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碩士論文

Department of Electrical Engineering
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Master Thesis

透過干擾管理與影片位元率選擇之改善自適性影音串流於效用感知

Utility-Aware DASH Improvement by Interference Management and Rate Selection

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中華民國 107 年 7 月
July, 2018

摘要

視訊串流是一種非常消耗網路資源的服務，在多重基地台的環境下，基地台間彼此的干擾（稱作細胞間干擾）會造成網路頻寬下降，為了維持視訊串流的服務品質，基地台間的資源管理及干擾抑制是非常重要的，不過只有提升頻寬是不夠的，還需要針對訊串流的應用層特性做考慮。

自適性影音串流是近年來最常被使用的視訊串流技術，主要的概念是透過客戶端自行監測網路狀況來挑選適當的影片片段品質做播放，然而在自適性影音串流的演算法中，影片品質挑選僅是由客戶端自己選擇，而且也只透過應用層的參數做決定，沒有來自實體層的資訊，若是能透過伺服器端輔助，則更能適應於當下的網路狀況。

在這篇論文中，我們綜合地考慮這兩個層面並提出一個整合式的干擾管理與影片位元率選擇策略來改善自適性影音串流服務於一個有細胞間干擾的環境，並且實作於長期演進技術（LTE）的實測平台上分析其表現。表現衡量是透過一個效用分數函數來做量化分析，結果顯示我們的方法在各個情境下皆大幅提升了自適性影音串流的效用分數。

中文關鍵字: 細胞間干擾協調; 自適性影音串流; 實測平台。

Abstract

Video streaming are now becoming a major service in wireless network. However, video streaming is a very consuming service that occupies lots of network bandwidth. In Long Term Evolution (LTE) multi-cellular network topology, the resource reuse factor is usually set to 1, which lets adjacent base stations use same frequency band to increase resources efficiency. However, User Equipments (UE) at cell edge may suffer from high interference from neighbor cells. The shortage of network bandwidth caused by the interference from the neighbor cells becomes an issue called *Inter-Cell Interference* (ICI). *Inter-Cell Interference Coordination* (ICIC) was introduced to solve ICI problem by 3GPP [3]. To maintain service quality, the management of radio resources and interference mitigation are crucial for multi-cellular networks. To improve video streaming services, increasing network bandwidth is not enough to enhance video streaming service. Application layer characteristics will be also considered.

Dynamic Adaptive Streaming over HTTP (DASH) is a popular video streaming technique in recent years. The main concept is that DASH service clients monitor the network conditions and select the video segments with proper quality. However, the network conditions considered in client-based DASH algorithm are usually application level parameters, such as buffer filled level, rebuffering time, historical throughput, etc. There is no physical layer information in DASH application. If the selection of the video quality can be aided by the physical channel information from server, it will more adapt to current network situation.

In this thesis, we jointly consider this two aspects and propose a integral interference management and rate selection strategy procedure to improve DASH service in ICI environment. The performance of our design was verified by real LTE testbed system. The quantification of performance analysis is by a DASH utility score function [25]. The results showed we largely improve the DASH utility in each scenario.

Keywords: Inter-Cell Interference Coordination (ICIC); Dynamic Adaptive Streaming over HTTP (DASH); Testbed.

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Chapter 1

Introduction

Video streaming are now becoming a major service in wireless network. However, video streaming is a very consuming service that occupies lots of network bandwidth. In multi-cellular network topology, the shortage of network bandwidth is more significant because of the interference from the neighbor cells, which becomes an issue called *Inter-Cell Interference* (ICI). *Inter-Cell Interference Coordination* (ICIC) was introduced to solve ICI problem by 3GPP [3]. To mitigate the interference, the management of radio resources is crucial for multi-cellular networks. To improve video streaming services, increasing network bandwidth by interference mitigation is just the first step. Physical layer resource management is not enough to enhance video streaming service. In other words, application layer characteristics will be also considered.

In recent application, Dynamic Adaptive Streaming over HTTP (DASH) is a popular video streaming technique and used by many video streaming services providers, such as *YouTube, Netflix*. The main concept is that DASH service clients monitor the network conditions and select the video segments with proper quality. However, the network conditions considered in client-based DASH algorithm are usually application level parameters, such as buffer filled level, rebuffering time, historical throughput, etc. There is no physical layer information in DASH application. In client-based rate selection algorithm, it will suffer from two occasionally cases: (i) the future throughput may be largely underestimated when the client's end-to-end bandwidth does not saturate by video segments; (ii) bandwidth prediction by historical bandwidth records sometimes leads to overestimation when the LTE network fluctuates suddenly. If the selection of the video quality can be aided by the physical channel information from server, it will more adapt to current network situation. As a result, we design a server-aided rate selection to solve the above problem.

A variety of research has focus on how to manage radio resources in ICI environment and how to design video quality adaption algorithm respectively. In this thesis, we jointly consider this two aspects and propose a integral interference management and rate selection strategy procedure to improve DASH service in ICI environment. First, we coordinate the ICI by signal power control and frequency band interleaving between adjacency cells. Through corresponding classification procedure, the interference of *User Equipments* (UE) will be in control. The client UE will be aided to select a proper video quality according to the instant interference level by system and be allocated with enough amount of coordinated resources to guarantee the streaming quality. The performance of our design was verified by real *Long Term Evolution* (LTE) testbed system. Further details are provided in the remaining of this thesis, and it is organized as follows. In chapter 2, we describe related works and background knowledge of this thesis. Chapter 3 introduces the characteristics of LTE testbed. Chapter 4 presents the problem formulation and the solving procedure. Chapter 5 shows the performance analysis with testbed implementation and gives the discussion of results from testbed experiments. Finally, conclusion are drawn in Chapter 6.

Chapter 2

Background and Related Works

The background and related works for this thesis are provided in this chapter. First, we introduces the basic concept of ICI and ICIC literatures. In order to real LTE testbed implementation, the physical property of LTE *Resource Block* (RB) is also important to be known. We offered that in section 2.2. Finally, the DASH characteristics, literature findings and performance analysis will be showed in section 2.3.

2.1 Inter-Cell Interference Coordination

In OFDMA-based cellular network, the coverage of adjacent base stations will overlap. The overlapping part is called *cell edge*. When adjacent Base Stations (BS) use the same frequency band, the UE in cell edge will receive not only the desired signal from its serving cell but also interference from the neighboring cell simultaneously, which is called *Inter-Cell Interference* (ICI). *Inter-Cell Interference Coordination* (ICIC) was first introduced in 3GPP Release 8 [3]. It pointed out in high-level that radio resource management is the key to solve ICI problem. *Frequency reuse* is the spectrum planning methodology combines the following two aspects as an ICIC solution. Frequency domain interleaving between BSs and downlink data channel power control are the two means in frequency reuse scheme. We will give the discussion in next paragraph. As time goes by, *enhanced ICIC* (eICIC) and *Further enhanced ICIC* (FeICIC) are proposed successively. eICIC deals with the heterogeneous network scenario (i.e., macro and small cell). There are two

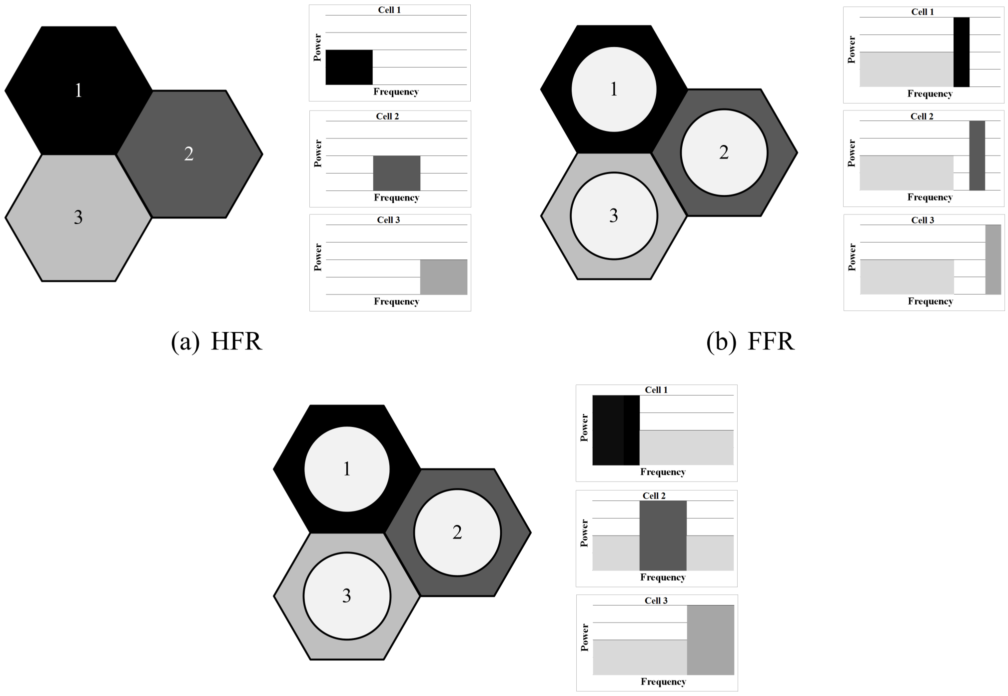
Table 2.1: ICIC Evolution

	ICIC	eICIC	FeICIC
3GPP Release	Release 8	Release 10	Release 11
Domain	Frequency Domain Interleaving	Time Domain Interleaving	Inter-Cell Interference Cancellation
Features	Data Channel Power Control	ABS and CRE	Antenna Processing

methods in eICIC: *Almost Blank Subframe* (ABS) and *Cell Range Extansion* (CRE). ABS is a subframe sent with no data and low-power control signal by macro cell and small cell can send their subframes with data in the same time. Time-domain interleaving is the main idea of ABS. CRE is a marco cell offloading mechanism. A UE is able to connect to small cell with lower signal strength threshold even though that the macro cell signal is more stronger. FeICIC is about interference cancellation and implemented at the UE side [27] [28]. The features are listed in table 2.1. However, time-domain coordination and cancellation design are not compatible with our testbed. Limited by our testbed implementation, the means of our design focus on ICIC approaches.

There are three kinds of frequency reuse: (1) *Hard Frequency Reuse* (HFR), (2) *Fractional Frequency Reuse* (FFR), (3) *Soft Frequency Reuse* (SFR). HFR divides whole spectrum into non-overlapping N parts and sets different frequency sub-band to each adjacency BS. Although avoiding the interference perfectly, HFR is a very inefficient method in using bandwidth and causes poor system throughput. The usage of spectrum in FFR is more efficient. In each cell, the spectrum divided into two regions: cell-center and cell-edge. The edge sub-band in each adjacency cell is strictly non-overlapping. UE can only use the corresponding sub-band by its position. Furthermore, the higher transmitting power is assigned to cell-edge band, which increase signal strength of UE in cell-edge. SFR is similar to FFR, but allows each BS to use the whole spectrum. The edge users is allowed to share sub-band with neighboring BSs. The cell configuration is illustrated in figure 2.1.

Based on frequency reuse schemes, there are many derived issues such as UE classification, adaptive spectrum division and power control. [6] gives the optimal distance ratio of cell-center to cell-edge. However, distance is not an availible parameter in net-



(a) HFR (b) FFR (c) SFR

Figure 2.1: Three Kinds of Frequency Reuse Schemes

work measurement. [42] [21] [22] used one-dimension *Signal-to-Interference-plus-Noise Ratio* (SINR) threshold to classify UE in both FFR and SFR schemes. They give the discussion in SINR threshold choosing. Logistic regression, a well-known classifier, has been used in [38]. The training input parameters are UE's SINR and received power. The higher dimension classifier has more accuracy. The band division of three frequency reuse schemes in above are all fixed. Some of researches take efforts on dynamic partitioning against this static configuration. Dynamic SFR is proposed in [18]. It coordinates BS band configuration through information about affinity between served UEs and sub-band. The edge band can be a discrete partitioning manner. [8] constructs interference graph between UEs, and finds optimal partitioning solution by graph theory. [31] proposed an adaptive SFR algorithm with flexibility in band division and also in transmitting power. In determining power level issue, not only [31], [32] uses Q-Learning, a model-free reinforcement learning technique, to find the optimal or sub-optimal power control value of cell-center power in SFR pattern. Power of cell-edge band is always at maxinum level in Q-Learning SFR [32]. [43] [44] considered the constraint on total power. The total transmitting power of each BS can not exceed the hard restriction. They looked the optimal

SFR power allocation by optimization process. [20] coordinated the power allocation by distributed game theory approach.

There are some others ICIC solution without frequency reuse based method. The algorithm in [45] is a dynamic BS on/off scheme which finds those BSs in serious interference and schedule these small cells to take turns in transmitting their data on each time slot. [24] also proposed a algorithm to turn BS on/off. [9] optimized different traffic type in *Quality of Experience* (QoE) by resource allocation and service scheduling. We discussed more details on QoE issue in section 2.3.

2.2 LTE Resource Block

LTE downlink communication uses the *Orthogonal Frequency Division Multiple Access* (OFDMA) technique. The bandwidth is spiltted into numbers of orthogonal subcarriers. The minimum time and frequency unit, which is called a *Resource Block* (RB), is formed by twelve adjacent sub-carriers and one time slot. With respect to SFR, one third of RBs are assigned to the cell-edge and two thirds for cell-center. Some important properties related to RB are listed below.

- Resource Allocation Type: LTE specification defines the resource allocation type to specify the way in that the BS allocates RB for each transmission [1]. There are three different resource allocation types in LTE: Resource Allocation Type 0, 1, 2. Type 0 is the simplest way of allocation resources. It divides resource blocks consecutively into multiple groups called *Resource Block Group* (RBG). The number of resource block in each group varies depending on the system bandwidth. The resource allocation is done at the level of RBG. In other words, RBG is minimum unit allocated to UE. Type 1 divides RBG into RBG subset in further. Allocation is more adaptive and in discrete way. Type 2 is virtual RB allocation. The allocation in physical may be discrete despite of contiguous allocation in virtual. RB is minimum unit allocated to UE in type 1 and 2.

- Power Factor: the downlink data channel power configuration have the 8 different level, which is defined in 3GPP LTE standard [2]. Transmit power of the data channel to a UE can be boosted or attenuated by $\{-6dB, -4.77dB, -3dB, -1.77dB, 0dB, 1dB, 2dB, 3dB\}$ compared with the reference signal power. Refer to figure 2.2, the tall beams in time slot 0,4,7,11 are reference signal and the most common beams are data channel. In this example, power of data channel is lower than reference signal by $-4.77dB$.

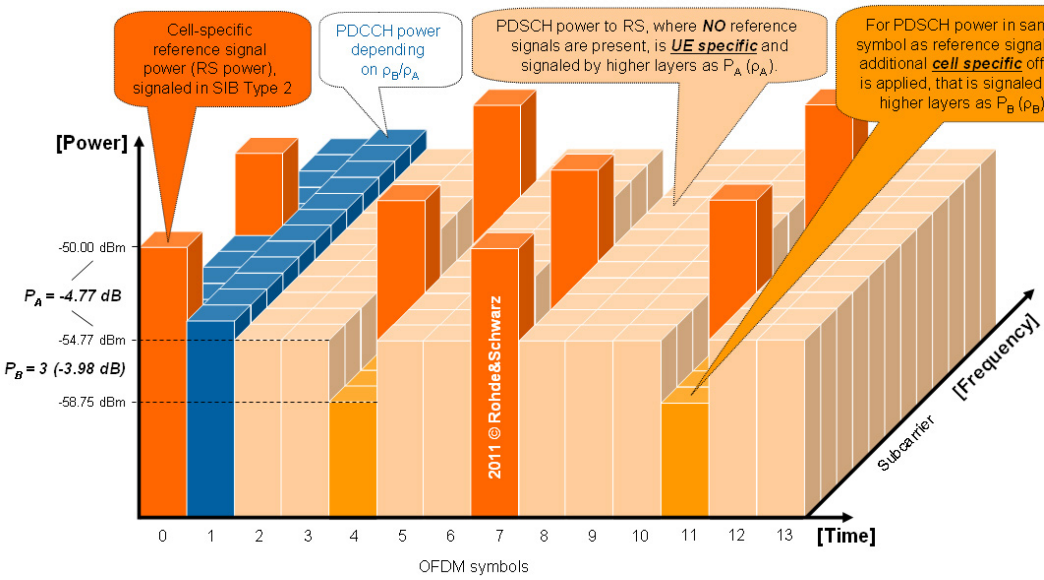


Figure 2.2: Downlink Power configuration of LTE RB [5]

2.3 Dynamic Adaptive Streaming over HTTP

DASH is an adaptive bitrate streaming technique and delivers media content over the Internet through conventional HTTP web servers.Traditional video streaming protocols require dedicated network infrastructure that cannot be used for other web content and have problems on local firewall connetion. Some content providers developed the *Dynamic Adaptive Streaming over HTTP* (DASH) specification with collaboration from 3GPP and others standard groups to replace the old-fashioned ones [36]. In 2011, DASH became as standard specification [4]. With the benefits of firewall friendly and HTTP-based communication, DASH is widely used in commercial development now. In DASH service server, video contents are divided into multiple continuous small segments, encoded into multiple copies with discrete encoding bitrate levels and thus different quality levels. Each segment is assigned a unique URL, an index and duration (typically 1 to 10 seconds). The main concept is that DASH service clients can adaptively request, by HTTP GET, the video segments with proper quality according to the network conditions. Refer to figure 2.3, there are different quality of video segments in DASH server. Also, there are different network link conditions on client A and B, so the demend of segment quality is adaptive according to their dicision policy (i.e., adaptive bitrate algorithm).

