國立交通大學

資訊科學與工程研究所

碩士論文

在 LTE 資料排程中考量通道環境及 QoS 限制以最小化耗電

Minimizing Power Consumption in LTE Data Scheduling with the Constraints of Channel Condition and QoS

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中華民國一百零二年六月

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碩 士 論 文

A Thesis

Submitted to Institute of Computer Science and Engineering

College of Computer Science

National Chiao Tung University

in partial Fulfillment of the Requirements

for the Degree of

Master

in

Computer Science

June 2013

Hsinchu, Taiwan

中華民國一百零二年六月

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摘要

LTE 已成為新一代的通訊技術，其擁有高傳輸率及廣涵蓋率，但也因此產生高耗電的問題。為此 LTE 制定了 Discontinuous Reception (DRX)省電機制，原理為周期性的關閉射頻電路以達到省電效果，但在關閉期間無法接收封包，而影響服務品質。為了最小化耗電並滿足服務品質，需要找出一組在最佳的 DRX 參數設定，但在變動的通道環境下，此參數設定也會有所變動。因此本論文提出一稱為 Dynamic Scheduling with Extensible Allocation and Dispersed Offsets (DXD)的方法，其分為兩個演算法：DRX 參數決定演算法及 DRX-aware 排程演算法，DRX 參數決定演算法會考量通道環境及服務品質限制以決定出最佳的 DRX 周期，並分散各使用者的開啟時間，使其在射頻電路開啟時，能完整利用 LTE 頻寬來快速傳輸資料，即有更多的時間關閉射頻電路以達到省電效果。而 DRX-aware 排程演算法判斷是否延長電路開啟時間使得服務品質不會受到 DRX 影響。實驗結果可發現 DXD 與未採用 DRX 省電機制時相比，最多可節省 96.9%的耗電，在服務品質滿足率方面，亦可接近未採用 DRX 省電機制的效能。

關鍵字: LTE，DRX，省電，服務品質，通道環境，排程

Minimizing Power Consumption in LTE Data Scheduling with the Constraints of Channel Condition and QoS

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Abstract

LTE has become the next generation of communication technology. It has high data rate and broad network coverage, but it conversely introduces high power consumption. To resolve this problem, 3GPP has developed the Discontinuous Reception (DRX) power saving mechanism, which periodically turns off the radio interface to reduce power consumption. However, packets cannot be received during the turn-off time, as a result that the Quality of Services (QoS) may be violated. Therefore, optimal DRX parameters should be configured. In addition, channel condition may be unstable during the transmission, so the optimal DRX parameters should also be dynamically adjusted. In this thesis, we propose the Dynamic Scheduling with Extensible Allocation and Dispersed Offsets (DXD) scheme, which is composed of two algorithms, DRX parameter decision algorithm and DRX-aware scheduling algorithm. DRX parameter decision algorithm determines the DRX period by considering channel condition and QoS constraints, and then interlaces the turn-on time of each user. The scheduling algorithm determines whether to extend the turn-on time or not, so that QoS will not be affected by DRX. Simulation results demonstrate that our DXD approach can reduce power consumption up to 96.9% compared to No DRX scheme and guarantee QoS as good as No DRX scheme.

Keywords: LTE, DRX, power saving, QoS, channel condition, scheduling

致謝

能夠有今日的研究成果，首先要感謝林盈達教授、賴源正教授及童莉萍教授的盡心指導。在指導的過程老師們總是能不厭其煩的給予指教與包容，昱賢在這兩年的研究生涯真的是受益良多。尤其在與童莉萍教授亦師亦友相處下，除了使研究所生活更加有趣、充實，在待人處事上亦是有所精進。而對於高速網路實驗室的同儕們，總是能在我遇到困難時伸出援手，感激之情當然難以言表，對於長期相處下來的感情在此時刻總有些依依不捨，但相信大家在未來必能有所成就。此外對於 BML、NBL、EBL 及交大的教職員們感謝你們提供的資源與協助，昱賢在此感激不盡。最後由衷的感謝長期給予我支持與鼓勵的家人、朋友，使我能無後顧之憂並一路順遂的完成碩士學位。

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Chapter 1 Introduction

Nowadays, a variety of powerful smart devices are designed to handle a wide range of traffic, such as VoIP, video streaming, mobile gaming, and so on. 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.

Discontinuous reception (DRX) vs. QoS

While the LTE transmission rate is many times faster than the 3G rate, 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 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. 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 minimize the power consumption and guarantee QoS simultaneously is still an open issue.

When Channel Condition is Considered

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 UE (user equipment). The UE uses channel quality indicator (CQI) [1] to report channel condition for base station, also called 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 assign 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 assign a lower MCS, which has a lower transmission rate. Thus, the UE needs to extend the turn-on duration in order to meet the QoS requirements. Therefore, CQI information should be considered when determining optimal DRX parameters.

Related Work

Previous studies have investigated how to dynamically adjust the DRX parameters based on channel condition [5, 6]. A multi-threshold adaptive DRX (M-ADRX) mechanism [5] is proposed, where UEs are divided into several states according to their channel condition. UEs with better channel condition will be configured with lower power consumption parameters, and vice versa. In [6], DRX parameters are adjusted depending on the system load and the channel variation to improve power saving efficiency. For UEs with slow-varying channel, power saving 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 turn-on time is proposed by [7]. 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 [8] is proposed to reduce the packet loss rate due to DRX sleep, but it increases power consumption. In [11], 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 [15], 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 condition. In addition, they propose DRX aware scheduling algorithm, but it increases power consumption too.

Dynamic Scheduling with Extensible Allocation and Dispersed Offsets (DXD)

In this study, a novel DRX scheme, called Dynamic Scheduling with Extensible Allocation and Dispersed Offsets (DXD) scheme, is proposed to meet QoS requirements, minimize power consumption, and increase system capacity in the DRX mode. In order to maximize of power savings, the UE should turn off the radio interface as long as possible under the QoS constraints. The proposed scheme dynamically determines DRX parameters depending on QoS. On the other hand, when the UE turns on the radio interface, the buffered packets should be forwarded as soon as possible. Thus, we disperse turn-on time of UEs so that each UE can fully utilize the bandwidth for resource efficiency and fast transmission. In addition, the proposed method includes a DRX-aware scheduler. It can determine whether or not to extend the turn-on time for QoS satisfaction. If system loading is high, extension may not improve QoS but only increases power consumption.

The rest of this thesis is organized as follows. In Chapter 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 Chapter 3. In Chapter 4, we describe the proposed DXD algorithm and illustrate the detailed operations with an example. In Chapter 5, the simulation results are presented. Finally, we conclude this work in Chapter 6.

Chapter 2 Background

There is a tradeoff between system performance and power consumption when DRX scheme is applied in the LTE systems. The parameters of DRX configuration could be optimized depending on some factors, such as channel condition, QoS, and scheduling.

2.1 Discontinuous Reception

DRX is a power saving mechanism in LTE system. When applying the DRX scheme, the UE periodically turn off the receiving circuit to save power. During the period in which the receiver 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 Figure 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 Timer, Opportunity for DRX, Short/Long DRX Cycle, DRX Short Cycle Timer, Inactivity Timer, and Cycle Start Offset. The DRX operation and the related parameters are illustrated in Figure 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 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. 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 macro 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 period when data is buffered. Cycle Start Offset denotes start time of On-Duration in each cycle.

