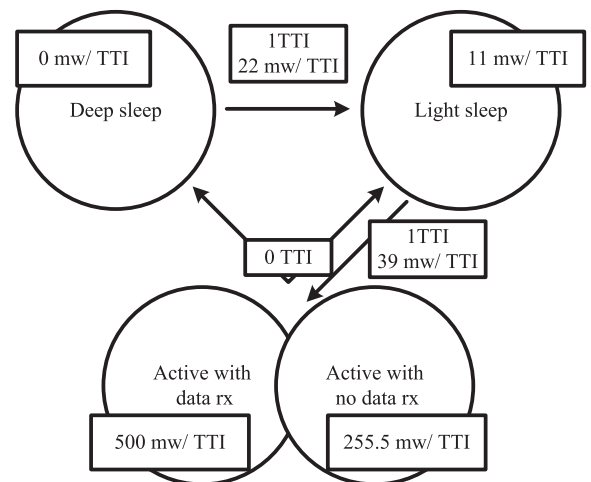


**Fig. 4.** The power consumption model for UEs [14,15].

maintain the required data rate. If on durations of UEs are not interlaced, the performance will decrease seriously. Thus, it is obvious that delay satisfaction ratio can be significantly improved when start offset decision is applied. Furthermore, *Fixed-DRX (100 ms), start-offset* scheme can reduce the resource competition to avoid the extension of on duration and consequently decrease the power consumption. The proposed DXD scheme has the best satisfaction ratio even in a poor channel condition because it dynamically determines the on duration to finish the data transmission as soon as possible.

Compared with TS algorithm [8], the proposed DXD has better performance of delay satisfaction ratio and the power consumption of DXD scheme is lower than TS in CQI 4–15. The reduction of power consumption compared to Fixed-DRX and TS schemes is up to 96.9% and 45.7% respectively because DXD dynamically configures the on duration according to channel condition (i.e., CQI). However, in TS algorithm, the on duration is determined by one packet transmission time with the worst possible channel condition. That is, the on duration is static and not responsive to the channel condition. In addition, the on duration may be too small to satisfy the QoS in the worst channel condition.

## 5.2. Multiple services handling

In the second scenario, we consider two service applications, VoIP and video streaming, in each UE to show how

## Table 5
Simulation configurations.

|  | Adaptability to channel condition | Multiple services handling | System capacity |
|---|---|---|---|
| Bandwidth | 5 MHz |  |  |
| # Of UE | 8 |  | 5–30 |
| Default DRX parameters | (*CLD*, *TOD*) = (20 ms, 2 ms), (100 ms, 10 ms), (120 ms, 12 ms), *TIA* = 3 ms, *CSO* = 0 ms |  |  |
| Scheduler | Proportional fair scheduler |  |  |
| VoIP | G.711, 64 Kbps, 160 bytes payload, QCI: 1 |  |  |
| Video streaming | MPEG 4, peak/mean bit rate = 2.1/0.1 Mbps, QCI: 4 |  |  |
| Services | VoIP | VoIP and video streaming |  |
| Channel condition | CQI = 1–15 |  | Random |
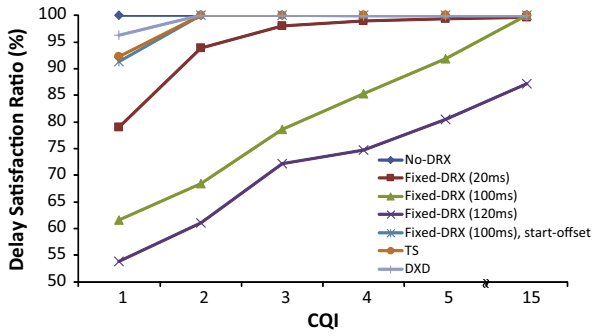
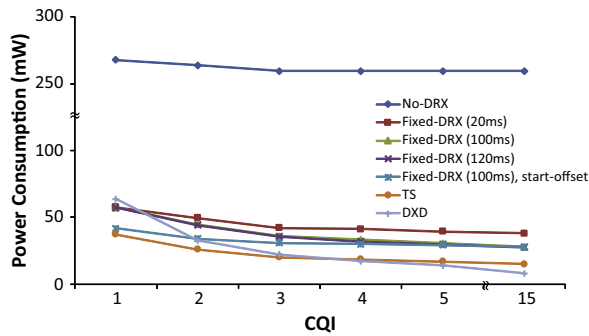**Fig. 5.** Impact of channel condition: delay satisfaction ratio.