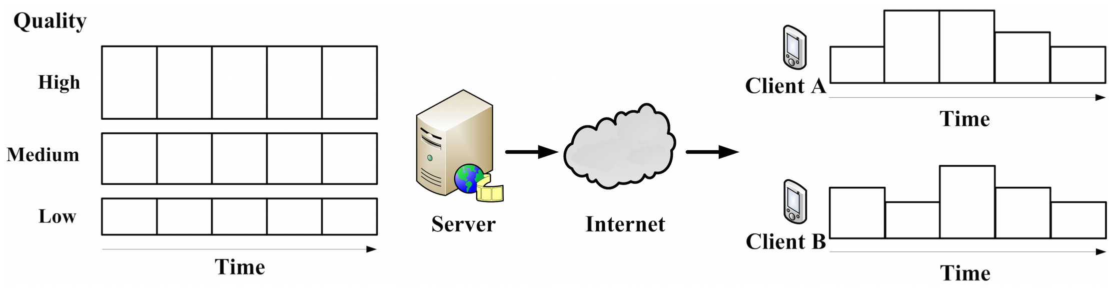


Figure 2.3: DASH Service Architecture: Server and Client

DASH mechanism requires the video to be splited into small segments which contain a short interval of playback time and availiable in different quality level on server side. As a result, how to request next video segment and how to divide segment length are the two design issues on DASH. The former corresponds to *Adaptive Bitrate Algorithm*, and the latter is *Segment Size Division*.

DASH primarily uses a client request paradigm for acquiring video segments from the server. The client measures some parameters such as bandwidth, buffer level and the request the next part of the video. Based on these information, there are many adaptive bitrate algorithm being proposed. Literature findings show that client side adaptive bitrate algorithm development takes two different ways: bandwidth-based and buffer-based. The representatives of the bandwidth approach algorithm are PANDA [23], Elastic [11], and Festive [19]. Accuracy of bandwidth estimation and prediction directly affect the performance of their proposed approaches. Buffer-based approaches, such as BOLA [37] and *T-Y. Huang et al* in [15] [16], avoid the inaccuracy of bandwidth estimation problem. They use client buffer size and remaining space for quality switching instead. Nevertheless of throughput-based or buffer-based algorithm, the selection of DASH client is inferred from the network conditions implicitly. [41] takes UE-side physical information into consideration. Their proposed method, called piStream, is a LTE client-centric video adaptation framework. It enables an LTE client to monitor the physical layer resource utilization status and instantaneously map it to the potential network bandwidth.

Segment is the entity of the response to the DASH client's request. A video content is encoded and divided in multiple segments. The duration of segments can be varied. Small segments (1-3 seconds) can adapt quickly to bandwidth changes and decrease propagation latency, but need more storage because of less efficiency encoding and cause server overloading due to more times of request overhead than large segment (6-10 seconds). It becomes a trade-off between small and large segment. [7], [14] discuss this dynamic varying selection of segment size issue.

Other issues also mentioned in [26]. Different mobile devices such as smart phone and tablet will need different adaptive algorithm to fit their requirement. Network architecture also influenced the traffic routing and data caching. It derived another problem scope called *Mobile Edge Computing* (MEC).

After understanding DASH design issues, we should know two terms (QoE and QoS) about measurement of video streaming service quality first. *Quality of Experience* (QoE) is the quantity of subjective human perception on services. On the contrary, *Quality of Service* QoS is the objective quantity of hardware and software performance. QoE is a comprehensive indicator of user experience on services. The factors that affect QoE are various types of QoS metrics. QoS metrics contain two aspect: *Application QoS* and *Network QoS* [13]. The former is concerned with frame rate, resolution, buffering time, etc. The latter involves jitter, and packet loss, scheduling, etc. There are many works dedicated to finding the correlation between QoE and QoS. Linear regression is a intuitive way to find best fitting function from QoS metrics to QoE score. [17] considered one-to-one mapping. It concluded that packet loss and packet reorder rate are exponential relationship to QoE score, and video bitrate is logarithmic relationship to QoE score. [10] considered multiple QoS parameters: video resolution, initial delay and stall frequency in one OoE score mapping function. Without regression, [40] gave statistical QoE score histograms of different QoS video. [39] uses clustering method. It constructed a high-dimension QoE space in that the axes are different QoS parameters. Each vector can find its representive QoE score by minimum distance adjacency pre-constructed point. [25] proposed a DASH specific utility score function. By conducting a variety of human tests and validation, it concluded out a final correlation between user experience score and four DASH metrics: *initial delay, number of stalls, total stalls duration* and *video quality variation*. At least three papers [33] [35] [34] cited this DASH utility score function in evaluating DASH performance. We also used this DASH utility score function as the improvement indicator in our design.

Chapter 3

LTE Testbed

3.1 LTE Small Cell Testbed Introduction

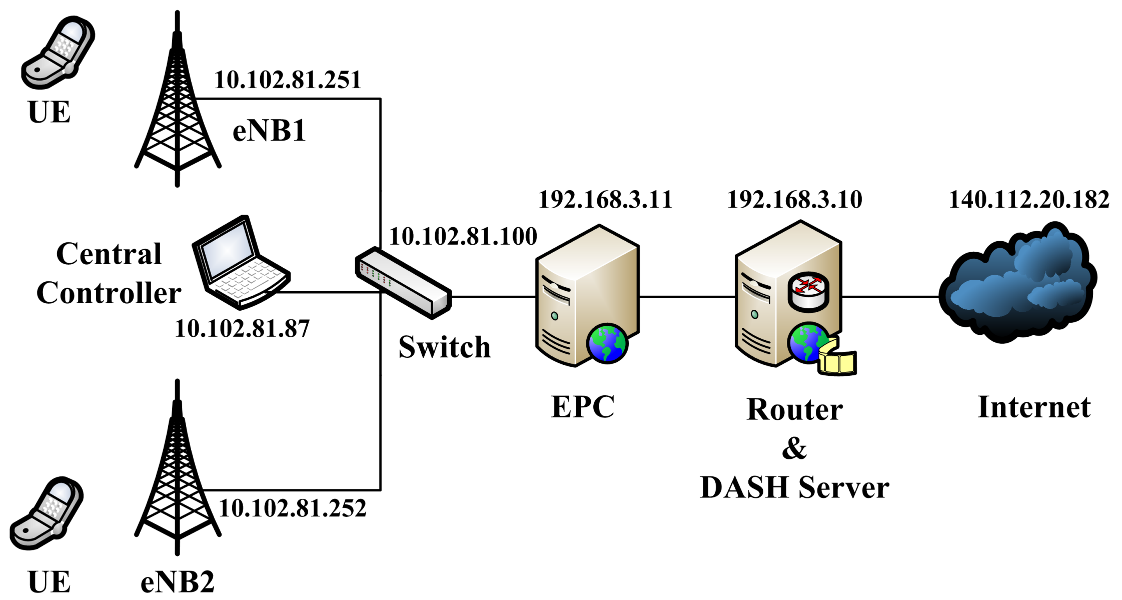


Figure 3.1: Architecture of LTE testbed

As shown in figure 3.1, the testbed includes following elements: (1) LTE small cell, (2) Evolved Packet Core (EPC), (3) Router, (4) UE, (5) Central Controller. The IP addresses of all components are also specified. eNB and EPC are the basic infrastructures in LTE system. Router is a laptop and it plays a role to connect whole system with Internet. Also, the laptop acts as DASH server to wait for requests from DASH clients. Central controller is a notebook to control two eNB's behavior including resource mask and power

Table 3.1: LTE Small Cell Testbed Parameters

Parameters	**Values**
Bandwidth	10 MHz
Number of RBs	50
Resource Allocation Type	Type 0
RBG size	3 RB
Downlink Central Frequency	2.66 GHz
LTE Frequency Band	Band 7
LTE EARFCN	3150
Reference Signal Power	-7 dBm
Cell Distance	5m

configuration. eNB will follow the command from central controller. The command details are drawn in section 3.2. Figure 3.3 show the real snapshots of testbed hardware and software elements.

The testbed parameters are specified in table 3.1. The bandwidth we used in testbed is 10 MHz. Followed by LTE standard [1], it should divided into 50 RBs, and group as RBG every 3 RBs. So, there are 17 RBGs and the last group only contains 2 RBs. Resource allocation type is type 0 which allows the minimum unit of resource allocation is RBG. The downlink central frequency is 2.66 GHz, and the corresponding LTE band number is band 7 and the EARFCN (EUTRA Absolute Radio Frequency Channel Number) is 3150. The maximum power of reference signal is -7 dBm. To resist noise and interference from environment, we set the eNB with this maximum transmitting values. The testbed is installed at our laboratory and the indoor scenario is illustrated in figure 3.2. The length of our lab is 5.5 meters and the width is 3.3 meters. The distance between two eNB is 5 meters. The information about testbed hardware and software are listed in table 3.5. The software *iPerf* is a tool to generate data traffic. The *iPerf* server is installed at UE side and the *iPerf* client is installed at the router laptop with DASH server. The *iPerf* client can generate arbitrary data traffic toward *iPerf* server (UE) and the *iPerf* server will record the data throughput. We use *iPerf* to measure system throughput. The software *NetMonster* is installed at UE side. It can monitor a variety of network metrics such like *RSRP, SNR*. Figure 3.3(d) and 3.3(e) are the screen snapshots of this two software respectively.

3.2 RB Mask and Power Control Command

There are two types of RB mask and power control commands. The first one is **gtkrb-mask** which specifies power control and mask of each RB. The second one is **p_aCfg** which points out UE can get which parts of RB. For example, if there are 10 RBs in the base station and it has two serving UEs: UE 0 and UE 1. The commands refer to 3.1.

gtkrbmask 10 0000777444 (3.1a)

p_aCfg 0 7 (3.1b)

p_aCfg 1 4 (3.1c)

The first argument specifies the command type. The second and third arguments of **gtkrb-mask** command are system RB amount and power control level sequence. The length of power control level sequence is equal to system RB amount and the digits in sequence specify the power control level of each RB. Through the command 3.1a, the data channel power of each RB is 0000777444 respectively. In command **p_aCfg**, the second and third arguments are UE ID and power control level. Refer to command 3.1b and 3.1c, the UE 0 can get the RBs in power level 7 and the UE 1 can get RBs in power level 4. As mentioned in chapter 2, the power level is defined in 3GPP specification. Refer to table 3.2, we listed the power control level and the corresponding exact values when reference signal power is -7 dBm.

Table 3.2: Power control level and its values when reference signal power is -7 dBm

Power Control Level	0	1	2	3	4	5	6	7
Difference with reference signal (dB)	-6	-4.77	-3	-1.77	0	1	2	3
Data Channel Exact Power (dBm)	-13	-11.77	-10	-8.77	-7	-6	-5	-4

3.3 DASH Service

The source codes of DASH service are from DASH.js projects [12]. The video contents are *Big Buck Bunny*. There are two data set we used in experiments. The first one is FHD data set in which the maximum resolution is 1920×1080. The other is 4K data set in which the maximum resolution is 3840×2160. The segment size is 6 and 4 seconds respectively. The quality index of each segment and corresponding video bitrate and resolution is referred to table 3.3 and 3.4. UE can simply use the web browser to request DASH video contents by entering server address. The snapshots of DASH server and client service are referred to figure 3.4. The most important API functions we used are listed as follows.

$$\textbf{setInitialBitrateFor(value)} \tag{3.2a}$$

$$\textbf{setQualityFor(value)} \tag{3.2b}$$

Function 3.2a is used in initial bitrate selection. The client is informed by server-aided to select the bitrate of first segment. Function 3.2b is used when video is playing and client will be informed by server to select video bitrate through this function. It is worth to mention that the arguments are different in two functions. One is *bitrate* and the other is *quality index*. The values of bitrate and quality are all referred to table 3.3 or 3.4.

Table 3.3: [FHD Data set] Quality index and its video bitrate and resolution

Quality Index	**Bitrate (Kbps)**	**Resolution**	**Quality Index**	**Bitrate (Kbps)**	**Resolution**
0	46	320×240	10	780	1280×720
1	89	320×240	11	1024	1280×720
2	128	320×240	12	1229	1280×720
3	177	480×360	13	1536	1280×720
4	218	480×360	14	2150	1920×1080
5	255	480×360	15	2458	1920×1080
6	321	480×360	16	2970	1920×1080
7	374	480×360	17	3379	1920×1080
8	506	854×480	18	3686	1920×1080
9	573	854×480	19	3994	1920×1080

Table 3.4: [4K Data set] Quality index and its video bitrate and resolution

Quality Index	Bitrate (Kbps)	Resolution
0	103	256×144
1	200	320×180
2	238	384×216
3	369	384×216
4	539	512×288
5	733	640×360
6	976	768×432
7	1464	1024×576
8	2247	1280×720
9	2933	1280×720

Quality Index	Bitrate (Kbps)	Resolution
10	4198	1920×1080
11	5644	1920×1080
12	6379	2560×1440
13	6863	2560×1440
14	7348	2560×1440
15	7877	3840×2160
16	11638	3840×2160
17	16372	3840×2160
18	19243	3840×2160

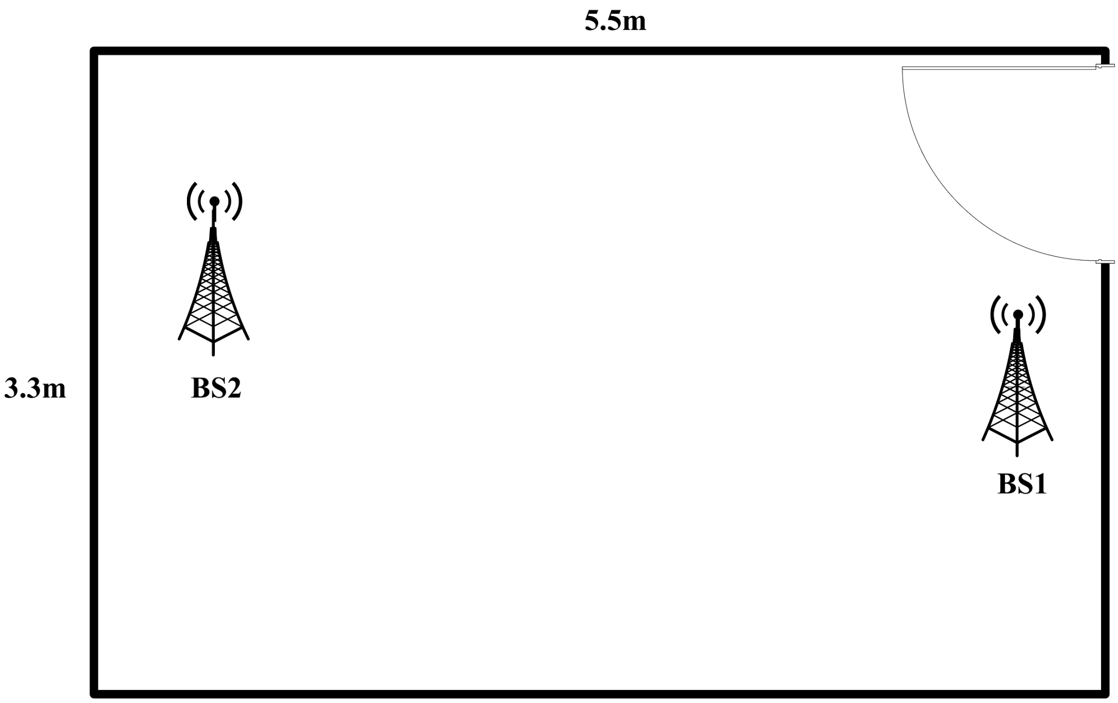


Figure 3.2: Indoor scenario of LTE testbed

(a) LTE Small Cell

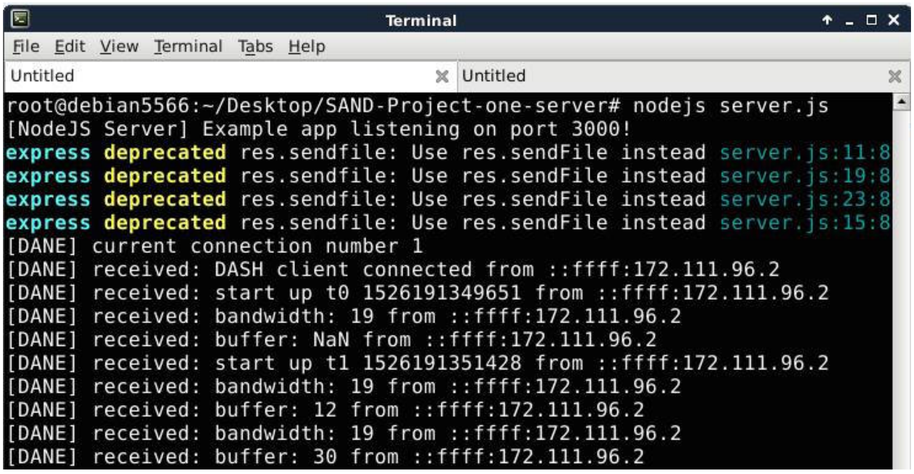
(b) UE (Mobile Phone)