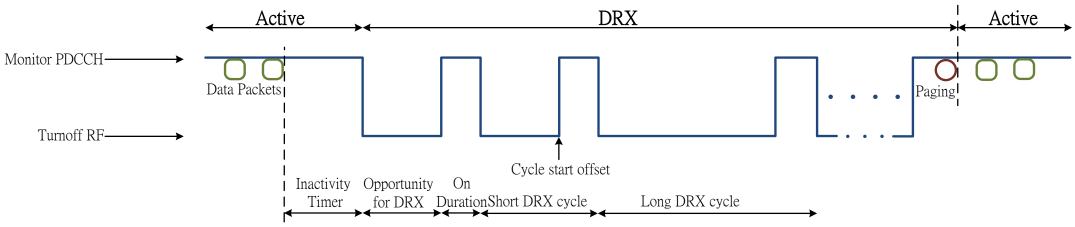


Figure 1: Operation of DRX

DRX parameters of all UEs are determined by the eNB. The eNB use 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 will affect the network capacity, we should take it into consideration when designing the scheduling algorithm or determining the DRX parameters. The UE uses CQI reporting [1] 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 the number of bits per symbol. The higher modulation is the more information a symbol can carry. 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.

Table 1: 4-bit CQI Table

CQI index	modulation	code 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

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 [2] 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. An evolved packet system (EPS) bearer is the tunnel for transporting traffic between the UE and the external network. Different QCI configuration could be adopted to an EPS bearer depending on what quality the application needs.

Table 2: Standardized QCI characteristics

QCI	Resource Type	Priority	Packet Delay Budget	Packet Error Loss Rate	Example Services
1	GBR	2	100 ms	10^{-2}	Conversational Voice
2		4	150 ms	10^{-3}	Conversational Video (Live Streaming)
3		3	50 ms	10^{-3}	Real Time Gaming
4		5	300 ms	10^{-6}	Non-Conversational Video (Buffered Streaming)
5	Non-GBR	1	100 ms	10^{-6}	IMS Signaling
6		6	300 ms	10^{-6}	Video (Buffered Streaming) TCP-based (e.g., www, e-mail, chat, ftp, p2p file sharing, progressive video, etc.)
7		7	100 ms	10^{-3}	Voice, Video (Live Streaming), Interactive Gaming
8		8	300 ms	10^{-6}	Video (Buffered Streaming)
9		9			TCP-based (e.g., www, e-mail, chat, ftp, p2p file sharing, progressive video, etc.)

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 radio frame structure as shown in Figure 2. One frame is 10 ms. Each frame is divided into 10 subframes and thus one subframe is 1 ms. 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 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.

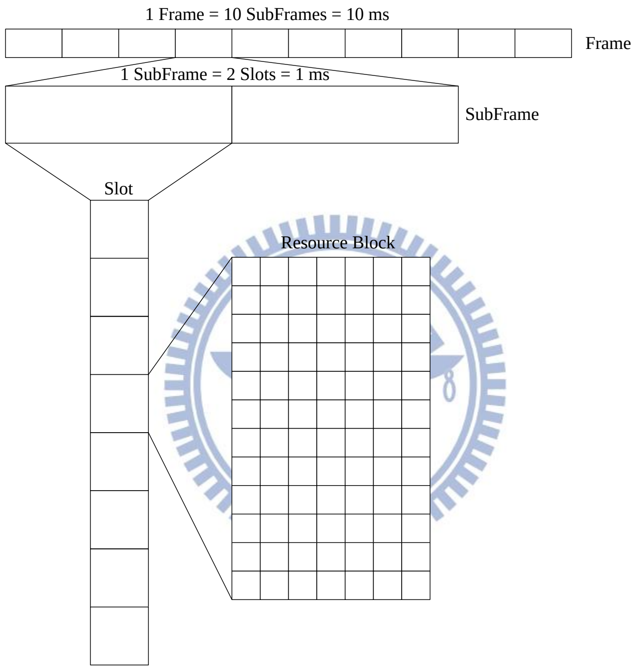


Figure 2: Radio frame structure

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 [5, 6]. A multi-threshold adaptive DRX (M-ADRX) mechanism [5] 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 [6], 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 [7].

In [12] and [13], the work considers the QoS requirements with multiple traffics when determining the DRX parameters. However, the channel condition is not taken into consideration. In [12], 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 filev DRX on duration. A traffic-based DRX cycles adjustment (TDCA) [13] 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 [8, 11]. The consideration 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 [8] 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 [11], the impact on the QoS requirements of VoIP is analyzed with dynamic and semi persistent packet scheduling schemes. In [10, 15], 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.

Table 3: The comparison of related work

Paper	Power saving	Channel condition	QoS constraints	Scheduling
Gao [5]	inactivity timer adjustment	Single CQI threshold, multiple CQI thresholds	X	X
Liu [6]	on-duration, inactivity timer adjustment	According to number and velocity of connected UE	X	X
Aho [7]	Fixed DRX	CQI preamble period add into on duration time	X	X
Jha [12]	inactivity timer and DRX cycle adjustment	X	delay requirement	X
Yu [13]	DRX cycle adjustment	X	delay requirement	X
Bo [8]	Fixed DRX	X	X	DRX parameters are introduced into the scheduling
Polignano [11]	Fixed DRX	X	VoIP	Dynamic and semi persistent scheduling
TS [15]	inactivity timer, on duration, DRX cycle, and start offset adjustment	static (based on worst CQI)	QCI	DRX parameters are introduced into the scheduling
Our DXD scheme	on duration, DRX cycle, and start offset adjustment	dynamic	QCI	DRX, CQI, and QCI are introduced into the scheduling

Chapter 3 Problem Statement

In this chapter, we define related parameters. Then we present the problem statement and the objective.

3.1 Definition

In this study, we consider the LTE network of an evolved Node B *eNB* serves N User Equipment $UE_i, i = 1, \dots, N$, where UE_i is the i-th UE. Each UE_i has M_i application services, which denoted as $S_{i,k}, k = 1, \dots, M_i$. Each $S_{i,k}$ is assigned to a QoS class identifier $QCI_{i,k}$ including Packet Delay Budget $L_{i,k}$ (ms) and Guaranteed Bit Rate $R_{i,k}$ (bits/s). Each UE_i is configured with a set of DRX parameters $D_{i,j}, j = 1, \dots, T$, where T is execution subframe. The DRX parameters $D_{i,j}$ includes On Duration Timer $TOD_{i,j}$ (ms), Opportunity for DRX $TOP_{i,j}$ (ms), Long DRX Cycle $CLD_{i,j}$ (ms), Inactivity Timer $TIA_{i,j}$ (ms), and Cycle Start Offset $CSO_{i,j}$ (ms). We denote $CQI_{i,j}$ and $P_{i,j}$ as channel quality indicator and power consumption of UE_i at subframe j.

Table 4: Definition of Symbols

Notation	Definition
eNB	A evolved Node B in LTE system
UE	A set of user equipments $UE = \{UE_i, 1 \le i \le N\}$
M_i	Number of application services in UE_i
S	A set of application services $S = \{S_{i,k}, 1 \le i \le N, 11k \le M_i\}$
QCI	A set of QoS class identifier $QCI = \{QCI_{i,k}, 1, i \le N, 1, k \le M_i\}$, where $QCI_{i,k} = (L_{i,k}, R_{i,k})$
L	A set of Packet Delay Budget $L = \{L_{i,k}, 1, i \le N, 1, k \le M_i\}$
R	A set of Guaranteed Bit Rate $R = \{R_{i,k}, 1, i \le N, 1, k \le M_i\}$
D	A set of DRX parameters $D = \{D_{i,j}, 1, i \le N, 1, j \le T\}$, where $D_{i,j} = (TOD_{i,j}, TOP_{i,j}, TIA_{i,j}, CLD_{i,j}, CSO_{i,j})$
TOD	On duration timer $TOD = \{TOD_{i,j}, 1, i \le N, 1, j \le T\}$
TOP	Opportunity for DRX $TOP = \{TOP_{i,j}, 1, i \le N, 1, j \le T\}$
TIA	Inactivity timer $TIA = \{TIA_{i,j}, 1, i \le N, 1, j \le T\}$
CLD	Long DRX cycle $CLD = \{CLD_{i,j}, 1, i \le N, 1, j \le T\}$
CSO	Cycle start offset $CSO = \{CSO_{i,j}, 1, i \le N, 1, j \le T\}$
CQI	A set of channel quality indicator $CQI = \{CQI_{i,j}, 1, i \le N, 1, j \le T\}$
P	Set of current power consumption $P = \{P_{i,j}, 1, i \le N, 1, j \le T\}$
N_{RB}	Number of RBs per slot
$CLCM$	LCM (least common multiple) of all UEs' DRX cycles $CLD_{i,j}$ at subframe j
NA	Number of UEs which stays in the active duration at each subframe $NA = \{NA_j, 1 \le j \le CLCM$
NS	A weighted version of NA as $NS = \{NS_j \| NS_j = (\mathrm{NA_j})^2, 1 \le j \le CLCM\}$
NRP	Number of UEs which active at the same offset in each cycle within the whole $CLCMNRP_x = \{NRP_{x,k}, 1 \le k \le CLD_x\}$