**Fig. 6.** Impact of channel condition: power consumption.

the proposed DXD algorithm tackle multiple services in a UE. Fig. 7 shows the delay satisfaction ratio of multiple services under different DRX algorithms. We can find that the delay satisfaction ratio of the proposed DXD scheme is as good as that of No-DRX scheme. In addition to high adaptability to channel condition, DXD determines the on duration based on the total required transmission rate of all GBR services. However, TS algorithm only considers the required data rate of services which have the strictest delay budget, thus the delay satisfaction ratio is less than ours.

The UE usually extends its on duration due to the bursty characteristic of video traffic. The scheduler will allocate one RB to the UE so as to extend the on duration (i.e., the inactivity timer will be reset). No matter how many RBs are allocated to the UE, the UE stays at the "active with data rx" state with power consumption of 500 mW/TTI [14]. As the channel condition worsens or the system load increases, the radio resource may not be sufficient to be allocated to the UE during its extended time period. Thus, TS algorithm need to allocate more time period to transmit data, and in consequence consumes more power compared to the No-DRX scheme, as shown in Fig. 8. Furthermore, if the radio resource does not be allocated to the UE during its extended on duration, the UE stays at the "active with no data rx" state, still consumes power with 255.5mw/TTI. As for the DXD scheme, the proposed DRX-aware scheduling algorithm will extend the on duration depending on the system load. Thus, the power consumption of DXD would be better than the TS algorithm. The overall
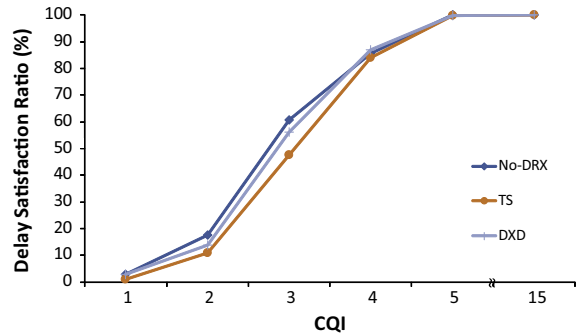
reduction ratio on power consumption of DXD compared to TS is 11.4–54.3% in CQI 1–15.

In addition to show the overall performance, the individuals of the delay satisfaction ratio for VoIP and video streaming services are illustrated in Fig. 9. Compared with the VoIP service, the video streaming service has lower delay satisfaction ratio. The reason is that the guaranteed bit rate for video service is set as the *mean* data rate, not the *peak* data rate, in our proposed algorithm. Due to the bursty characteristic of video traffic, it is more challenging to guarantee the transmission delay of video traffic. Furthermore, TS algorithm does not take the guaranteed bit rate of video service into consideration when determining the on period because
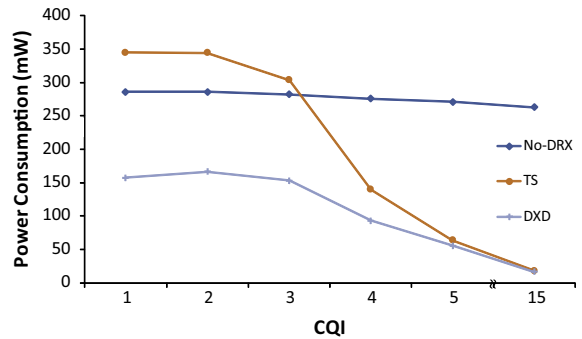


**Fig. 7.** Multiple services handling: delay satisfaction ratio.



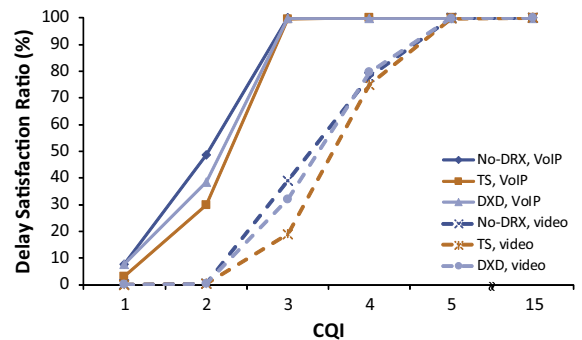**Fig. 8.** Multiple services handling: power consumption.