(c) EPC

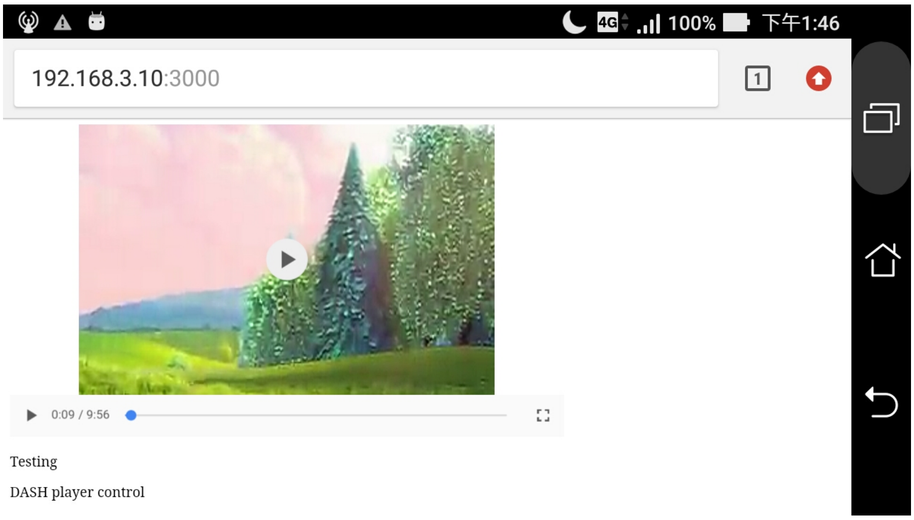
(d) Software iPerf

(e) Software NetMonster

Figure 3.3: Real testbed hardware and software snapshots



(a) DASH server side snapshot



(b) DASH client side snapshot

Figure 3.4: Testbed DASH service

Table 3.5: Hardware and Software Information

Hardware Information		
Name	**Specification**	**Number**
EPC	CPU: Cavium SoC OS: Embedded Linux	1
Small Cell	CPU: Cavium SoC OS: Embedded Linux	2
Mobile Phone	Brand: Asus CPU: Mediatek MT6737T SoC Model: ZenFone Max 3 OS: Android 6.0	6
Router and DASH Server	Brand: Asus CPU: Intel i7-7700HQ Model: GL753 OS: Debian 6.0	1
Central Controller	Brand: Asus CPU: Intel i7-7700HQ Model: GL753 OS: Ubuntu 12.04	1

Software Information		
Name	**Function**	**Version**
Small Cell Firmwire	Small cell used	2.1.1554.756
iPerf	Data traffic generation	2.06
NetMonster	Mobile network monitor	2.1.14

Chapter 4

Utility-Aware DASH Improvement in ICI Environment

Improving DASH utility in ICI environment is the problem considered in this thesis. In problem formulation, the details of DASH utility score function are introduced in first section. Next, we define the system models and control variables about our desired problem in section 4.1.2. After formulation, we proposed our interference management and rate selection strategy to determine system parameters and solve the problem. Section 4.2 and 4.3 describe the interference management and rate selection strategy respectively. The whole approaches include the following steps: band division, power control, interference level classification, resource allocation and server-aided rate selection. In section 4.4, we provide the flowchart to describe the working flow of system. Finally, we applied these methods to improve DASH service with utility-aware in section 4.5.

4.1 Problem Formulation

4.1.1 DASH Utility Function

There are three important factors that impact user-perceived video quality in adaptive video streaming: *initial delay, stalls* and *video quality variation*. The three factors causes the impairment of user experience on DASH service. [25] derived three corresponding impairment score functions and concluded out a integrated utility score function to quantitatively measure user experience on DASH service. The impairment score functions are introduced as follows.

- Impairment of Initial Delay I_{ID}: L_{ID} is the duration of initial delay in seconds and the impairment of initial delay I_{ID} is defined as equation 4.1.

$$I_{ID} = min\{(3.2 \times L_{ID}), 100\} \tag{4.1}$$

- Impairment of Stalls I_{ST}: There are two parts on impairment of stalls. The first is D_{ST}, which indicates the total duration of playback stalls and the second is N_{ST}, which stands for the number of stalls. The impairment of stalls I_{ST} is defined as equation 4.2.

$$I_{ST} = (3.8 \times D_{ST}) + (4.2 \times N_{ST}) - (2.6 \times \sqrt{D_{ST} \times N_{ST}}) \tag{4.2}$$

- Impairment of Quality Variation I_{QV}: There are also two parts on impairment of quality variation. The first one is caused by low quality level and the second one is quality level fluctuations. The P_1 and P_2 stand for this two parts respectively. The impairment of quality variation I_{QV} is defined as equation 4.3.

$$\begin{aligned} I_{QV} &= (75.6 \times P_1) + (48.2 \times P_2) \\ P_1 &= \frac{1}{N}\sum_{s=1}^{N} M_s \times e^{0.02 \times T \times D_s} \\ P_2 &= \frac{1}{N}\sum_{s=1}^{N-1} |M_s - M_{s+1}|^2 \times sign(M_{s+1} - M_s) \end{aligned} \tag{4.3}$$

  where N is the number of transmitted segments during the streaming sessions, T is segment size and D_s means how many continuous segments before segment s have the same level with segment s. The M_s is the *Video Quality Metric* (VQM) values. VQM is widely accepted objective video quality metric, which has been proven to have good correlation with human perception [30] and the VQM value is a number between 0 and 1. A lower VQM value indicates a better video quality and it is a one-to-one mapping from video quality index. The $sign(\cdot)$ function is defined as following equation 4.4.

$$sign(x) = \begin{cases} 1, & x > 0 \\ 0, & \text{otherwise} \end{cases} \tag{4.4}$$

The perfect score of DASH service session is defined as 100 and the final score of a arbitrary DASH service session is deducted by the above three impairment I_{ID}, I_{ST} and I_{QV}. The mathematical expression is as following equation 4.5. All the coefficients in the above functions are applied according to the definition in [25]. We use U_i^k to denote the utility score of DASH UE i in base station k.

$$\text{Score} = 100 - I_{ID} - I_{ST} - I_{QV} \tag{4.5}$$

4.1.2 System Models and Control Variables

The network is a multi-cell deployment topology with inter-cell interference and the UEs demand different traffic. The network consisting of a set of base stations denoted by $\mathbb{K} = \{1, 2, ..., N_{bs}\}$, where N_{bs} is the total number of base station. The total number of UEs in base station k is denoted by N_U^k. We specify the set of DASH users by $\mathbb{D}$. Let P_j^k represent the downlink data channel power of resource unit j in base station k. The number of resource unit in one base station is denoted by N_R. It should be noted that the resource unit is RB or RBG depending on using which resource resource type mentioned in chapter 2. Refer to equation 4.6, R_{ij}^k is defined as a binary variable to specify resource allocation.

$$R_{ij}^k = \begin{cases} 1, & \text{if resource } j \text{ is allocated to UE } i \text{ at base station } k \\ 0, & \text{otherwise} \end{cases} \tag{4.6}$$

The severity of ICI can use *SINR* to evaluate. SINR is defined as the power of desired signal divided by the sum of all the others interference signal and background noise. The SINR for UE i using resource j in base station k is denoted by $SINR_{ij}^{k}$ and can be computed as mathematical equation 4.7.

$$SINR_{ij}^{k} = \begin{cases} \dfrac{P_j^k - L^k(k,i)}{N + \sum\limits_{k' \in \mathbb{K}, k' \neq k} [P_j^{k'} - L^{k'}(k,i)]}, & \text{if } R_{ij}^{k} = 1 \\ \text{meanless}, & \text{if } R_{ij}^{k} = 0 \end{cases} \tag{4.7}$$

where k' is the index of the neighboring base station, N represents the power of the suffering noise per resource unit, and $L^m(k,i)$ means the path loss of radio signal from base station m to UE i in base station k. As a result, $L^k(k,i)$ is the path loss between UE and its serving base station k and $L^{k'}(k,i)$ is the path loss between UE and its adjacency base stations k'. $SINR_{ij}^{k}$ only exists when $R_{ij}^{k} = 1$. If $R_{ij}^{k} = 0$, UE is not allocated with resource unit j. Thus, the SINR on this resource does not exist. By mathematical operation, we re-write equation 4.7 into 4.8.

$$SINR_{ij}^{k} = R_{ij}^{k} \frac{P_j^k - L^k(k,i)}{N + \sum\limits_{k' \in \mathbb{K}, k' \neq k} [P_j^{k'} - L^{k'}(k,i)]} \tag{4.8}$$

Next, the data rate estimation is considered. Shannon capacity is the most popular formula to obtain theoratical data rate in previous works. It calculates UE data rate by the function of sub-bands SINR. However, we take real system implementation in this thesis. In LTE system, the instant data is transmitted with the same coding rate. The coding rate is determined according to the CQI reported from UE. The CQI reported by UE is determined by average SINR of all allocated resource. After realizing the relationship between these indicators, we model the average SINR in first. The calculation of average SINR of UE i in base station k ($SINR_k^i$) is according to equation 4.9. The summation term at denominator is number of resource allocated to UE i.

$$SINR_i^k = \frac{\sum_{j=1}^{N_R} SINR_{ij}^k}{\sum_{j=1}^{N_R} R_{ij}^k} \tag{4.9}$$

Instead of Shannon formula, there are two pratical methods to estimate expected data rate. One is CQI efficiency, and the other is *transport block size* (TBS). When UE selects a certain CQI, its data rate can be estimated by CQI efficiency. CQI efficiency is given by 3GPP in TS36.213, Sect. 7.2.3 [1]. The mapping relation is referred to table 4.1. The calculation of CQI-based data rate is as following equation 4.10.

$$\begin{aligned} &T_c = N_{ra} \times f_R \times \eta_c \\ &\begin{cases} T_c : & \text{UE CQI Data Rate} \\ N_{ra} : & \text{Number of Resources Allocated to UE} \\ f_R : & \text{Frequency Width per Resource (Hz)} \\ \eta_c : & \text{CQI Efficiency (bit/s/Hz)} \end{cases} \end{aligned} \tag{4.10}$$

When base station encodes the transmitting data with a certain MCS, the data rate of UE been served can be estimated by TBS corresponding to the MCS. TBS is defined as how many bits are transferred in 1 millisecond on whole bandwidth. The mapping from MCS to TBS is also given by 3GPP in TS36.213, Sect. 7.1.7.1 [1]. The mapping relation is referred to table 4.2. The calculation of TBS-based data rate is as following equation

4.11.

$$T_t = N_{ra} \times \left(\frac{f_R}{BW}\right) \times S$$

$$\begin{cases} T_t : & \text{UE TBS Data Rate} \\ N_{ra} : & \text{Number of Resource Allocated to UE} \\ f_R : & \text{Frequency Width per Resource (Hz)} \\ BW : & \text{Transmitting Bandwidth} \\ S : & \text{Transfer Block Size, TBS (bit/ms)} \end{cases} \tag{4.11}$$

Table 4.1: CQI and its Efficiency

CQI Index	**Efficiency**(bit/s/Hz)	**CQI Index**	**Efficiency**(bit/s/Hz)
0	0	8	1.9141
1	0.1523	9	2.4063
2	0.2344	10	2.7305
3	0.3770	11	3.3223
4	0.6016	12	3.9023
5	0.8770	13	4.5234
6	1.1758	14	5.1152
7	1.4766	15	5.5547

Table 4.2: MCS and its TBS

MCS	**TBS**(bit/ms)	**MCS**	**TBS**(bit/ms)	**MCS**	**TBS**(bit/ms)
0	2792	10	15840	20	39232
1	3624	11	17568	21	43816
2	4584	12	19848	22	46888
3	5736	13	22920	23	51024
4	7224	14	25456	24	55056
5	8760	15	28336	25	57336
6	10296	16	30576	26	61664
7	12216	17	30576	27	63776
8	14112	18	32856	28	75376
9	15840	19	36696		

T_c is the function depending on N_{ra} and η_c, and T_t is the function depending on N_{ra} and S. Both η_c and S are obtained directly or indirectly from average SINR of UE. To simplify equations 4.10 and 4.11 into one expression, we define a general capacity function $K(\cdot)$ to map average SINR into data rate directly. The capacity function $K(\cdot)$ is an abstract logical interface which can be implemented by CQI-based or MCS-based, or even Shannon formula. Undoubtedly, the capacity function $K(\cdot)$ is a non-decreasing function of $SINR_i^k$. We introduce the notation C_i^k to record the resource capacity of UE i in base station k. The value is assign from capacity function $K(\cdot)$ and written as equation 4.12.

$$C_i^k = K(SINR_i^k) \tag{4.12}$$

In our previous defined notation, N_{ra} can be re-write to the summation form of R_{ij}^k. As a result, the UE expected data rate can be expressed as function of R_{ij}^k and C_i^k. For UE i in base station k, its expected data rate, denoted by T_i^k is carried out as following equation 4.13.

$$T_i^k = \left(\sum_{j=1}^{N_R} R_{ij}^k \right) \times C_i^k \tag{4.13}$$

Improving DASH service in a multi-cell environment with inter-cell interfenece is the problem we are interested. The two aspects in solving this problem are (i) interference management and (ii) server-aided rate selection. The strategies to solve the former are band division and power control. The latter is applied with heuristic determination of video rate and resource allocation by server. The mathematical formulation for our desired problem can be written as follows:

$$T_i^k \geq T_{i,min}^k \qquad \forall k, i \in \mathbb{D} \tag{4.14a}$$

$$\sum_{i=1}^{N_U^k} R_{ij}^k \leq 1 \qquad \forall j, k \tag{4.14b}$$

$$\sum_{i=1}^{N_U^k} \sum_{j=1}^{N_R} R_{ij}^k \leq N_R \qquad \forall k \tag{4.14c}$$

$$R_{ij}^k \in \{0, 1\} \qquad \forall i, j, k \tag{4.14d}$$

$$P_j^k \in \{0, P_{min}, ..., P_{max}\} \qquad \forall j, k \tag{4.14e}$$

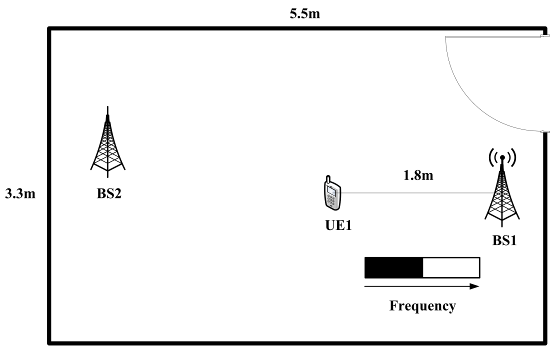
Where the N_U^k stands for the total number of UEs in base station k. The T_i^k is the UE expected data rate which we defined in equation 4.13. The DASH services have minimum bandwidth (data rate) requirement to maintain the streaming quality. In constraint 4.14a, $T_{i,min}^k$ specifies the minimum data rate requirement for UE i in base station k. Only DASH clients have the data rate requirement, so the range of i is in the set of DASH clients $\mathbb{D}$. To ensure that the one resource unit cannot be assigned to more than one user simultaneously within the same base station, equation 4.14b is necessary. Equation 4.14c is also necessary because the resources being used cannot exceed total resources in system. The property of R_{ij}^k is referred to equation 4.6 and maintained by constraint 4.14d. The last expression 4.14e describes the data channel power level can be used of individual resource. As mentioned in chapter 2, there are several power level can used. In problem modeling, the set of power level is denoted by $\{0, P_{min}, ..., P_{max}\}$ in which the P_{min} means the lowest level of transmitting power and the P_{max} is the highest level.