3.2 Problem Description

The DRX parameters optimization problem is described as follows. Given an *eNB*, a set of user equipments $UE = \{UE_i, 1 \le i \le N\}$, which have a set of services $S = \{S_{i,k}, 1 \le i \le N, 1 \le k \le M_i\}$ and $CQI = \{CQI_{i,j}, 1 \le i \le N, 1 \le j \le T\}$. The objective is to design an approach to allocate the resource blocks and optimize the DRX parameters, $D_{i,j}$, of each UE_i, including $TOD_{i,j}$, $TOP_{i,j}$, $TIA_{i,j}$, $CLD_{i,j}$, and $CSO_{i,j}$ depending on the channel conditional $CQI_{i,j}$, such that the QoS requirement $QCI_{i,k}$ can be satisfied as good as the no DRX situation and power consumption $P_{i,j}$ for each UE_i can be minimized at the same time.

Chapter 4 Dynamic Scheduling with Extensible Allocation and Dispersed Offsets Scheme

In this chapter, we discuss how DXD scheme works. Then, some examples are demonstrated.

4.1 Overview

First, we determine the optimal DRX period by considering channel condition and QoS constraints under the assumption that the UE can fully utilize the 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 the on duration and finish its transmission as soon as possible to go to sleep for more time. DRX parameters are taken into consideration during scheduling process so that the active period can be dynamically extended or not.

In this study, a novel DRX scheme, called Dynamic Scheduling with Extensible Allocation and Dispersed Offsets (DXD), is proposed with the objectives of satisfying the QoS requirements, minimizing the power consumption, and increasing the system capacity with DRX operations. As illustrated in Figure 3, the architecture of DXD is implemented in the eNB, and it can be divided into two parts: 1) DRX parameter decision algorithm, and 2) DRX-aware scheduling algorithm.

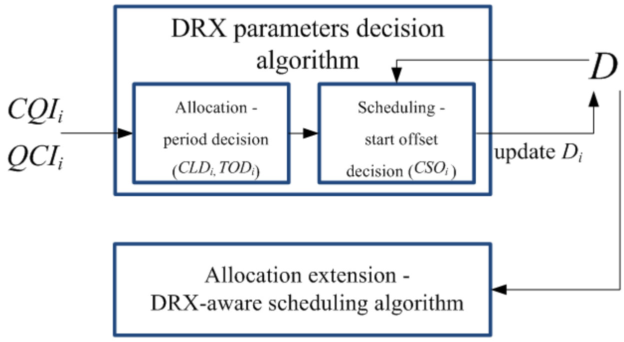


Figure 3: Dynamic Scheduling with Extensible Allocation and Dispersed Offsets (DXD) architecture

DRX parameter decision algorithm will be executed when one of UE (UE_i) needs to update its DRX parameters ($D_{i,j}$). DRX parameter decision algorithm includes two parts. In the first part, period decision method determines *how much* turn-on time is allocated to UE_i as well as the long DRX Cycle $CLD_{i,j}$ so that the UE can turn off the radio interface as long as possible to maximize the power saving but without violating the QoS requirement. Thus, we set the value of $CLD_{i,j}$ as large as the delay constraint. On the other hand, the packets arrived during the turn-off time period will be buffered and should be forwarded immediately when the UE turns on the radio interface. Thus, we also need to set the On Duration, $TOD_{i,j}$, as the transmission time for all buffered packets. Here, the packet transmission time will be estimated based on the channel quality $CQI_{i,j}$. In the second part, the start offset decision determines *when* the turn-on time is allocated to UE_i. We need to determine the cycle start offset $CSO_{i,j}$ to disperse the active period of UEs. In this way, the UE can fully utilize the resource blocks so that the buffered packets could be forwarded as soon as possible with a minimal active time period. When finishing the transmission, the UE can turn off the radio interface immediately to save power.

In addition to determine the DRX parameters, we also design a new scheduler, called DRX-aware scheduling, which cooperates with the DRX parameter decision algorithm to extend the turn-on time. DRX-aware scheduling algorithm takes the DRX parameter *D* into account. When the UE is able to turn off its radio circuit, but some packets have not been serviced, the active period would be extended to satisfy QoS with DRX.

4.2 Detailed Operations of DXD

4.2.1 Allocation - Period Decision

When the *x*-th UE, UE_x attaches to the eNB or detects the change of channel condition, period decision algorithm calculates DRX cycle CLD_x and on duration TOD_x, as shown in Figure 4. To maximize power saving and meet the strictest delay budget, we set long DRX cycle CLD_x as the minimum delay budget in each service as follows:

$$CLD_x = \min_{1 \le k \le M_x} \{L_{x,k}\}.$$

In order to save power, UE_x should turn off the circuit immediately after its all packets are transmitted. Therefore, we set its on duration TOD_x as the expected transmission time according to its channel quality indicator CQI_x. TOD_x is obtained as

$$TOD_x = \left\lceil CLD_x \cdot \min\left\{\frac{\sum_{1 \le k \le M_x} R_{x,k}}{B(CQI_x) \cdot N_{RB}/0.0005}, 1\right\}\right\rceil.$$

TOD_x is obtained from multiplying the long DRX cycle, CLD_x, by the ratio of the sum of guaranteed bit rate, $R_{x,k}$, to the available transmission rate. Available transmission rate is obtained based on current channel condition, thus we use $B(CQI_x)$ to denote 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 0.0005 seconds. If the required data rates is larger than the available transmission rate, we set the on duration TOD_x as the DRX cycle CLD_x.

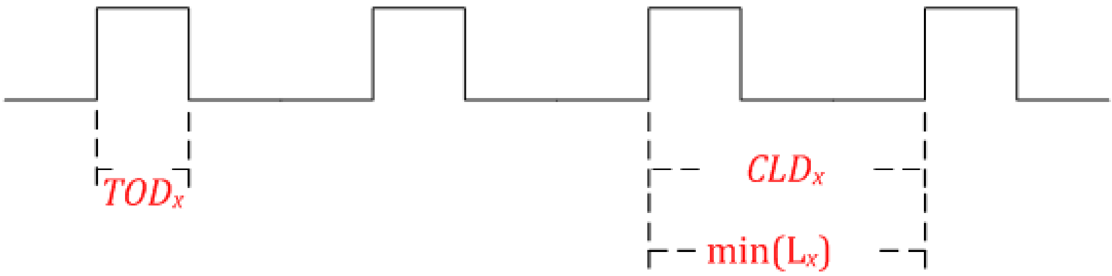


Figure 4: The parameters used in the period decision method

4.2.2 Scheduling - Start Offset Decision

In order to improve radio resource efficiency in the active period, we disperse the on duration of each UE by assigning different cycle start offsets. It can fully utilize the bandwidth during the on duration if it does not overlap with other UEs.