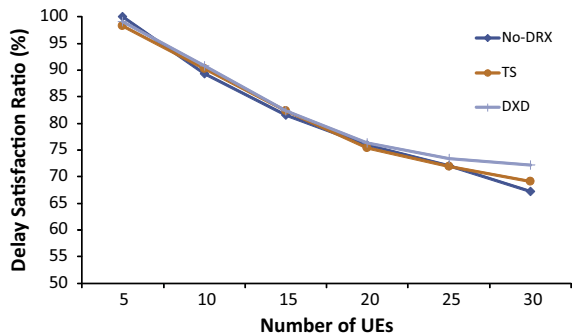**Fig. 9.** Multiple services handling: delay satisfaction ratios of different services.

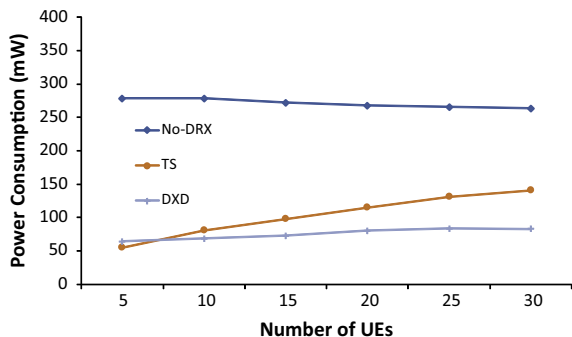**Fig. 10.** Impact of number of UEs: delay satisfaction ratio.



**Fig. 11.** Impact of number of UEs: power consumption.

the delay budget of video service is 300 ms which is not the strictest one. Therefore, the results show that the delay satisfaction ratio of TS is worse than DXD.

### 5.3. System capacity problem

The effect of system loading upon QoS satisfaction and power consumption are shown in Figs. 10 and 11 receptivity. The performance of our proposed DXD approach is as good as that of No-DRX scheme in a lightly-load environment. In the high system load environment, the performance of DXD algorithm is better than that of No-DRX scheme. The number of satisfied UEs in the DXD scheme is more than that in No-DRX scheme with PF scheduler. The reason is that when the system loading gradually increases, the delay satisfaction ratio could be improved by applying the proposed DRX-aware scheduling.

In Fig. 11, DXD can save more power than TS when system loading is high. Power consumption can reduce up to 41.1%. The main reason is that TS algorithm will continue to extend the on duration, but our DXD approach will determine whether it is necessary to extend or not. DXD only turn off UEs which are impossibly served according to system loading. So power can be saved without affecting the system performance.

### 6. Conclusion

In this paper, we propose the Dynamic Scheduling with Extensible Allocation and Dispersed Offsets (DXD) scheme to reduce power consumption and meet QoS in varied

channel conditions. DXD is composed of period decision, start offset decision, and DRX-aware scheduling algorithm. First, in order to enhance the channel condition adaptability and satisfy multiple services in a UE, period decision method configures an optimal DRX period according to CQI and QCI of each service. Second, start offset decision method effectively disperses on duration of each UE, so that the radio resource can be utilized more efficiently. Third, the proposed DRX-aware scheduling will dynamically extend the on duration of UEs to increase delay satisfaction ratio for the bursty traffic.

Simulation results show the out-performance of our approach. In the case of dynamic channel conditions, the delay satisfaction ratio is only slightly lower than that of No-DRX scheme in poor channel condition, but the power consumption can be reduced by 96.7%. In the meantime, the power consumption can be reduced by 70.1% and 45.7% compared to the *Fixed-DRX (100 ms), start-offset* scheme and TS algorithm in good channel condition. When the number of UEs increases gradually, the power consumption is reduced up to 41.1%, compared to the TS algorithm. Our approach effectively reduces power consumption from TS algorithm in varied channel conditions and high loading system. Furthermore, the delay satisfaction ratio is better than the TS algorithm.

### Acknowledgements

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