We use DASH utility function as optimization goal in problem formulation. However, we have no direct formula to map network parameters into DASH utility. Also, the problem model is mixed with continuous data rate function and discrete integer desicion variables. Nobody would want to exhausitively test all feasible combinations to find the optimal solution. We will describe the methods and heuristic algorithm to determine these values in following two sections.

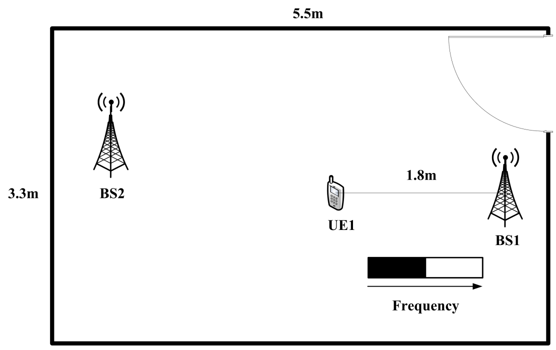
4.2 Interference Management

4.2.1 Band Division and Power Control

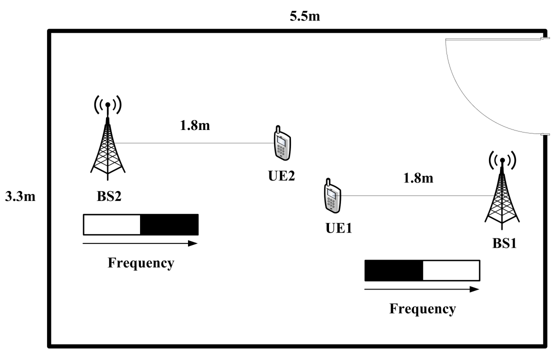
The use of FFR leads to tradeoffs between improvement in region throughput, coverage for cell-edge UEs and spectrum efficiency comparing to SFR. Refer to the simulation result from [29], it claimed FFR provided the greater overall system throughput and higher cell-edge user SINR than SFR. In real system, however, the control and reference signals exist in whole bandwidth. It means the fractional division of cell edge band is only in data channel. The control and reference signals cannot be perfectly mute. Although the FFR pattern is applied, the interference from adjacency control and reference signals still exist. We conducted 4 throughput experiments to show the effect of band interleaving, band collision and interference from control and reference signal. The figure 4.1 shows the scenario we tested and the table 4.3 is the throughput results.



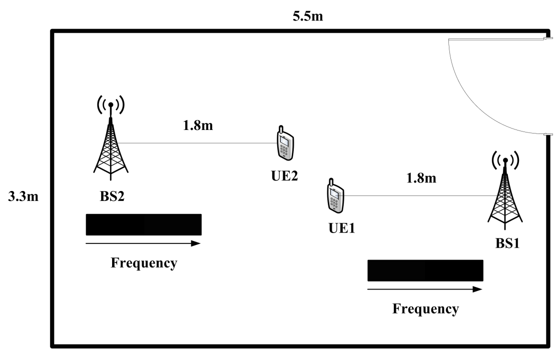
(a) BS1: Using first half band and serving UE1; BS2: Turn-off



(b) BS1: Using first half band and serving UE1; BS2: Turn-on but serving no UE



(c) BS1: Using first half band and serving UE1; BS2: Using second half band and serving UE2



(d) BS1: Using full bandwidth and serving UE1; BS2: Using full bandwidth and serving UE2

Figure 4.1: The four experiments of band division throughput testing

Table 4.3: Throughput results and interference types of the four band division experiments

Experiment	Throughput of BS1	Throughput of BS2	Control and Reference Signal Interference	Data Channel Interference
a	25.1 Mbps	N/A	×	×
b	18.9 Mbps	N/A	✓	×
c	18.7 Mbps	17.9 Mbps	✓	×
d	26.7 Mbps	26.1 Mbps	✓	✓

Comparing experiment 4.1(a) and 4.1(b), we can know the control and reference signal from adjancency base station reduce the system throughput from 25.1Mbps into 18.9Mbps. Both throughputs of BS1 and BS2 in experiment 4.1(c) are in the same level comparing to 4.1(b). The band interleaving is useful in anti-interference. However, if base station only uses the non-overlapping parts of band, the overall throughput is no higher than band overlapping. This phenomenon can be observed by comparing experiment 4.1(c) and 4.1(d). In experiment 4.1(d), throughput of BS1 has 42.9% enhancement and throughput of BS2 has 45.8% enhancement than 4.1(c). Twice of resources are used by each base station, but the throughputs only increase about half than non-overlapping scheme. However, the higher of overall throughput is what we want. Non-overlapping scheme will restrict the system throughput in a certain order. Despite that non-overlapping between base stations has better resource efficiency, but the bandwidth efficiency and overall throughput are worse than overlapping scheme.

Both HFR and FFR do not fully use bandwidth, and only SFR uses full bandwidth in configuration. Based on the experiment result, we use SFR-based band division instead of FFR-based to enhance the system throughput and bandwidth efficiency. However, when a UE in cell-center is nearly close to cell-edge, the UE will have poor performance in traditional SFR scheme. As a result, we introduce a new kind of region: *cell-middle* to handle this problem. Each base station reserves three region for cell-center, cell-middle and cell-edge UE respectively. The cell-middle region is partitioned from cell-center in origin SFR. The band division of *middle enhancement* (ME) scheme in standard multi-cell topology is illustrated in figure 4.2.

In SFR scheme, the cell-center band is configured with the lowest power level (P_{min}) and the cell-edge band is configured with the highest power level (P_{max}). In our design,

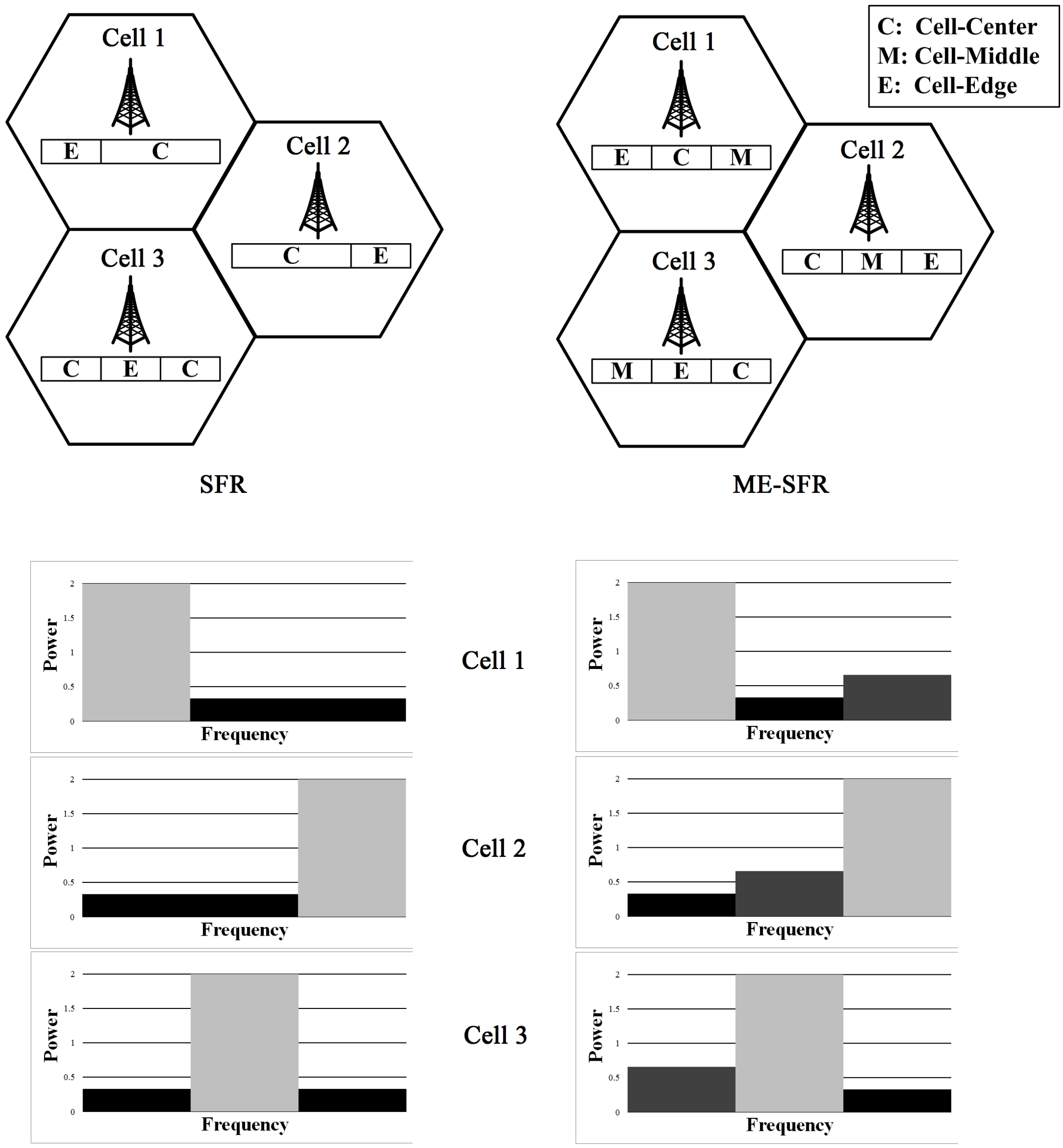


Figure 4.2: Band Division and Power Control Comparison of SFR and ME-SFR

there is a new class: cell-middle. The signal power for UEs in cell-middle should be enhanced in order to have better quality of signal. However, maintaining the whole system stability and interference is also important. As a result, the cell-middle band is assigned with the power in middle level (P_{mid}) between P_{min} and P_{max}. The given mathematical expression is as follows.

$$P_j^k = \begin{cases} P_{max}, & \text{if } R_{ij}^k = 1 \wedge \text{UE } i \text{ in base station } k \text{ is cell-edge UE} \\ P_{mid}, & \text{if } R_{ij}^k = 1 \wedge \text{UE } i \text{ in base station } k \text{ is cell-middle UE} \\ P_{min}, & \text{if } R_{ij}^k = 1 \wedge \text{UE } i \text{ in base station } k \text{ is cell-center UE} \\ 0, & \text{if } R_{ij}^k = 0 \end{cases} \tag{4.15}$$

Here we combine the previous defined notation R_{ij}^k into the expression. In base station k, $R_{ij}^k = 1$ means the UE i is allocated with resource j. Therefore, the data channel power is 0 when resource j does not allocate to any UE (i.e., $R_{ij}^k = 0$). When resource j allocate to the UE i (i.e., $R_{ij}^k = 1$), the data channel power of resource j (P_j^k) is determined by the class of the UE i.

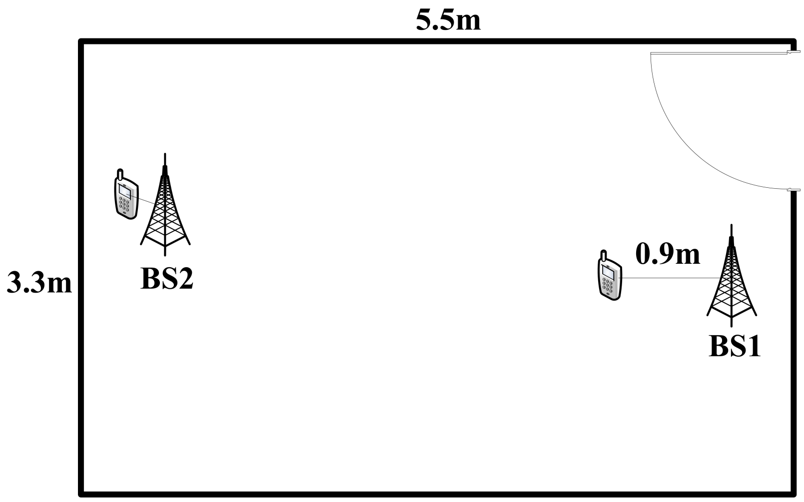
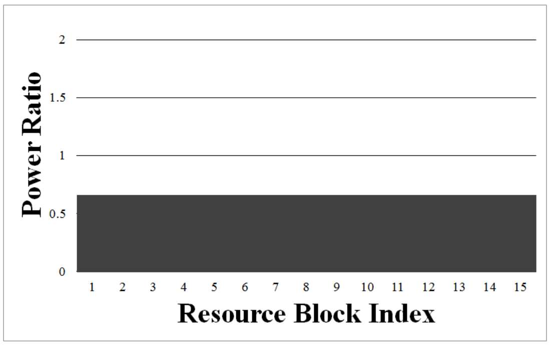


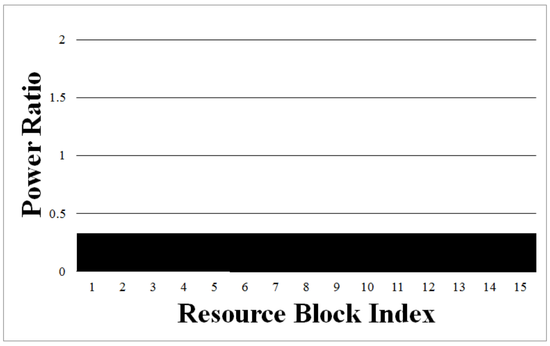
Figure 4.3: Middle UE Experiment Scenario: a middle UE located in base station 1 suffers interference from base station 2

We conducted experiments to show the effect of middle power enhancement. Figure 4.3 is the experiment scenario. There is a middle UE in the base station 1 and the UE suffer the interference from the base station 2. The two different power control values are applied to the middle UE. The power enhancement corresponds to the notation P_{mid} and the power in lowest level corresponds to the notation P_{min}. In testbed setting, the lowest data channel power P_{min} is -13 dBm and the highest data channel power P_{max} is -4 dBm.

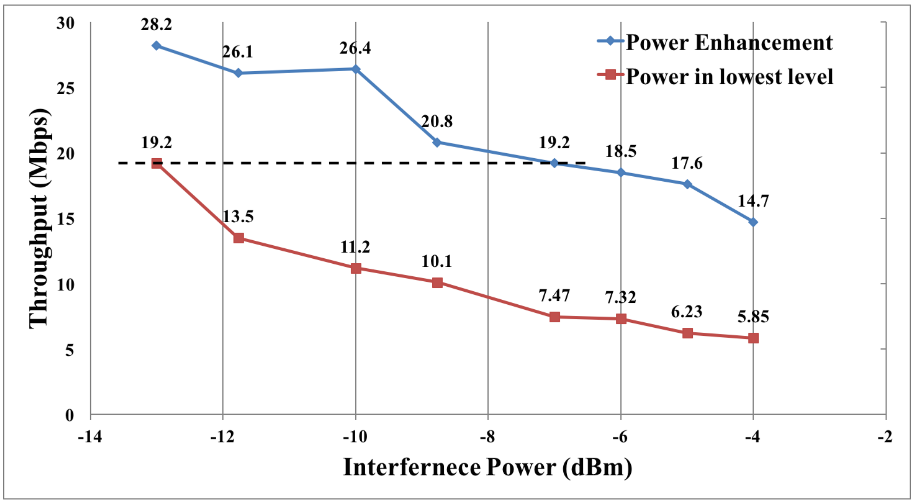
In experiment, the value we set for P_{mid} is -8.77 dBm. We tested the throughput of middle UE from low interference to high in two power control values. The power configurations are in figure 4.4(a) and 4.4(b) and the throughput results are in figure 4.4(c).



(a) Power enhancement



(b) Power in lowest level



(c) Throughput versus Interference Power

Figure 4.4: Middle UE Experiment Results: power configurations and throughput results

As figure 4.4(c) shown, middle UE with power enhancement has better throughput in every interference cases. In two base stations deployment, there are two kinds of power control values: P_{min} and P_{max} in SFR scheme, and there kinds of power control values: P_{min}, P_{mid} and P_{max} in ME-SFR scheme. When the middle power enhanced, the system interference is also enhanced. The dashed line describes the best throughput case of the UE in SFR scheme. It beats ME-SFR only when the UE suffering from P_{max} interference. As a result, our design of band division and power control will avoid this situation. In two base station scenario, the middle UE will never suffer from the highest power of interference. In general multi-cell deployment case, our design also avoid the enhancement of interference.

The details are described in section 4.2.3.