We maintain $NA = \{NA_j, 1 \le j \le CLCM\}$, in which NA_j is the number of UEs which stays in the active duration at subframe *j*. Let $CLCM$ denote the least common multiple (LCM) of all long DRX cycles CLD_i i.e., $CLCM = \text{lcm}(CLD_1, CLD_2, \dots, CLD_N)$. If current least common multiple, $CLCM'$, which is recalculated with the CLD_x, is larger than the original $CLCM$ then we should update current $NA' = \{NA'_j, 1 \le j \le CLCM'\}$ according by original NA, where $NA'_j = NA_{((j-1) \bmod CLCM)+1}$. That is, NA' is formed by combing multiple of NA because $CLCM'$ is multiple of $CLCM$. Otherwise, $CLCM$ and NA remain unchanged. Since the long DRX cycle CLD_x will repeat multiple times within the $CLCM$ time period, so we use $NRP_x = \{NRP_{x,k}, 1 \le k \le CLD_x\}$ in unit of CLD_x to indicate the number of UEs which active at the same offset in each cycle within the whole $CLCM$. So, we have NRP_x as:

$$NRP_{x,k} = \sum_{\forall j,((j-1) \bmod CLD_x)+1=k} NA_j\,, 1 \le j \le CLCM, 1 \le k \le CLD_x.$$

Then, the cycle start offset CSO_x can be found by

$$CSO_x = \arg \min_{1 \le k \le CLD_x} \left\{ \sum_{j=k}^{k+TOD_x-1} NRP_{x,((j-1) \bmod CLD_x)+1} \right\}.$$

The formula means that during the on duration of UE_x, the number of UEs which stay in the on duration is minimal within the whole $CLCM$ time period. Therefore, UE_x can fully utilize the bandwidth during the on duration if it does not overlap with other UEs, finish its transmission as soon as possible, and go to sleep for more time.

However, we observe that the value of NRP_x may not be sufficient to grasp the impact come from other UEs. Take Figure 5 as an example. Here, there are 3 UEs with different long 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_x, the value of NRP_x in both cases are the same (i.e., $NRP_{x,1} = 3$ and $NRP_{x,j} = 0, \text{if } j \neq 1$). 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_x 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_x only competes with one UE.

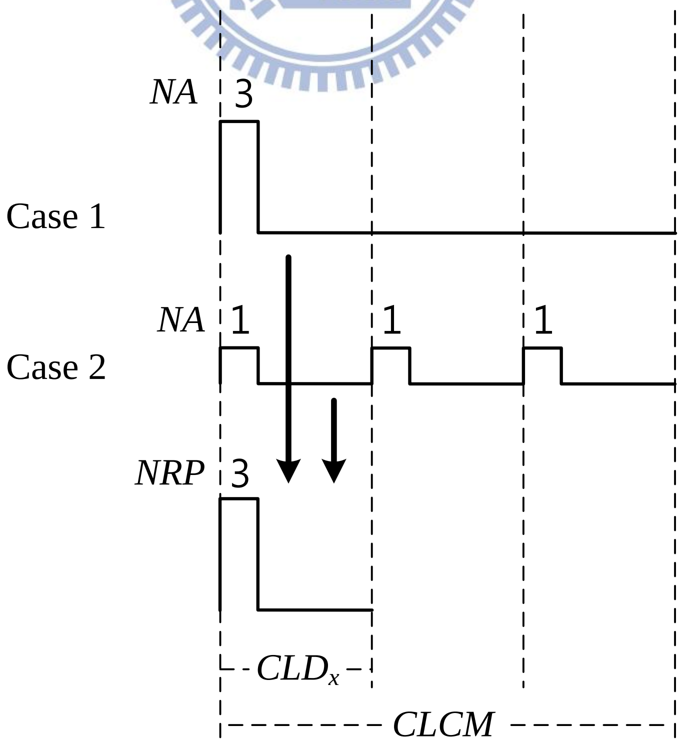


Figure 5: The impact of other UEs for UE_x

So we consider a weighted version of NA as $NS = \left\{ NS_j \middle| NS_j = \left(\mathrm{NA_j}\right)^2, 1 \le j \le CLCM \right\}$ in order to differentiate the degree of dispersion of UEs' on duration. A subframe with more active users makes more impacts on the decision of start offset. So we utilize the square function to emphasize such phenomenon. Then, we have the new NRP_x as

$$NRP'_{x,k} = \sum_{\forall j, ((j-1) \bmod CLD_x)+1=k} NS_j \,, 1 \le j \le CLCM, 1 \le k \le CLD_x.$$

Then, the *optimal* cycle start offset (CSO_x) can be found by

$$CSO_x = \arg \min_{1 \le k \le CLD_x} \left\{ \sum_{j=k}^{k+TOD_x-1} NRP'_{x,((j-1) \bmod CLD_x)+1} \right\}$$

4.2.3 Allocation Extension - DRX-aware Scheduling

The DRX aware scheduling in [15] dynamically extends the active period in order to increase the satisfaction ratio on delay budget. DRX inactivity timer will be reset if the UE is scheduled. With this feature, the UE that will be closed at the next subframe is scheduled one RBG to extend the inactivity timer if RLC buffer, which is waiting transmission queue, is not empty. However, frequent extending the active period will significantly increase power consumption especially in the case of poor channel condition or high system load. It is because the system does not have sufficient radio resources that can be allocated to the UE in UE's extended active period. Therefore, our scheme does not extend the active period of UE if the system is unable to serve the UE in the current active period. The detail formula of scheduling priority handling is described as follow,

$$p_x(t) = \begin{cases} p_x^*(t) + \alpha \text{, if } TOD_x \le 1 \text{ and } TIA_x \le 1 \text{ and } loading_x < off\_ratio_x \\ p_x^*(t), \text{otherwise} \end{cases},$$

$$loading_x = \sum_{\forall i, p_i^*(t) > p_x^*(t)} \frac{R_i(t)}{r_i(t)},$$

$$off\_ratio_x = \frac{TOP_x}{CLD_x},$$

where $p_x^*(t)$ denotes priority of original scheduling which can be any scheduling scheme. $p_x(t)$ denotes DRX-aware scheduling at subframe t for UE_x, respectively. Let $loading_x$ denotes the total loading of active UEs whose priorities are higher than UE_x, and it is calculated by $R_i(t)$ and $r_i(t)$ which are average data rate and achievable data rate depending on CQI_i at subframe t, respectively. Let off_ratio_x denotes the ratio of opportunity for DRX to DRX cycle. So $loading_x \geq off\_ratio_x$ means that system loading is too high to serve UE_x during the rest of time in its DRX cycle. Therefore, when UE_x will turn off its radio interface at the next subframe (i.e., $TOD_x \leq 1, TIA_x \leq 1$) and the system load is less than the free resource from turn-off, the priority of UE will be increased by α. Here, we let $\alpha > \max_{\forall i}\{p_i^*(t)\}$ to raise the priority of UE which need to be scheduled.

4.3 Example

In this sub section, we give some examples to illustrate the algorithm.

Example for period decision

There are three services in UE_x. The required data rate and delay budget for each service are shown in Table 5. The system bandwidth is 20MHz which has 100 RBs, and the channel condition is 15.

Table 5: Application services in UE_x

	R (Mbps)	L (ms)
VoIP	1	100
video	3	150
FTP	2	300

DRX cycle CLD_x and on duration TOD_x are calculated as follows:

$$CLD_x = \min\ \{100, 150, 300\} = 100\,\text{ms},$$

$$
\begin{aligned}
TOD_x &= \left\lceil CLD_x \cdot \min\left\{ \frac{\sum_{1 \le k \le M_x} R_{x,k}}{B(CQI_x) \cdot N_{RB}/0.0005}, 1 \right\} \right\rceil \\
&= \left\lceil 100 \cdot \frac{1 + 3 + 2 \text{ Mbps}}{(5.55 \text{ bits} \cdot 12 \cdot 7\,) \cdot 100/0.0005 \text{ bps}} \right\rceil = \left\lceil 100 \cdot \frac{6 \text{ Mbps}}{93.2 \text{ Mbps}} \right\rceil \\
&= 7\text{ms},
\end{aligned}
$$

where one RB has $12 \cdot 7$ symbols. Each symbol can carry 5.55 bits depending on the CQI table.