4.2.2 Interference Level Classification

In frequency reuse scheme, the UE resource allocation and power usage are determined by the position of UE. In previous literature, SINR, received power or even distance are the indicators being used to classify UE. In simulation level, the distance is definitely the best indicator to classify UE, but, in real system, there is no distance measurement. We only can use the available parameters in system. SINR is not defined in the 3GPP specifications but defined by the UE chipset vendors. In general, all quantities in SINR formula are measured over the whole bandwidth and normalized to one average value. As a result, SINR is a good indicator of distance when the deployment of cell is single reuse factor, which means that the sub-bands are suffer the interference from the same frequency set of adjacency base stations. However, the SINR to distance relationship starts to fail when band division for cell-center and cell-edge within the same cell. Due to the power control employed, the different sub-band may suffer from different level of interference. The wideband SINR measurement manner has poor classification result in frequency reuse schemes [38]. *Reference Symbol Received Power* (RSRP) is defined as the linear average over the power contributions of the resource elements that carry cell-specific reference signals within the considered measurement frequency bandwidth. It is usually used as the handover decision to target base station or not. UE will measure RSRP to the base stations in neighbor and report to LTE *Self-Organizing Network* (SON) server. When RSRP from the target base station is stronger than the serving base station for a certain period, the LTE SON server will trigger handover procedure to make UE hand over to the target base station. RSRP value can directly be seen as how close between UE and base station and the LTE SON server records all RSRP measurement informations. Both of the characteristics motivate us to propose the RSRP-based interference level classification method. All UEs are classified as cell-center UE, cell-middle UE, or cell-edge UE by their RSRP value. We give the mathematical expression as follows.

$$\text{UE is in} \begin{cases} \text{cell-edge,} & \text{if } RSRP_i - RSRP_j < I_E \\ \text{cell-middle,} & \text{if } RSRP_i - RSRP_j > I_E, RSRP_i < I_M \\ \text{cell-center,} & \text{if } RSRP_i - RSRP_j > I_E, RSRP_i > I_M \end{cases} \tag{4.16}$$

For a UE, if the difference between RSRP from the serving base station i ($RSRP_i$) and RSRP from the neighboring base station j ($RSRP_j$) is lower than the edge threshold (I_E), the UE will be classified as a cell-edge UE. If the UE is not a cell-edge UE (i.e., $RSRP_i - RSRP_j > I_E$), $RSRP_i$ will be compared with the middle threshold (I_M). When $RSRP_i$ is lower than I_M, the UE is classified as cell-middle UE. Otherwise, it is cell-center UE. The schematic diagram is referred to figure 4.5.

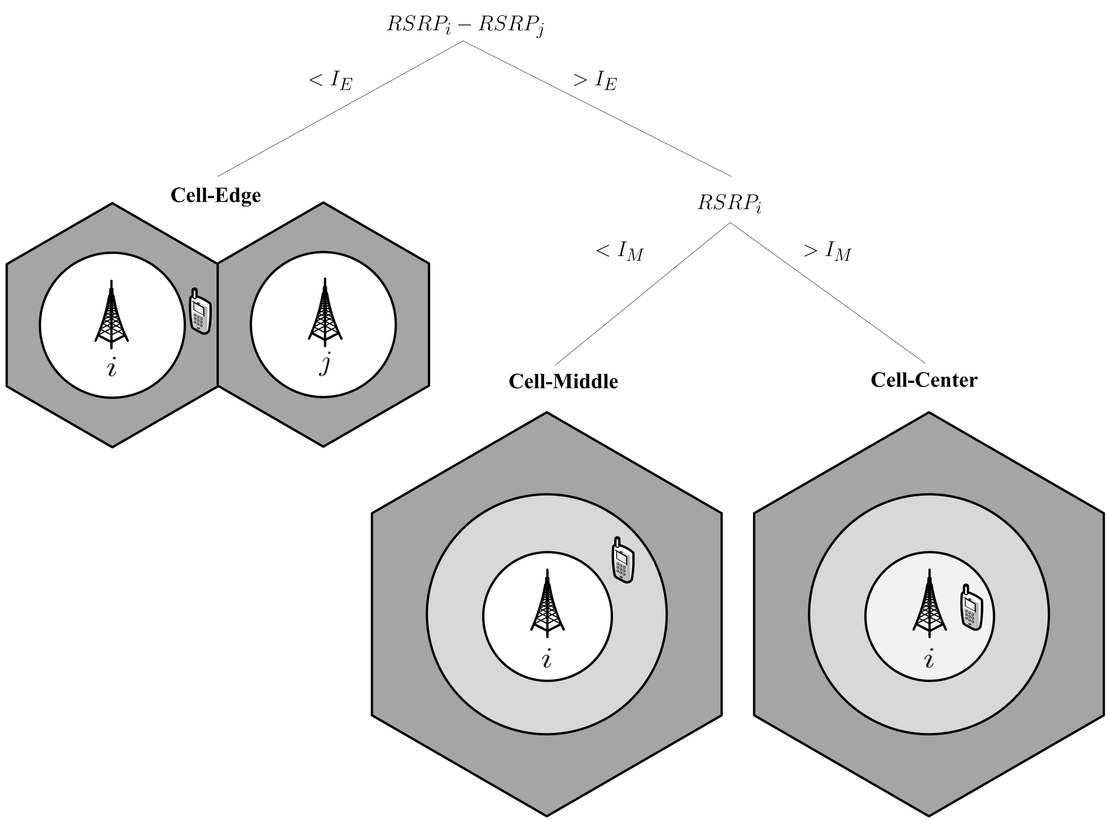


Figure 4.5: RSRP-Based Interference Level Classification

4.2.3 Exception Handling

When there are three kinds of UE in a certain cell, each kinds of UE only can use the reserved band. However, when there exists the missing UE class in a certain cell, the band planning should adaptively adjust. There are 6 combinations of class missing and we list that in table 4.4.

Table 4.4: Six situations of UE class missing in a certain cell

Situations	Center	Middle	Edge	Description
(a)	✓	×	×	only center, missing middle and edge
(b)	✓	✓	×	only center and middle, missing edge
(c)	✓	×	✓	only center and edge, missing middle
(d)	×	✓	×	only middle, missing center and edge
(e)	×	×	✓	only edge, missing center and middle
(f)	×	✓	✓	only middle and edge, missing center

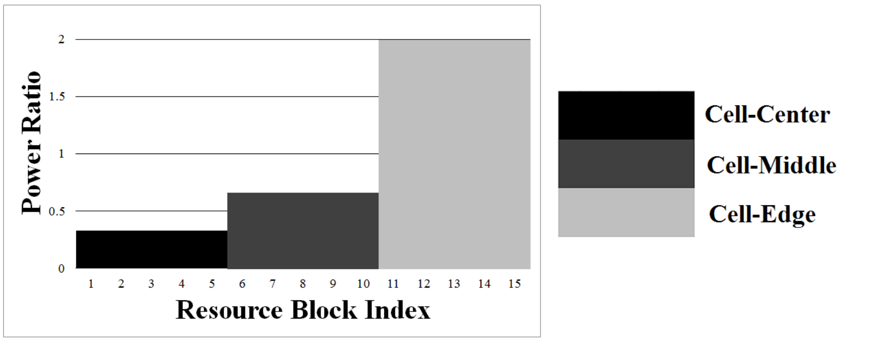


Figure 4.6: Band division and power level example of origin ME-SFR in a certain cell

To handle the 6 situations, the criteria of cell planning is *reducing the transimming power* to avoid causing interference to other cells. We give an example to explain the cell planning. The origin cell configuration without missing class is referred to figure 4.6. When only cell-center UEs exist, they can use the whole bandwidth (figure 4.7(a)). When there are only cell-center and cell-middle UE, the origin cell-edge band is reserved to cell-middle UEs and the origin cell-middle band is shared by cell-center and cell-middle UEs (figure 4.7(b)). The power depends on class of the using UE. When there are only cell-center and cell-edge UEs, the situation degrades to SFR pattern (figure 4.7(c)), the origin cell-middle band is allocated to cell-center UEs. Situations (a)-(c) can be perfectly solved by above re-planning method. Situations (d)-(f) can be seen as extreme cases that

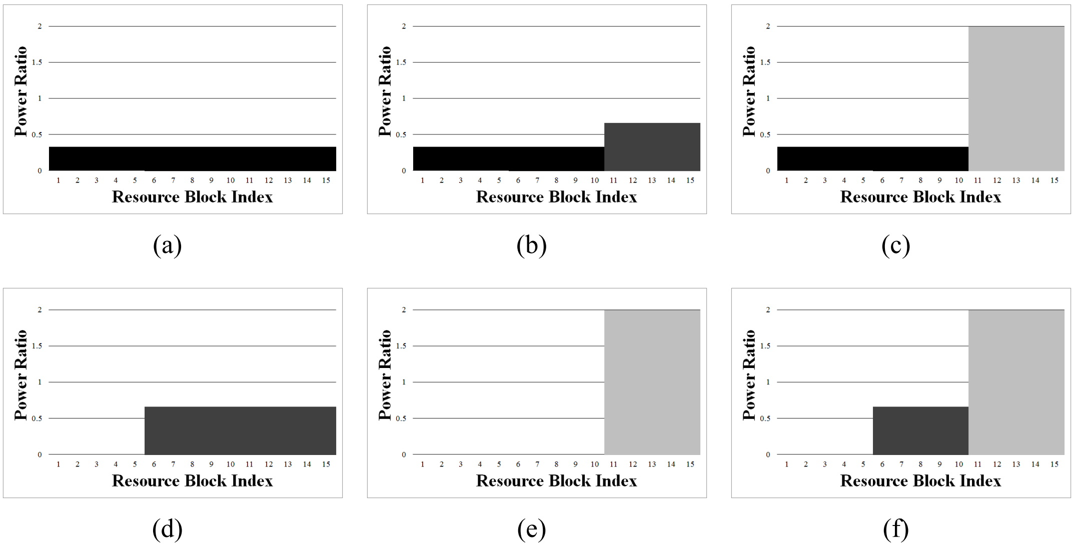


Figure 4.7: Band division and power level of the six UE class missing situations in a certain cell

UEs distribute only on cell-middle and/or cell-edge. To control system interference, the cell-center band is suspended for these three situations in which the base station cannot use whole band to transmit data. When only cell-middle UEs exist, the origin cell-edge band is aggregated to cell-middle band (figure 4.7(d)). Figure 4.7(e), 4.7(f) show the cell planning for situations (e) and (f) respectively. The planning strategy follow the criteria we mentioned above. The power comsumption of these 6 cases of class missing are lower than origin no-missing case (figure 4.6), that is to say, the origin no UE class missing case will cause the most interference to other cells.

4.3 Resource Allocation and Rate Selection

4.3.1 Resource Allocation

Through the above steps, the UE are allocated with the deterministic power and frequency band. This section is going to discuss the amount of resources allocated to UE. Although the interference is mitigated through band division and power control, the UEs in network still suffer from interference. Each UE has its channel conditions. To satisfy UE requirement in different channel conditions, the amount of resources is adaptively allocated to the UE based on its interference level. The adaptive resource allocation means the UE in poor channel conditions should be allocated with more resources to maintain its performance, which is referred to constraint 4.14a. Because the band division and power control are done in advance, the signals and interferences are in control already. As a result, the SINR of all resources are also in control and do not change severely. Through substituting equation 4.13 into constraint 4.14a and moving the resource capacity C_i^k to the right of the equal sign, the amount of resources allocated to the UE can be determined by equation 4.17.

$$\sum_{j=1}^{N_R} R_{ij}^k \geq \frac{T_{i,min}^k}{C_i^k} \tag{4.17}$$

$T_{i,min}^k$ means the minimum data rate requirement of a UE. When the user request a high definition video segment, the value of $T_{i,min}^k$ should be higher than the user whose request is standard definition. As a result, once the UE minimum data rate requirement is determined, the required resource amount can be calculated through this equation.

The minimum data rate requirement $T_{i,min}^k$ is determined by what level of video does a user want. However, when a user is in bad channel conditions, it results in low resource capacity. If the UE still requests high definition video chunks, the required amount of radio resources will very high. This is not a situation that the system can tolerate. In previous section, we regulate each class of UE can only be allocated the resources in corresponding band division. The resource allocation cannot exceed the upper bound. Even with the maximum amount of resource allocation, if the UE does not request a lower quality level of video segments, it will still have poor experience caused by frequent stalls and tremendous buffering time.

As a result, the resource allocation and the video quality should be jointly considered in the viewpoint of the system designer. We proceed the determination of quality selection and the resource amount for a certain DASH client in next section and propose as an algorithm finally.

4.3.2 Server-Aided Rate Selection

In this section, we will describe our rate selection procedure and final algorithm of resource allocation and quality selection. Our approach is a server-aided selection mechanism. It will trigger in two situations: (a) when the user starts requesting video segment; (b) when base stations configuration (band division and power control) change, which is because when configuration changes, the channel conditions will also have a larger change. The one of the input to our algorithm is initialized quality. The determination of initialized quality is different in above two cases. In case (a), when user starts DASH service, the initialized quality is the quality of first video segment which is an empirical determined value according to the user aspiration or server default setting. If user requests a specific quality level, our server-aided selection algorithm will try its best to satisfy this requirement. Otherwise, if user does not specify the quality, server will assign an empirical quality level to user by its position class. In case (b), when base stations configuration change, the server should help users select video quality. The server would compare the quality level of previous segment and the empirical quality level according to its position class. The higher one would be the input to our algorithm. The empirical quality requirement is based on the position class of UE, but UE has the right to request the desired quality. We reserve the flexibility on quality demand. Also, [26] pointed out that the frequency of adaption should be kept small to maintain the user experience. As a result, the server-aided selection procedure will trigger when base station configuration changing and origin adaptive mechanism run in other duration of the video playback.

Table 4.5: Quality index and its video bitrate

Quality Index q	Video Bitrate (Kbps)	Quality Index q	Video Bitrate (Kbps)
0	46	10	780
1	89	11	1024
2	128	12	1229
3	177	13	1536
4	218	14	2150
5	255	15	2458
6	321	16	2970
7	374	17	3379
8	506	18	3686
9	573	19	3994

Now, we give the quantitive expression between quality and data rate. Video segments are encoded with different bitrate and stored in server. We use the quality level index q to specify the bitrate from low to high. The index q and its corresponding video bitrate mapping is as table 4.5. For each quality level q of the video segment, it has a minimum data rate requirement to be downloaded in time for playing. We use the bandwidth mapping function $B(\cdot)$ to denote the mapping from video quality level to its data rate (bandwidth) requirement. $B(\cdot)$ is the quantinized bandwidth mapping function and specifies a series of bandwidth data rate values. The higher index of $B(\cdot)$ corresponds to the higher data rate. In other words, for an arbitrary quality level q, the minimum data rate requirement can be obtained by the bandwidth mapping function $B(q)$. Besides, when minimum data rate requirement is determined, the required resource amount can also be determined by equation 4.17. DASH users have the priority to access resources. However, a user cannot be allocated with unlimited amount of resources. We regulate the resource upper bound. When resource is not enough, we would level down quality. The whole mechanism of access priority and dynamic quality down is the concept of *proportional fairness*. We proposed the following algorithm to jointly determine the resource allocation and the video quality.

Algorithm 1: Determine quality selection and resource allocation

Input : Input Quality Index q_{in}
Resource Capacity C_i^k

Output: Data Rate Requirement $T_{i,min}^k$
Required Resource Amount R
Quality Selection q_{out}

$R \leftarrow N_R$
$q \leftarrow q_{in}$
while $R > R_{up}$ **do**
  $R \leftarrow \lceil B(q)/C_i^k \rceil$
  $q \leftarrow q - 1$
end
$q_{out} \leftarrow q + 1$
$T_{i,min}^k \leftarrow B(q_{out})$
Update R_{up}
return $T_{i,min}^k, R, q_{out}$

In algorithm 1, the q_{in} is the input to point out the initial quality index. The value might be request from user, server default assigned or inheritance from previous segment. Our algorithm will try the best effort to satisfy this requirement. In algorithm first, the required resource amount is initialized as total system resource amount N_R to keep algorithm proceeding. In while loop, the amount of resources in specified quality requirement is calculated at forth line which is related to equation 4.17. $B(\cdot)$ is quality to bandwidth mapping function and $B(q)$ meams the empirical bandwidth requirement. $C(\cdot)$ is resource capacity function. The purpose of ceiling function is to make the amount of resource be an integer. R_{up} means the available resources in partitioned band and acts as the upper bound of resources amount. The while loop will check the calculated result. If the required resource amount R exceed R_{up}, the quality should level down (fifth line in algorithm) until a feasible solution been found. When exiting the while loop, the appropriate quality index is found and the data rate requirement for DASH client $T^k_{i,min}$ is assigned with $B(q)$. The nineth line updates the upper bound to remaining amount of resources. Finally, the algorithm will return the required resource amount R, the appropriate quality index q_{out} of the video and the minimum data rate requirement $T^k_{i,min}$.