Example for start offset decision

UE_X is attaching to the eNB and needs to determine its cycle start offset CSO_X. The relevant DRX parameters are shown in Table 6. Figure 6 shows how to determine the start offset CSO_X for UE_X.

Table 6: Example of start offset decision

	DRX cycle	On duration	Cycle start offset
UE_X	100 ms	50ms	CSO_x

First, we assume lowest common multiple is 300. We maintain the number of awaken UEs, NA, in 300 subframes. Then we generates square weighted value, NS, from NA. Since the DRX cycle of UE_x (CLD_x) is 100ms, so NS is divided into three cycles (i.e., $CLCM/CLD_x$). Then, we have the NRP'_x value. The value of $NRP'_{x,j}$ is 4 when j = 1 to 25 and the value of $NRP'_{x,j}$ is 1 when j = 26 to 100. Therefore, we can find that CSO_x could be set within the range of 26 to 100, which means that the impact from other UEs during the on duration is minimal. Since the start offset in this case is not a unique value, we use the following formula to obtain a unique start offset for the UE.

$$
\text{the number of candidate values} \cdot \left\lceil \frac{\text{index of } UE_X}{\text{number of UEs}} \right\rceil = 75 \cdot \left\lceil \frac{3}{3} \right\rceil = 75 \; .
$$

Thus, we obtained the start offset CSO_x as 25 + 75 = 100. The reason is that we can uniformly interlace the on duration of all UEs.

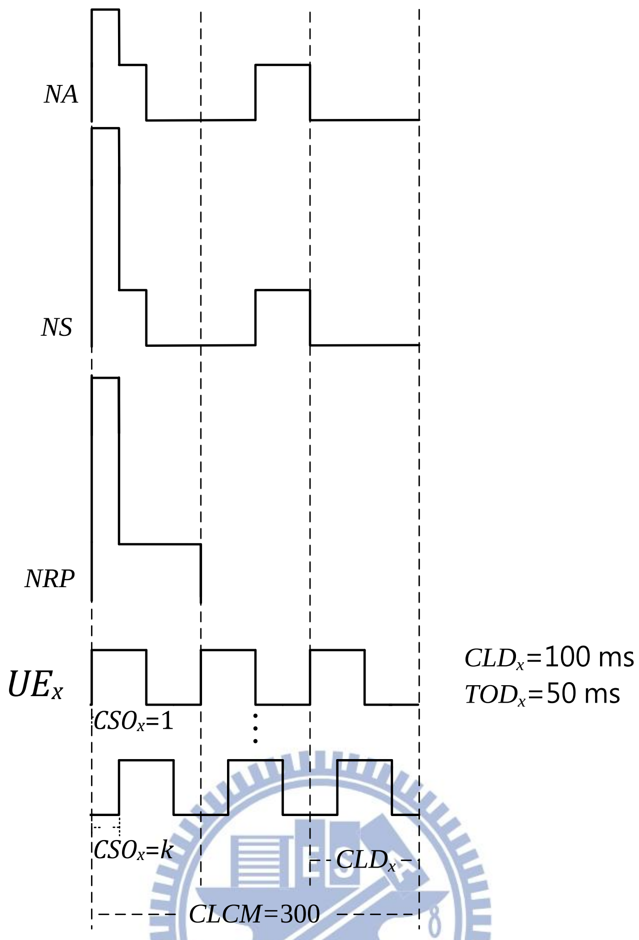


Figure 6: Example for start offset decision

4.4 System Overhead Analysis

We discuss signaling overhead of DRX parameters configuration first. 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 $O(N)$. TS algorithm, which is similar to our work, need to recalculate parameters of all UEs when one particular UE needs to configure DRX parameters, so the signal overhead is $1+2+3+\cdots+N = \frac{(1+N)\cdot N}{2} = O(N^2)$.

For the time complexity part, we assume that the maximum least common multiple of DRX cycle is C. Since C is the maximum LCM, we need to update NA, and the cost is $O(1)$. Therefore, the time complexity of obtaining NS is $O(C)$.

The calculation of each $\mathrm{NRP}'_{x,k}$ needs $\frac{C}{CLD_x} - 1$ additions. Thus, the total number of operations is $\left(\frac{C}{CLD_x} - 1\right) \cdot CLD_x$ and the cost is also $O(C)$. For the loading of calculating each CSO_k, we have

$$CSO_1\_loading = NRP_1 + NRP_2 + NRP_3 + \cdots + NRP_{TOD_x},$$

$$CSO_2\_loading = NRP_2 + NRP_3 + NRP_4 + \cdots + NRP_{TOD_x+1}$$

$$= CSO_1\_loading - NRP_1 + NRP_{TOD_x+1},$$

$$CSO_3\_loading = \cdots,$$

$$CSO_{CLD_x}\_loading = NRP_{CLD_x} + NRP_1 + NRP_2 + \cdots + NRP_{TOD_x-1}$$

$$= CSO_{CLD_x-1}\_loading - NRP_{CLD_x-1} + NRP_{TOD_x-1}.$$

Therefore, the number of operations is $(TOD_x - 1) + 2 \cdot (CLD_x - 1)$. In the worst case, $TOD_x = CLD_x = C$. Thus, the cost is $(\mathrm{C} - 1) + 2 \cdot (C - 1) = O(C)$, and the selection of the smallest loading is $\mathrm{O}(C)$. Finally, the overall time complexity of cycle start offset decision is $O(C)$.

Chapter 5 Performance Evaluations

First, we describe the simulation environment and parameter settings in Section 5.1. Then, we present the simulation results, such as adaptability to channel condition, multiple services handling, and system capacity problem.

5.1 Simulation Environment

We developed the proposed DXD scheme in NS-3 simulator [14]. Since NS-3 did not support DRX mechanism yet, we implemented the DRX module in NS-3. Figure 7 shows the radio protocol stack architecture. DRX scheme is added into the MAC [3] layer. Radio Resource Control (RRC) [4] layer sets DRX parameters by RRC signaling. The packets of each service are buffered in a different Radio Link Control (RLC) buffer to wait for scheduling. The architecture is associated with service access points (SAPs) between different components. DRX and Scheduler can communicate with each other via SAP to implement DRX aware scheduling scheme.

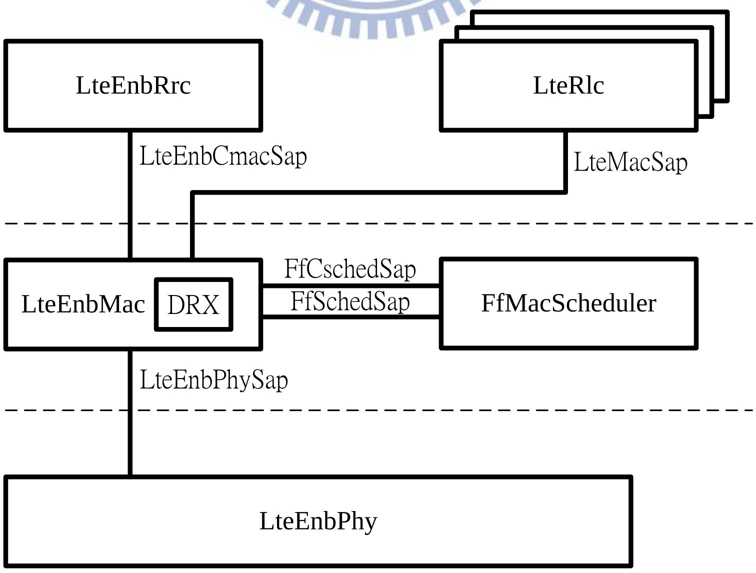


Figure 7: LTE radio protocol stack architecture

5.2 Parameter Setting

The power consumption model [10] as shown in Figure 8 is used to simulate the power consumption of UE. It 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 state transitions. Deep sleep and light sleep correspond to long DRX cycle and short DRX cycle, respectively.

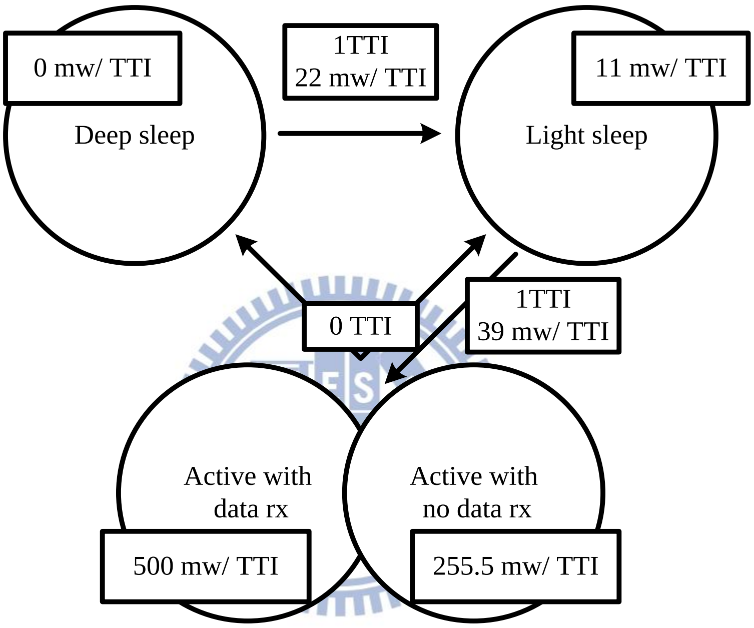


Figure 8: Power consumption model

We design three simulations according to adaptability to channel condition, multiple services handling, and system capacity problem to verify the effectiveness of our proposed approach. Simulation configurations of three simulations are shown in Table 7. The system bandwidth is 5 MHz which has 12 RBG at each subframes. If DRX scheme is enabled with a set of *static* settings, the default DRX parameters listed in Table 7 are used. Otherwise, the DRX parameters will be obtained from the proposed approach. Furthermore, the scheduler used in our simulation is our DRX aware algorithm Proportional Fair (PF) scheduler [16]. Our proposed DRX aware scheduling is also integrated with the PF scheduler.

Table 7: Simulation configuration

	Adapt to channel condition	Multiple services handling	System capacity problem
Bandwidth	5 MHz		
Number of UE	8		5~30
default DRX parameters	$CLD = 20$ ms, 100 ms, 120 ms $TOD = 2$ ms, 10 ms, 12 ms $TIA = 3$ ms $CSO = 0$ ms		
Scheduler	Proportional Fair		
VoIP	G.711, 64Kbps, 160 bytes payload, QCI: 1		
Video streaming	MPEG 4, peak/ mean bit rate = 2.1/ 0.1 Mbps, QCI: 4		
Services of UE	VoIP	VoIP and video streaming	
Channel condition	1~15		random

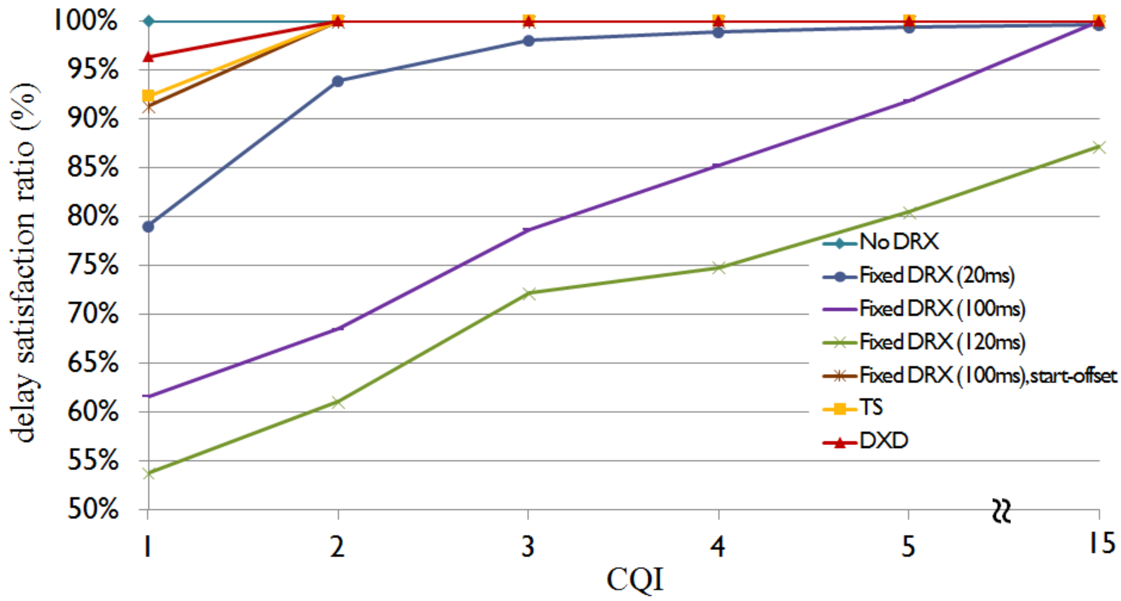
DXD is compared with "No DRX" scheme and TS scheme in the following sections. Performance metrics of measurement are: delay satisfaction ratio and power consumption. Delay satisfaction ratio indicates the percentage of packets that satisfy the delay budget.

5.3 Adaptability to Channel Condition

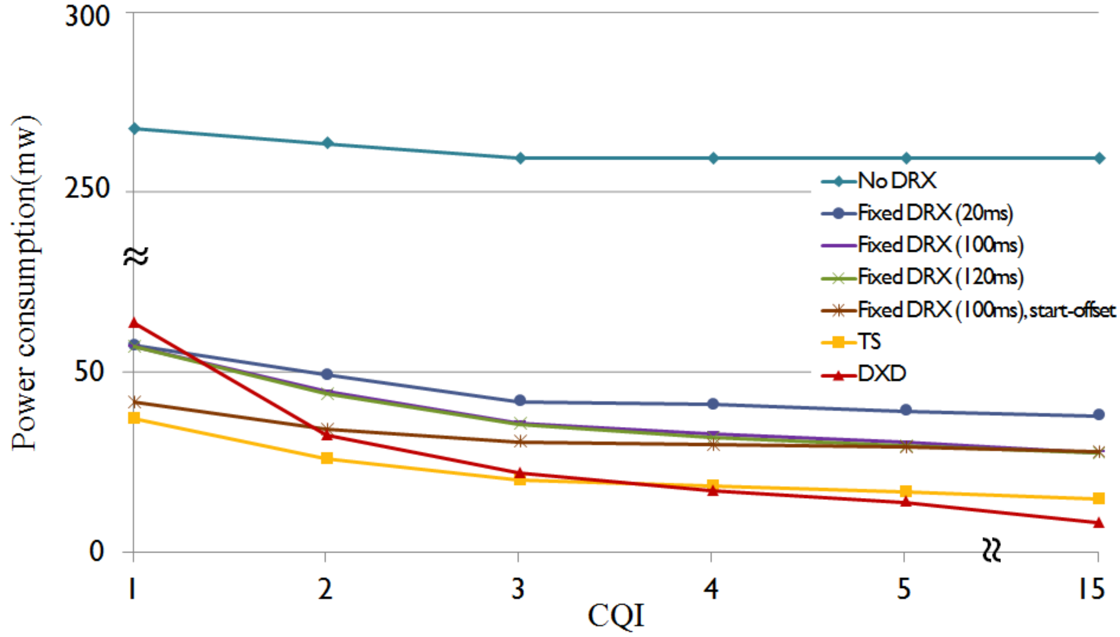
In order to observe the adaptability to channel condition, we investigate the relationship between CQI and delay satisfaction ratio in Figure 9 (a). A scheme has higher adaptability to channel condition means it achieves high delay satisfactory ratio regardless of the channel condition.