4.4 Flowchart of Cross-layer Approaches

Figure 4.8 decribes the whole working flow of our cross-layer design. In the beginning, the UEs in system are classified into different interference levels. Next, the band division and power control of base stations will be configured according to the UE interference level class. The physical interference management flows are done and correspond to the part above the dash line in figure 4.8. Below the dash line, the application layer rate selection procedure is served. Server will determine the video quality selection and resource allocation amount of each UE. Last, if there is any UE leave or join, the system will loop to the beginning and re-configure. If no any change, the system will keep consistent.

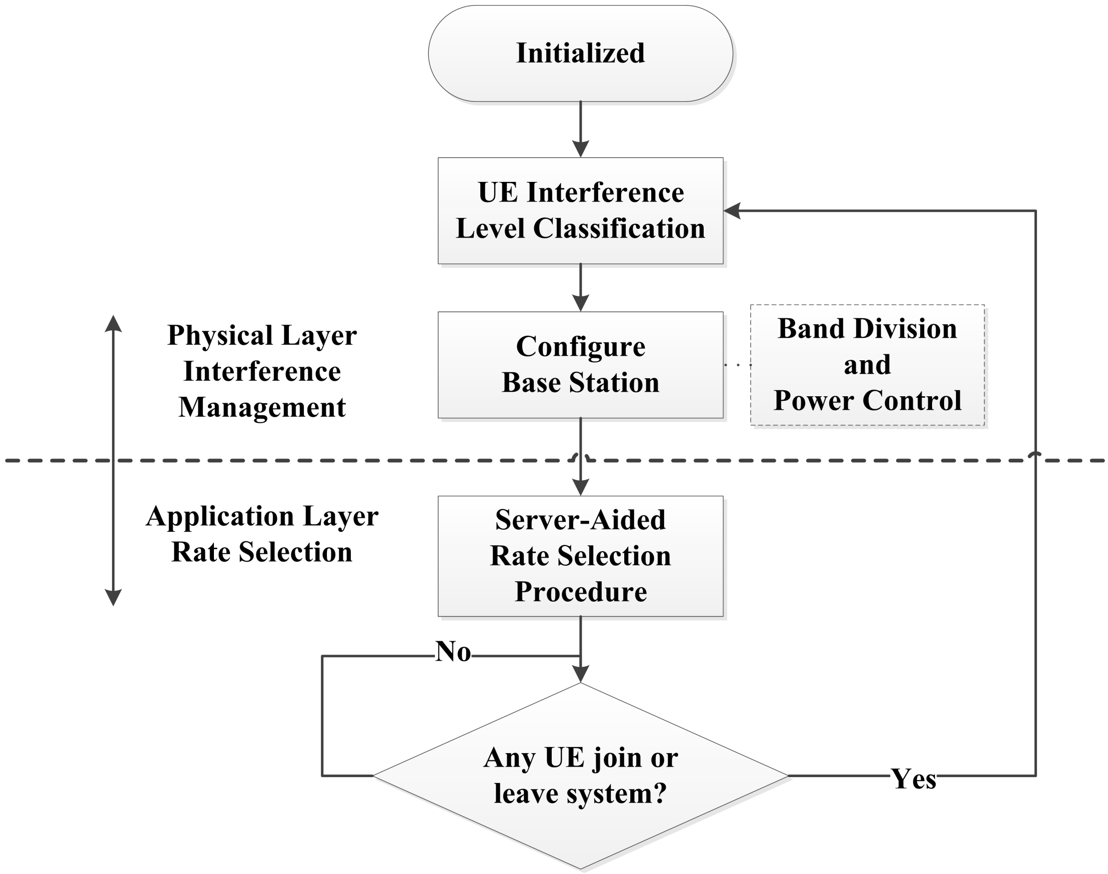


Figure 4.8: Flowchart of cross-layer approaches

4.5 Utility-Aware DASH Improvement Procedure

$$max \sum_{\forall k,i} U_i^k \tag{4.18}$$

Referred to equation 4.18, to maximize the utility score of all DASH UEs is the ultimate goal. As mentioned above, there is no direct mapping of network parameters to DASH utility. As a result, it cannot find a analytic solution to maximize DASH utility function. In this section, we applied our methods to observe the improvement of the three impairments in DASH utility function, which is called utility-aware DASH improvement procedure. It is also a way to find the sub-optimal solution of the max-utility optimization problem. In previous two sub-sections, we proposed several methods to deal with the interference and DASH rate selection. Corresponding to the title of two sub-sections, our method can be categorized as two parts: interference management and rate selection. Furthermore, there are two cases to trigger rate selection: (a) clients initial request and

(b) base stations configuration change. In summary, interference management, rate selection case (a) and rate selection case (b) are the three means we applied to improve the impairment functions in DASH utility, and we gave discussions in following sections.

4.5.1 Initial Delay Improvement

Initial delay is caused by *network latency* and *download time*. The *download time* is in our interesting. In our problem scope, the quality of first segment will impact the initial delay. Given a fixed bandwidth, the following experiments are conducted to observe the relationship between quality and initial delay. The experiments are conducted with one UE in interference-free environment to make sure no other variable factors. The given data bandwidth for UE is 1.98 Mbps. The three different quality segments: $0, 10, 19$ are sent for UE in initial. The results are as following table 4.6.

Table 4.6: Three different initial quality values and its initial delay

Initial Quality	0	10	19
Five Tests of Initial Delay (sec)	1.092	1.849	1.824
	1.290	1.468	2.004
	1.175	1.670	2.186
	1.132	1.297	2.113
	1.200	1.724	1.901
Average (sec)	1.178	1.602	2.006

The experiments showed the higher of first segment's quality leads to longer initial delay. However, low quality will cause utility deduction in I_{QV} term. As a result, a proper quality to maintain the utility and tolerable initial delay is important to be selected. It should also consider the resource allocation to provide client with enough resources. The situation totally corresponds to the case (a): *client initial request* in our server-aided rate selection and resource allocation procedure. Instead of sniffering channel conditions and reaching the full resource utilization adaptively by client itself, our server-aided video rate selection and resource allocation procedure will trigger to help client. According to the interference coordination result, clients are classified to center, middle or edge. The algorithm 1 is initialized with different quality index respectively and output the final computing results including resource allocation amount and selected quality. Also, our server-aided video rate selection and resource allocation procedure will saturate the channel bandwidth perfectly. By handling the resource allocation, the algorithm 1 can select the most proper video rate to achieve full utilization of resource bandwidth and send the first segment with this best quality to maximize the DASH utility objective function.

4.5.2 Stall and Quality Variation Improvement

Stall in streaming is caused by the empty buffer. When video segments can not be downloaded in time, the buffer will be empty. Allocate enough resource and make UE download in time are the key to avoid stall. Quality variation has two parts to cause utility deduction: (1) Low Quality Level, (2) Quality Fluctuation. The following experiments are conducted to show the stall and quality variation. The scenario is referred to figure 4.9. There is a UE in base station 1 requesting DASH service and a UE in base station 2 acting as interference source. When the DASH UE starts to request video segment, the given resource block amount for it in initial is 3 and the given data bandwidth is 1.94 Mbps. After 10 seconds, the UE in base station 2 starts receive data. As a result, the data rate of DASH levels down to 0.96 Mbps due to the interference from base station 2. Both the data channel transmitting power in base station are -4 dBm. That is to say, the signal power and interference power for DASH UE are both -4 dBm.

The dash lines in figure 4.10 specify the time of interference occurence. Figure 4.10(a) showed that if video quality maintained invariance, the playback will stall because of the insufficient data bandwidth. To prevent stall, figure 4.10(b) showed that the video would level down to bad quality when interference occured. By our server-aided rate selection and resource allocation approach, server allocated 6 resource blocks to UE instead of 3 in order to maintain the quality in the same level (i.e., 13) when interference occured. Furthermore, the data rate after resource allocation is 2.15 Mbps. We maintain the UE acquisition of resources to prevent stall and quality variation. Figure 4.10(c) showed the time traces of buffer size and quality results.

The unstable channel conditions are the main reason to make UE suffer from stall and quality variation. Stall and quality variation improvement correspond to the two strate-

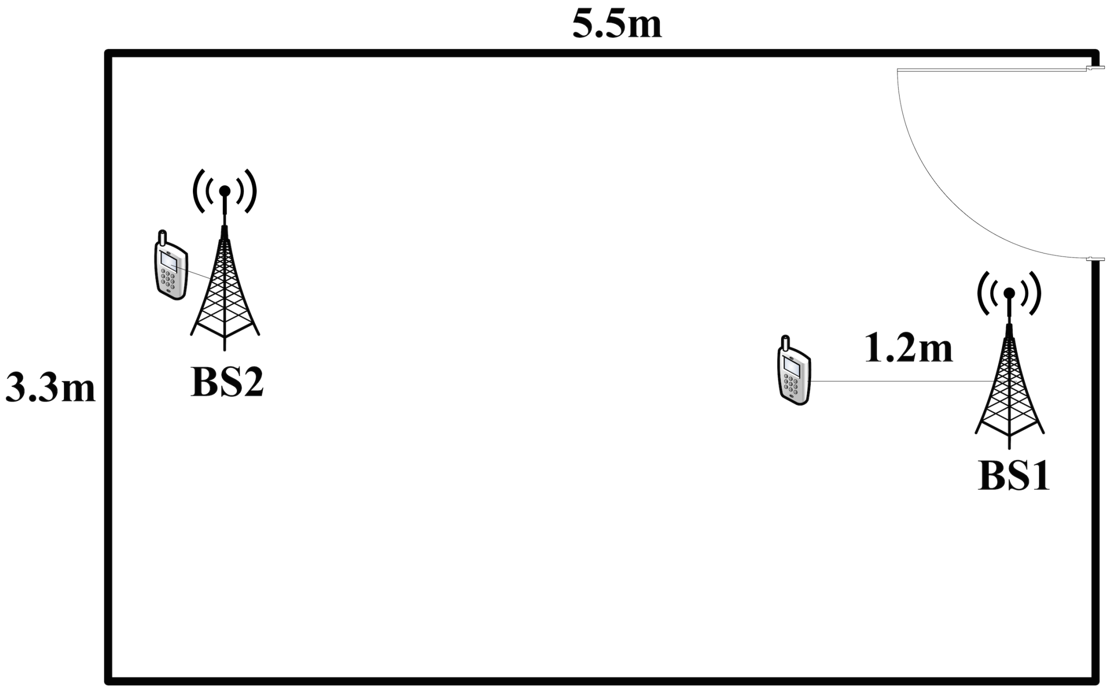
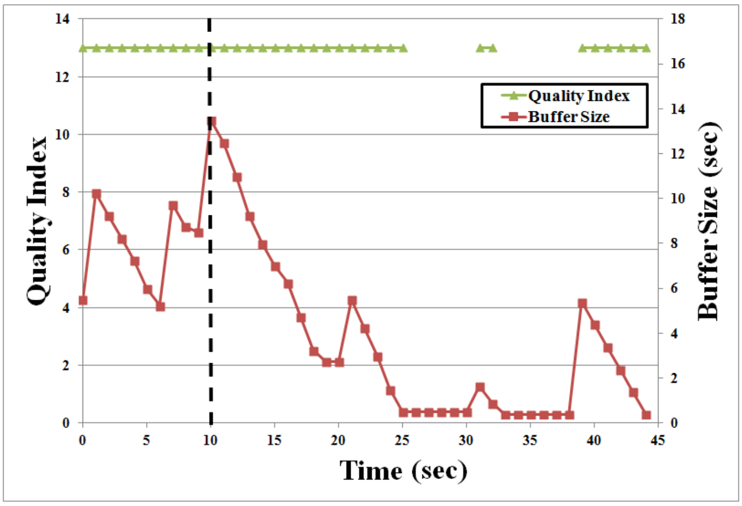
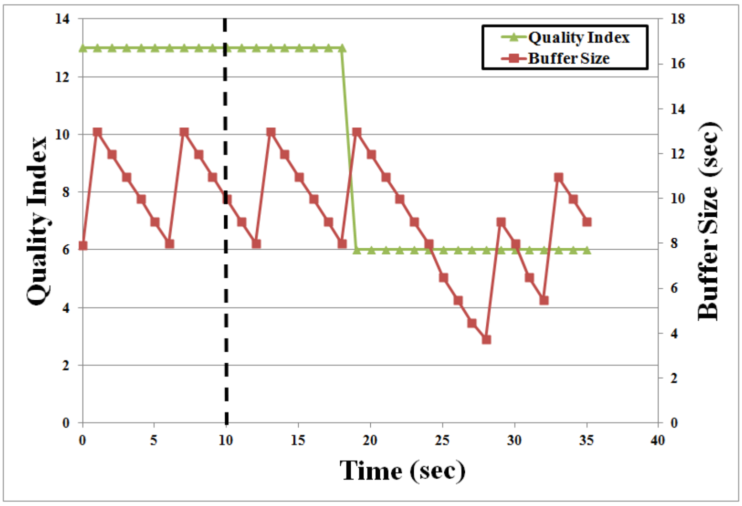


Figure 4.9: Scenario of stall and quality variation experiments

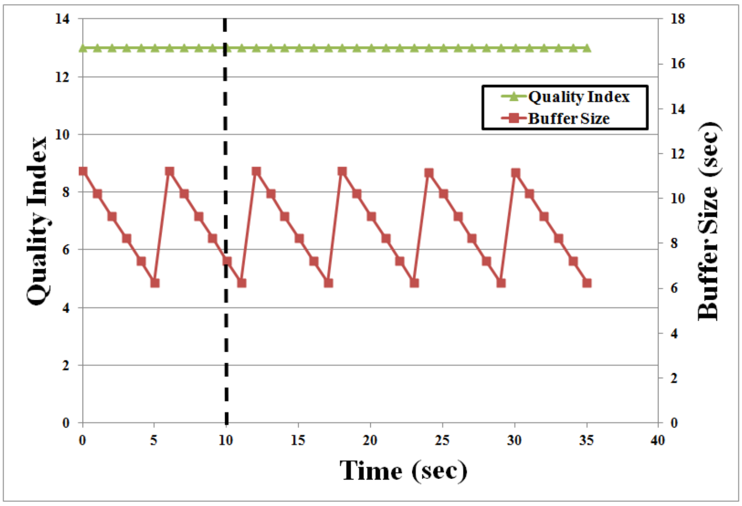
gies in our design: interference management and server-aided rate selection and resource allocation. By the interference management strategy such as coordination of base station power and band division, the system can maintain channel stability and achieve a higher resource efficiency. When base station configuration changed, the server-aided rate selection case (*b*) is triggered to handle the influence of interference. The more pratical use cases to verify the performance of our approaches are provided in the next chapter.



(a) Stall is caused by quality invariance



(b) Quality variation is caused by stall prevention



(c) Stall and quality variation improvement by server-aided rate selection and resource allocation

Figure 4.10: Quality and buffer size time traces of stall and quality variation experiments

Chapter 5

Performance Analysis

In this chapter, we conducted several experiments corresponding to different situations and scenario on the LTE testbed to validate the performance and feasibility of our proposed utility-aware DASH improvement methodology. Also, we gave discussions on these experiments in details.

5.1 [Scenario 1] Congestion in center

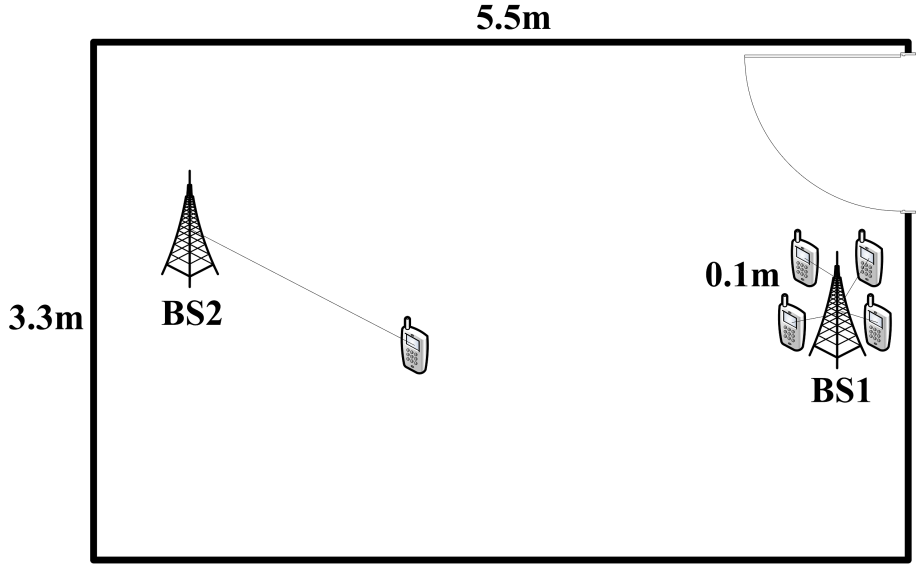


Figure 5.1: [Scenario 1] Congestion in center

The first scenario we considered is congestion in center. There are 4 center UEs requesting DASH service in base station 1 and a edge UE in base station 2 acts as interference source. The signal power of base station 1 is -11.77 dBm and the interference power from base station 2 is -4 dBm. The comparison scheme is default setting. The time traces of buffer size and video quality are referred to figure 5.2 and 5.3.