In Figure 9 (a), “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 Figure 9 (b). We observe the results of fixed DRX with different lengths of DRX cycles. DRX scheme with longer DRX cycles has lower power consumption. Nevertheless, if the DRX cycle is longer than the delay budget of the services, delay budget cannot be satisfied even in the best channel condition. In addition, the results under the fixed DRX scheme with fixed 100ms DRX cycle shows that when CQI decreases, delay satisfaction ratio also decreases significantly. The reason is that when CQI decreases, the UE needs more radio resources to maintain the required data rate. If active periods 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. DRX (100 ms) with start offset also reduces resource competition at the same time so active period is seldom extended and the power consumption is decreased significantly as well. DXD 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, DXD has better performance of delay satisfaction ratio and the power consumption of DXD is lower than TS in CQI 4~15. The reduction of power consumption compared to "No DRX" and TS is up to 96.9% and 45.7% respectively because DXD dynamically configures 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 because TS determines on duration only according to one packet size of service.



(a)



(b)

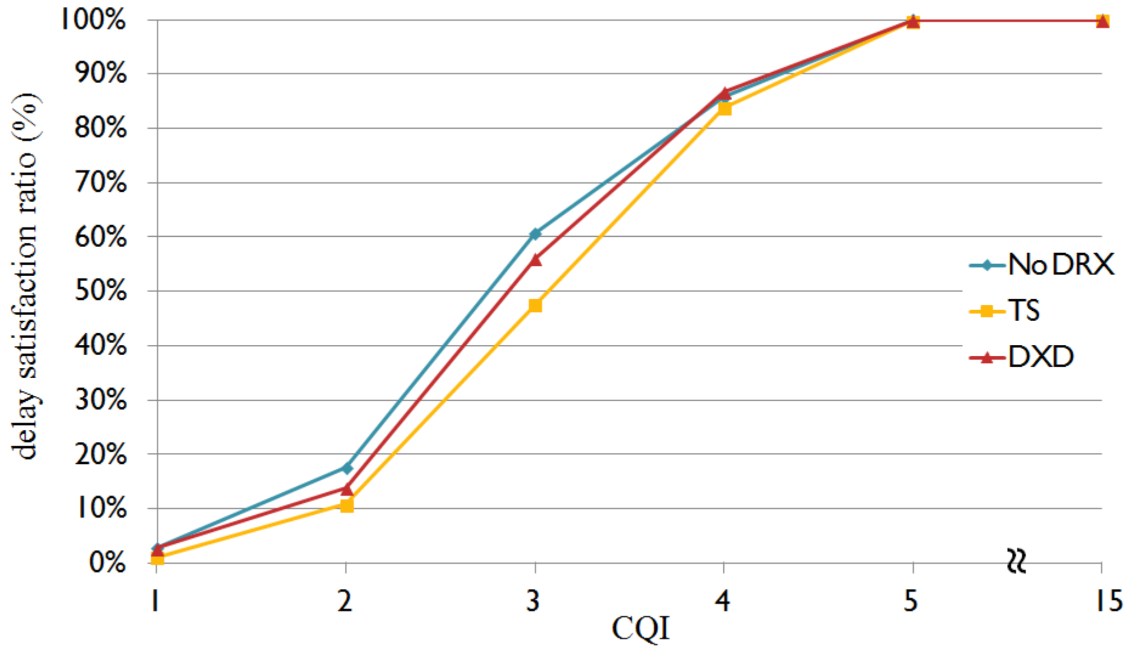
Figure 9: adaptability to channel condition (a) delay satisfaction ratio (b) power consumption

5.4 Multiple Services Handling

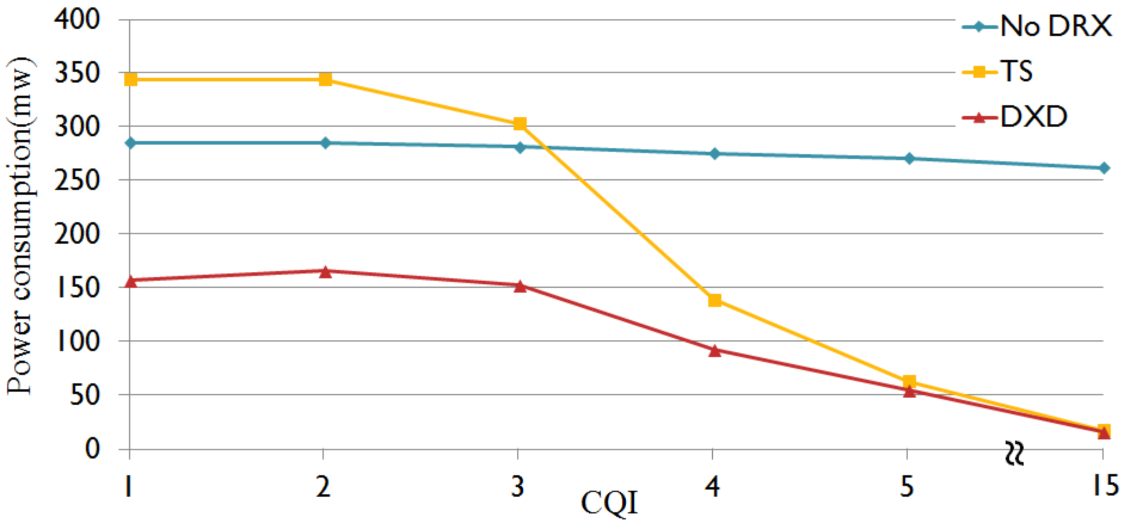
There are two services, VoIP and video, in each UE in this set of simulations. Figure 10 (a) shows the delay satisfaction ratio of multiple services under different DRX algorithms. We can find that the delay satisfaction ratio of DXD is as good as that of “No DRX” scheme. In addition to high adaptability 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.

In DXD, the UE usually extends its active period due to the bursty characteristic of video traffic. The scheduler will allocate one RBG to the UE so as to extend the active period (i.e., the *inactivity timer* will be reset). No matter how many RBGs are allocated to the UE, the UE stays at the “active with data rx” state with power consumption of 500 mW/TTI. As the channel condition worsens or the system load increases, the radio resource may not 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 Figure 10 (b). Furthermore, the UE will stays at the “active with no data rx” state (i.e., with 255.5mw/TTI) if the radio resource may not be allocated to the UE during its *extended* time period. Therefore, the scheduler of DXD algorithm will not extend the active period to reduce the power consumption. The overall reduction ratio on power consumption of DXD compared to TS is 11.4%~54.3% in CQI 1~15.

The delay satisfaction ratios of VoIP and video services are illustrated in Figure 11. Compared with the VoIP service, the video 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 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.