The resources contention resulted in unfairness. In figure 5.2(a), UE3 filled its buffer quickly, but buffer of UE2 was nearly empty. Also, resource occupation by UE3 caused long initial delay on UE2 and UE4. In further, the UE3 suffered from low video quality impairment (figure 5.3(a)). In comparison, UE2, UE3 and UE4 won the availability to resources, so they enjoyed higher quality of video session. In our server-aided rate selection and resource allocation scheme, server allocated each UE with 3 RBs and the data bandwidth of each DASH UE is 1.98 Mbps. The fair resource allocation avoid the resource contention and ensure the stable data rate. In figure 5.2(b), the buffer time series of four UE are in the same trend and level. Besides, figure 5.3(b) also showed our server-aided selection results. Each UE used bandwidth effectly and maintained stable quality in video sesssion.

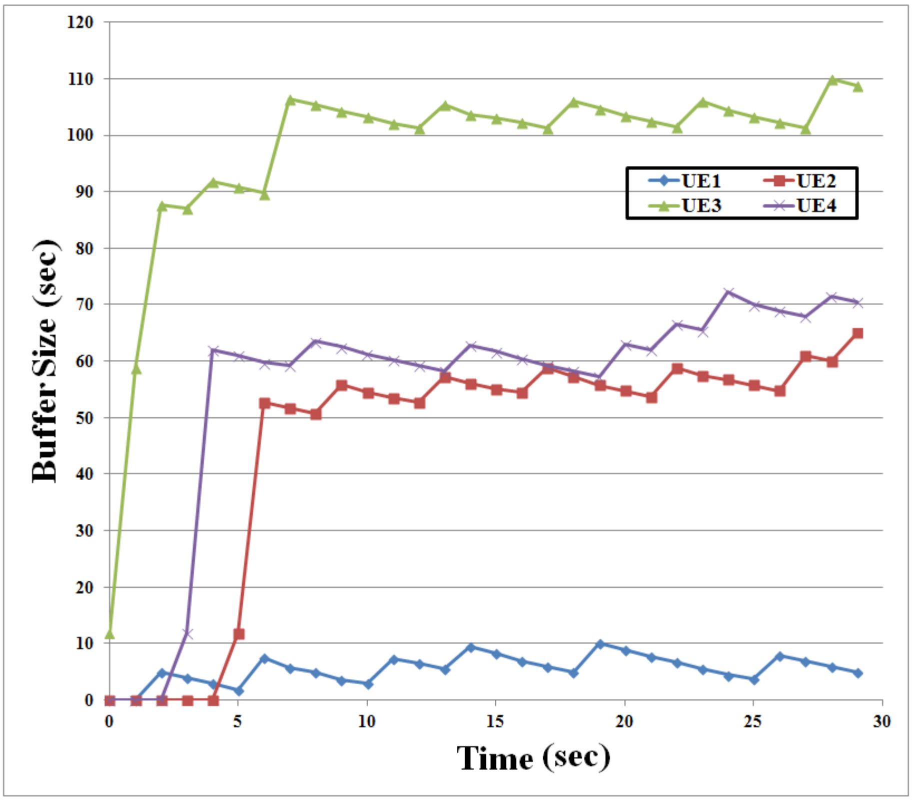
Table 5.1 and 5.2 are the DASH utility score results. Our approaches prevent stall and quality variation. The average initial delay impairment is also lower. The final utility scores beat the default setting in all UE.

Table 5.1: DASH UE utility scores of default setting in scenario 1

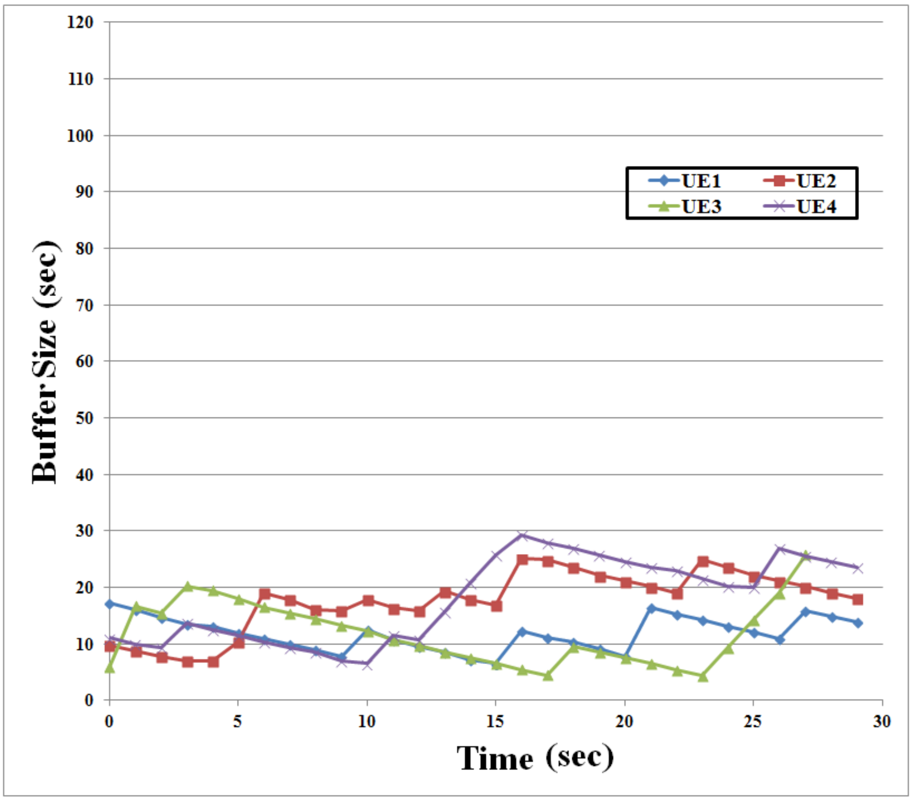
	UE1	**UE2**	**UE3**	**UE4**	**Avg.**
Impairment of Initial Delay	8.9728	19.76	3.9392	14.8608	11.8832
Impairment of Stall	0	0	0	0	0
Impairment of Quality Variation	20.913	0	0	0	5.2283
Final Utility Score	70.1142	80.24	96.0608	85.1392	82.8886

Table 5.2: DASH UE utility scores when server-aided rate selection and resource allocation triggers in scenario 1

	UE1	**UE2**	**UE3**	**UE4**	**Avg.**
Impairment of Initial Delay	5.7088	3.2608	3.264	5.1232	4.3392
Impairment of Stall	0	0	0	0	0
Impairment of Quality Variation	0	0	0	0	0
Final Utility Score	94.2912	96.7392	96.736	94.8768	95.6608

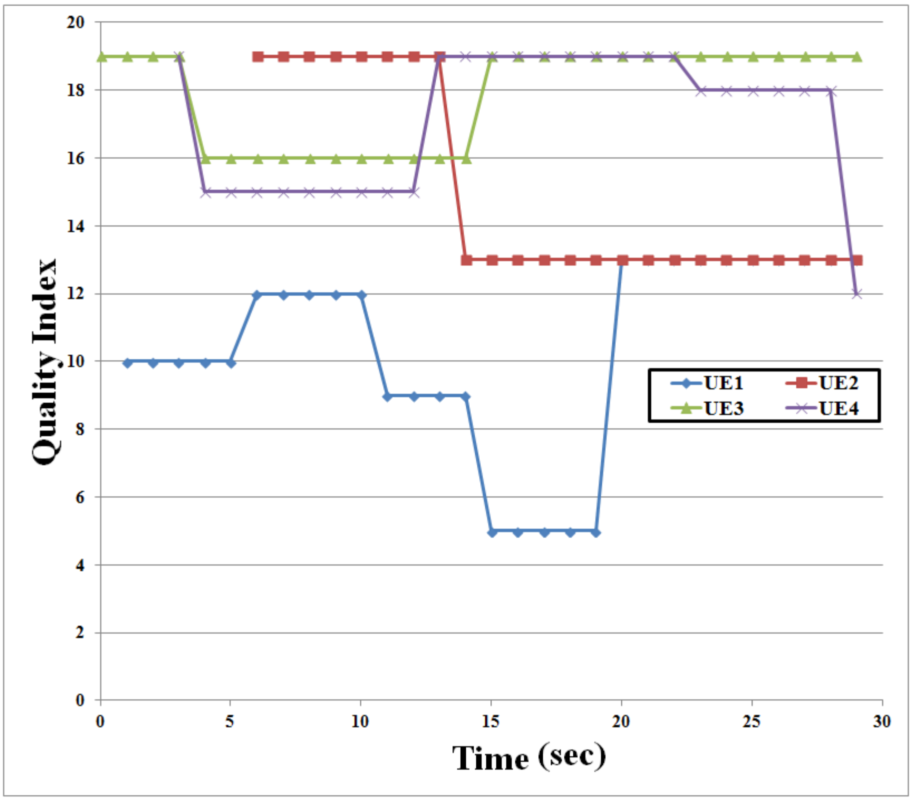


(a) Buffer size time traces of each UE in default setting

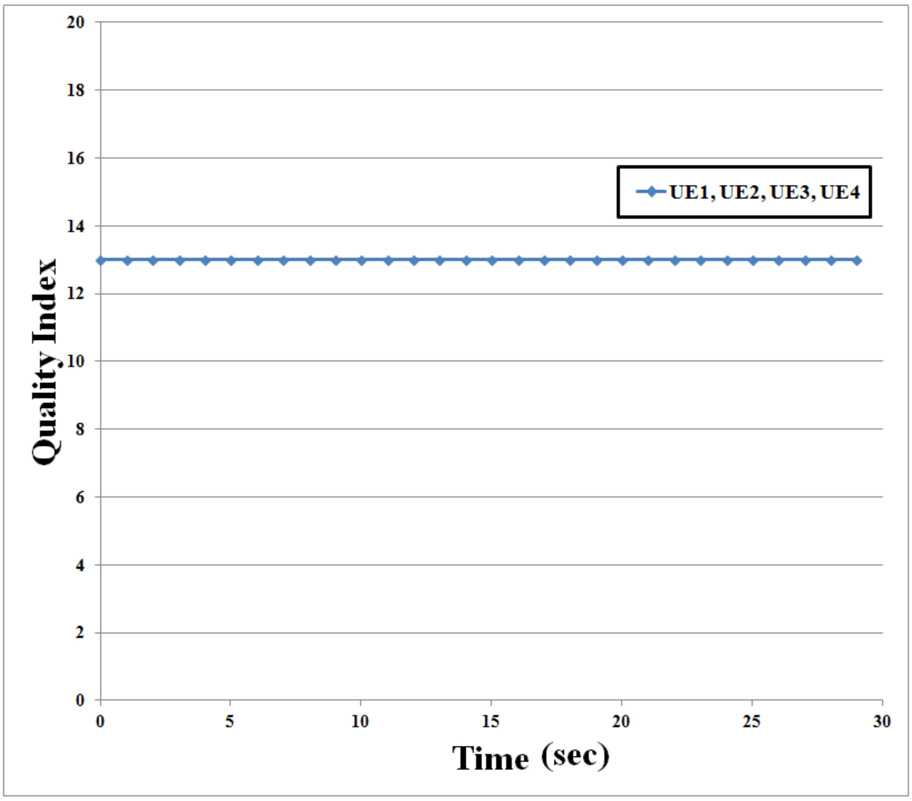


(b) Buffer size time traces of each UE when server-aided rate selection and resource allocation triggers

Figure 5.2: Time traces of buffer size in scenario 1



(a) Video quality time traces of each UE in default setting



(b) Video quality time traces of each UE when server-aided rate selection and resource allocation triggers

Figure 5.3: Time traces of video quality in scenario 1

5.2 [Scenario 2] Interference applied when resources are enough

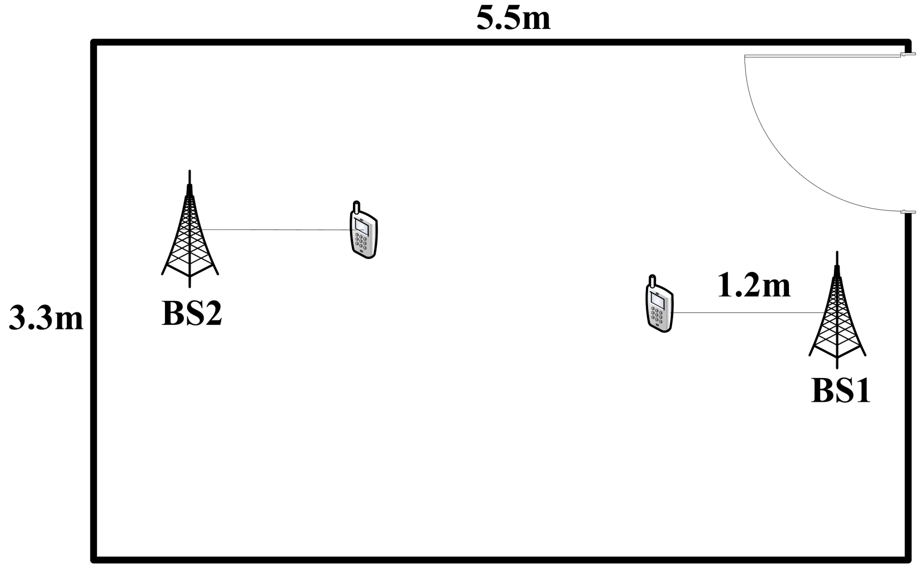


Figure 5.4: [Scenario 2] Interference applied when resources are enough

The second scenario we considered is interference applied when resources are enough. There is a middle UE requesting DASH service in base station 1 and a middle UE in base station 2 acts as interference source. The time traces of buffer size and video quality are referred to figure 5.5. The interference occured at 10 seconds after DASH service started and ended at 40 seconds. The dashed lines specify the interference duration. The signal power of base station 1 and the interference power from base station 2 are all -8.77 dBm. In initial, the DASH UE is allocated with 6 RB and the data bandwidth is 2.72 Mbps. The comparison scheme is default setting.

After interference applied, the throughput is down to 2.1 Mbps. Referred to figure 5.5(a), the segment download cannot be on time. The buffer size declined to zero and caused a severe stall. Also, the quality selection by UE itself cannot reach convergence quickly. In figure 5.5(b), the non-proper selection caused the second times of stall about at 40 seconds. In our server-aided rate selection and resource allocation, server allocated the UE with 9 RB instead of 6 RB when interference occured and the data bandwidth became to 3.62 Mbps. The buffer growed up stably and video quality maintain in same on whole video session. Server aided UE with more resource allocation to prevent stall and quality variation in this scenario.

Table 5.3 is the DASH utility score results. Our approaches prevent stall perfectly and beat the default scheme in final utility score.