(a)



(b)

Figure 10 : Multiple services handling (a) Delay satisfaction ratios (b) Power consumptions

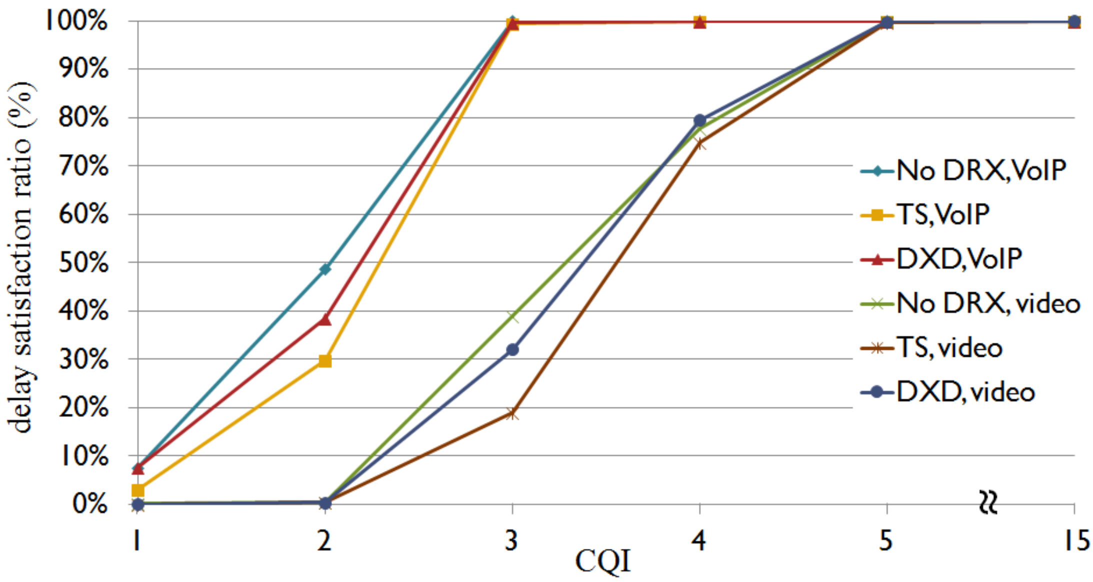
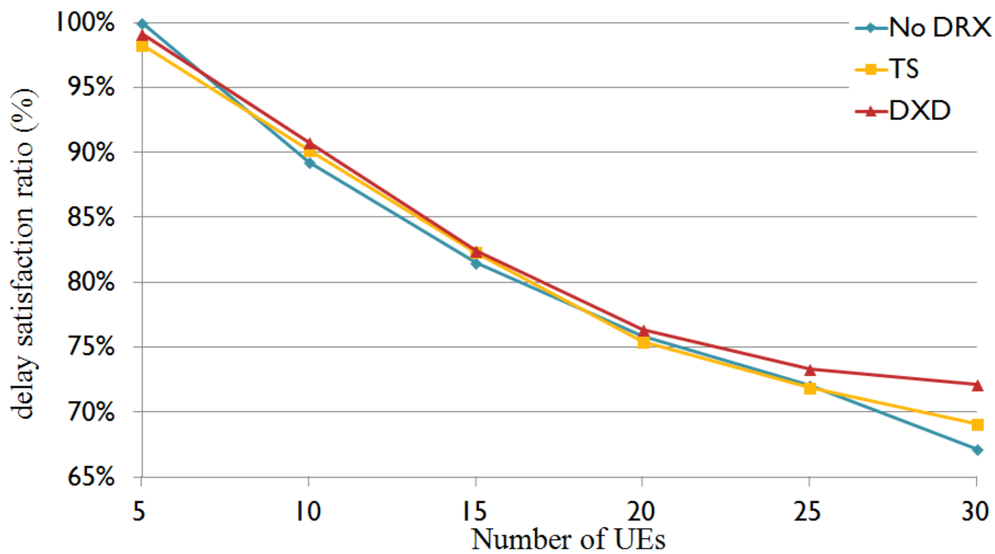


Figure 11: Delay satisfaction ratios of different services of multiple services handling

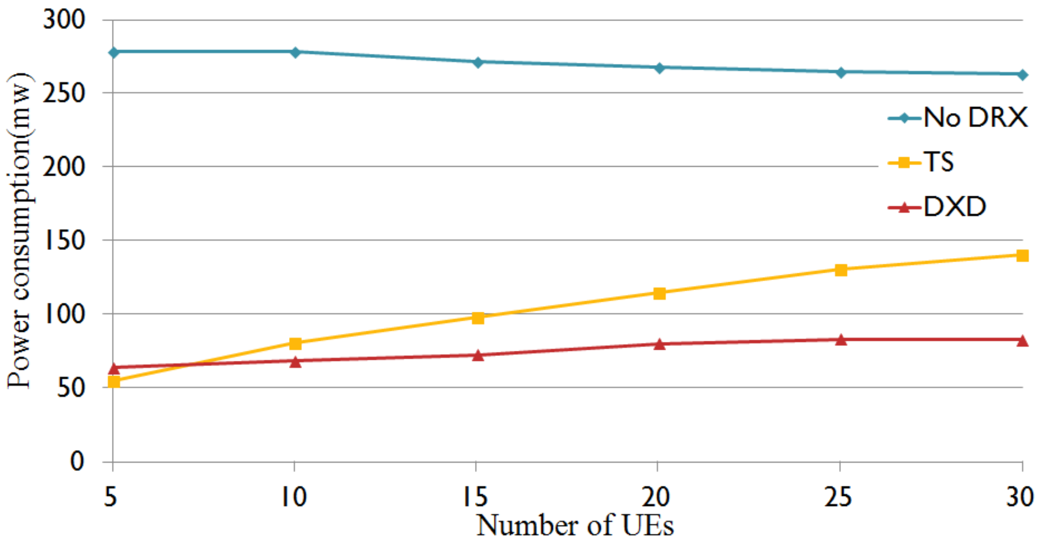
5.5 System Capacity Problem

The effect of system loading upon QoS satisfaction and power consumption are shown in Figure 12 (a) and Figure 12 (b) receptivity. The performance of our proposed DXD approach is as good as that of "No DRX" scheme in a lightly-load environment. When the system loading gradually increases, the requirement of delay satisfaction ratio could be improved by applying the DRX-aware scheduling. 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 algorithm is more than that in "No DRX" algorithm with PF scheduler. Because PF scheduler usually serves UEs with high CQI firstly, these UEs have low delay but delay of other UEs must be very high. However in DXD algorithm, if the UE turns off radio interface, it can only be served at next DRX cycle and in consequence the transmission delay in DXD algorithm approaches its delay budget. Thus, the delay satisfaction ratio of DXD can be better than "No DRX" scheme.

In Figure 12 (b), 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 active periods, but our approach will determine whether it is necessary to extend or not. DXD only closes UEs which are impossibly served according to system loading and next on duration time. So power can be saved without affecting performance. In addition, our approach can determine cycle start offset of one UE, but power consumption is not increased by our approach.



(a)



(b)

Figure 12: System capacity problem (a) delay satisfaction ratios (b) power consumptions

Chapter 6 Conclusion

In this thesis, we propose the Dynamic Scheduling with Extensible Allocation and Dispersed Offsets (DXD) scheme to reduce power consumption and meet QoS in unstable channel condition. DXD is composed of period decision, start offset decision, and DRX aware scheduling. 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. In addition, it can flexibly determine DRX start offset of one UE without updating the other UEs' DRX parameters. Hence, it can reduce signaling overhead. Third, the proposed DRX aware scheduling will dynamically extend the active period of UEs to increase delay satisfaction ratio for the bursty traffic.

Simulation results show the outperformance of our approach. In the case of dynamic channel condition, the delay satisfaction ratio is only slightly lower than that of "No DRX" scheme in poor channel condition. In the meantime, the power consumption can be reduced by 45.7% compared to the TS algorithm in good channel condition. In multiple services environment, our approach is able to satisfy the constraint of delay budgets as good as "No DRX" scheme. Compared to the TS algorithm, the power consumption is reduced between 11.4% and 54.3% depends on different channel conditions. 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 in unstable channel condition and high loading system. Furthermore, the delay satisfaction ratio is better than TS.

In the future, we will optimize DRX parameters and find the most suitable DRX period according to other environmental factors. For example, if the UE does not have traffic for a period of time, the state of the UE turns into RRC idle mode to reduce the consumption of system resources. In order to minimize power consumption of UEs which stay in RRC idle mode, we will investigate the DRX mechanism in RRC idle mode.

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