Table 5.3: DASH UE utility scores in scenario 2

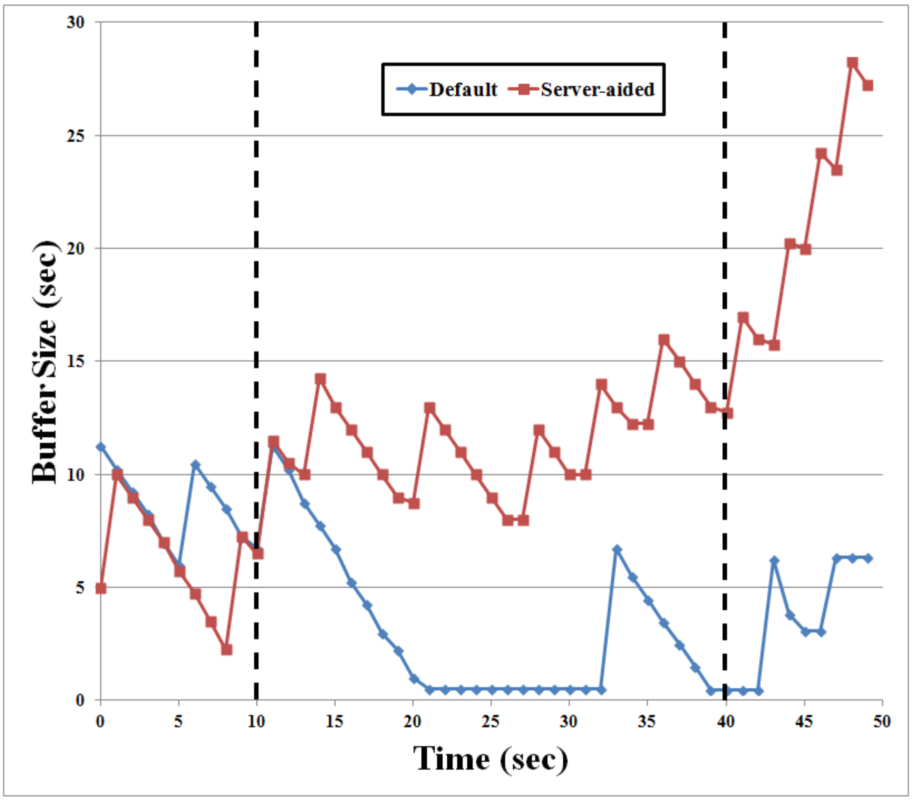
	Default	**Server-aided**
Impairment of Initial Delay	5.4464	5.8688
Impairment of Stall	51.1592	0
Impairment of Quality Variation	0	0
Final Utility Score	43.3944	94.1312

5.3 [Scenario 3] Interference applied when resources are insufficient

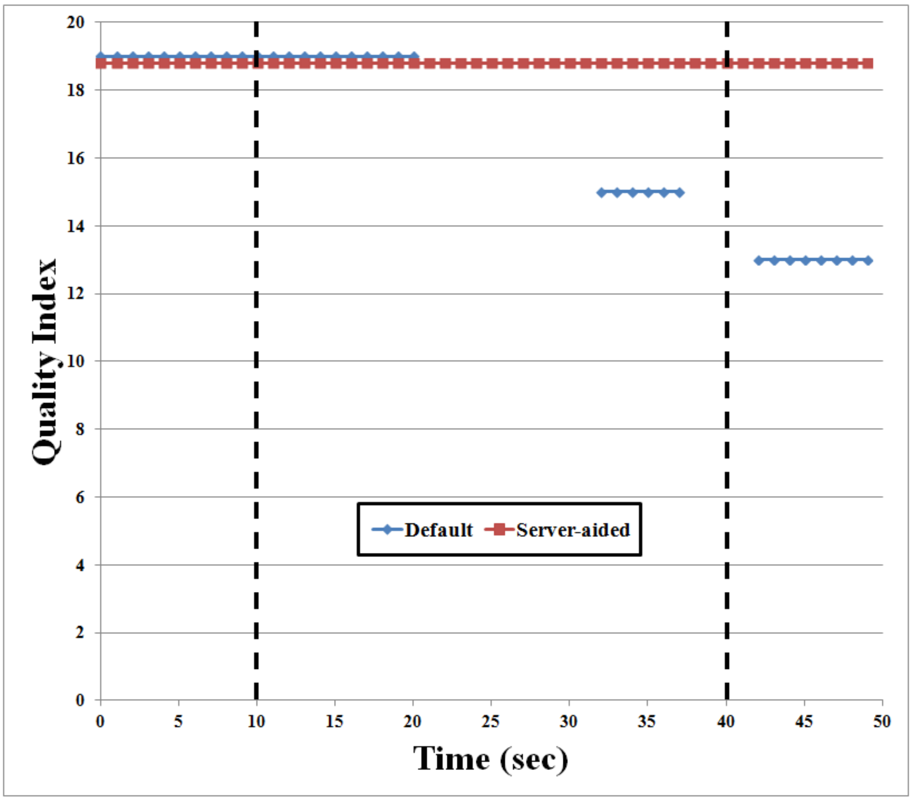
The third scenario we considered is interference applied when resources are insufficient. There are two middle UEs requesting DASH service in base station 1 and a middle UE in base station 2 acts as interference source. The time traces of buffer size and video quality are referred to figure 5.7. The interference occured at 10 seconds after DASH service started and ended at 40 seconds. The dashed lines specify the interference duration. The signal power of base station 1 and the interference power from base station 2 are all -8.77 dBm. The comparison scheme is default setting.

In congestion scenario, different from scenario 2, UE cannot get more resources to maintain quality when interference occured. The data bandwidth of each DASH UE in initial and when interference applied is 2.72 Mbps and 2.1 Mbps respectively. Referred to figure 5.7(a), the UE buffer size in our scheme is stable, but in default scheme, the buffer size varied drastically because of the interference and resource contention. Figure 5.7(b) showed the video quality series. UE cannot respond to channel variation in time and stall when interference occured. In our approaches, server aided UE to select lower quality when interference occured to prevent stall.

Table 5.1 and 5.2 are the DASH utility score results. Our approaches prevent stall and



(a) Buffer size time traces in default and server-aided



(b) Video quality time traces in default and server-aided

Figure 5.5: Time traces of buffer size and video quality in scenario 2

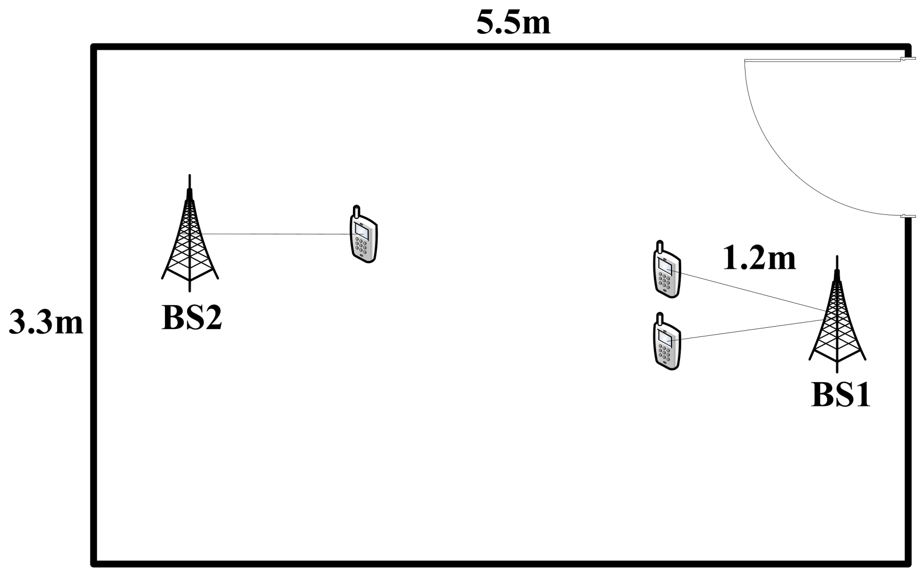


Figure 5.6: [Scenario 3] Interference applied when resources are insufficient

quality variation. Besides, we maintain the quality in a tolerable level when interference applied. The final utility scores beat the default setting in all UE.

Table 5.4: DASH UE utility scores of default setting in scenario 3

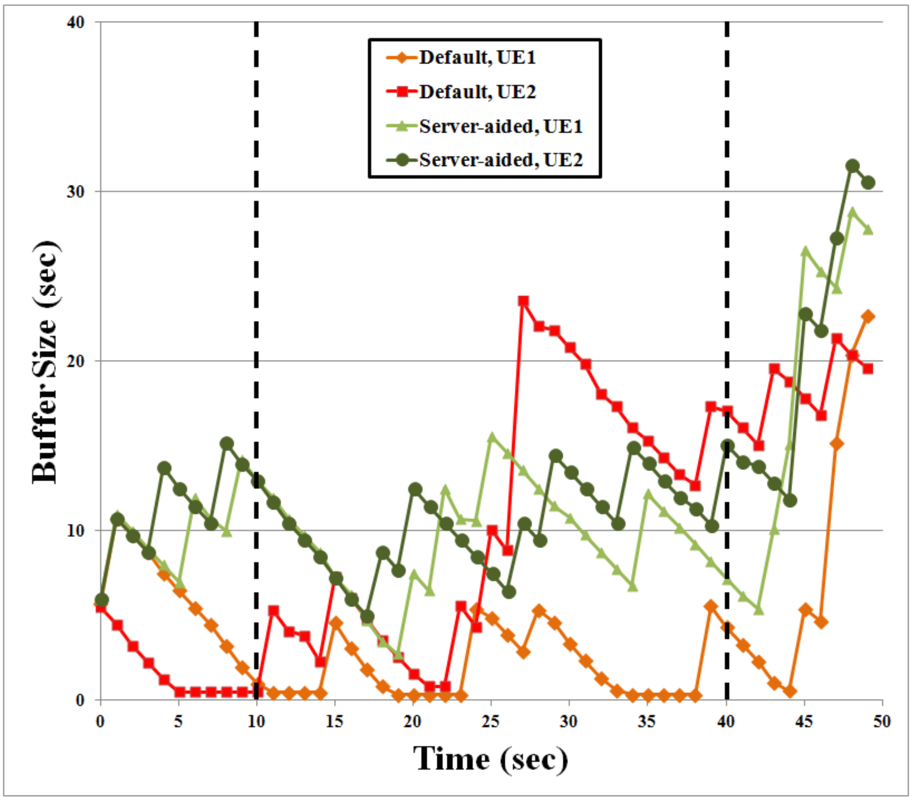
	UE1	UE2	Avg.
Impairment of Initial Delay	4.8704	5.1328	5.0016
Impairment of Stall	52.1587	28.4	40.2794
Impairment of Quality Variation	6.6679	2.7177	4.6928
Final Utility Score	36.303	63.7496	50.0263

Table 5.5: DASH UE utility scores when server-aided rate selection and resource allocation triggers in scenario 3

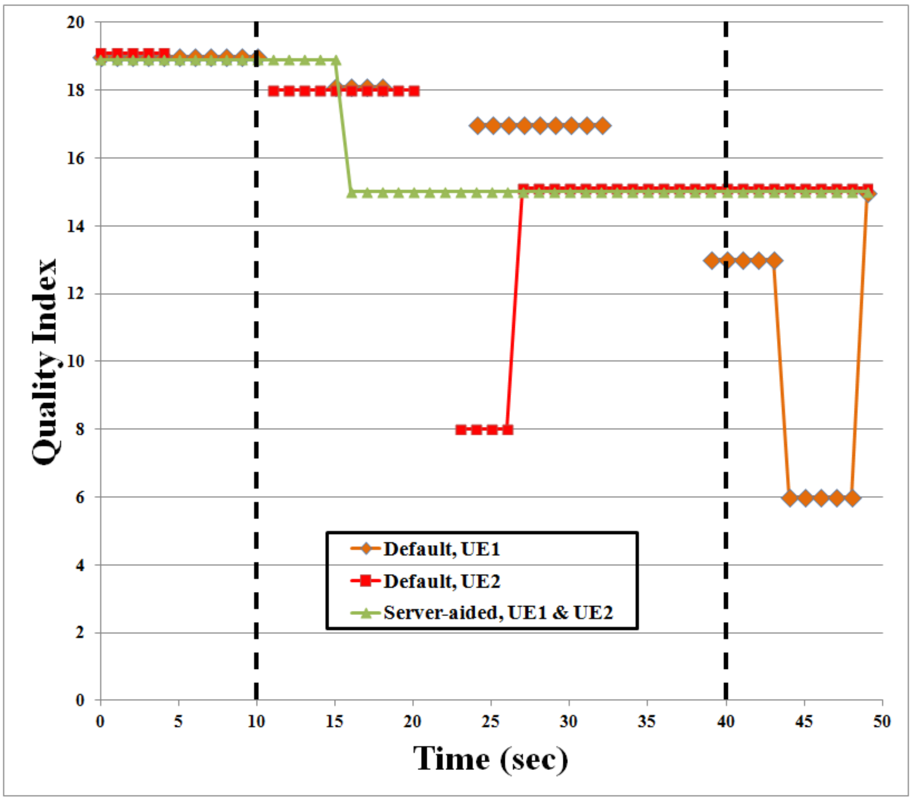
	UE1	UE2	Avg.
Impairment of Initial Delay	3.28	3.6096	3.4448
Impairment of Stall	0	0	0
Impairment of Quality Variation	0	0	0
Final Utility Score	96.72	96.3904	96.5552

5.4 [Scenario 4] Power enhanced in edge

The forth scenario we considered is power enhanced in edge. There is a edge UE requesting DASH service in base station 1 and a center UE in base station 2 acts as interference source. The signal power and interference power in default scheme are -11.77



(a) Buffer size time traces of each UE in default and server-aided



(b) Video quality time traces of each UE in default and server-aided

Figure 5.7: Time traces of buffer size and video quality in scenario 3

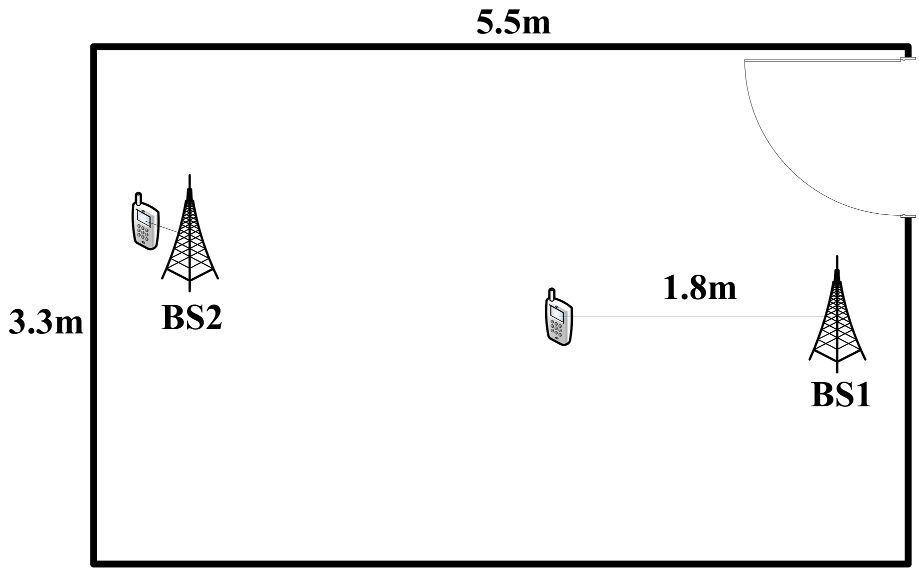


Figure 5.8: [Scenario 4] Power enhanced in edge

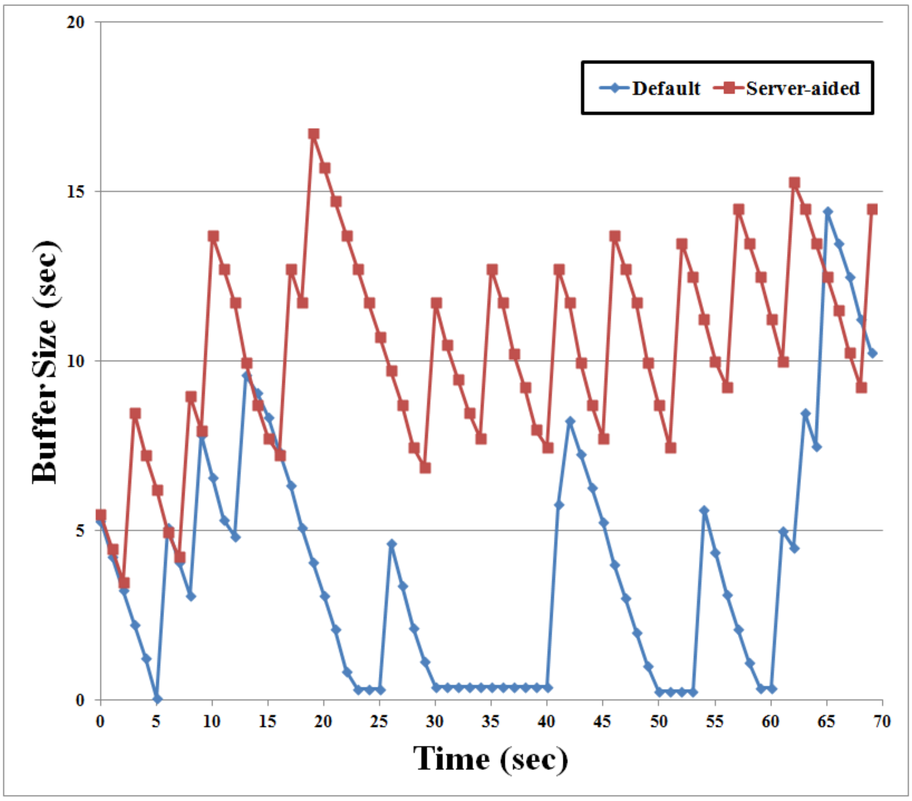
dBm. In our scheme, the signal power enhanced to -4 dBm. The time traces of buffer size and video quality are referred to figure 5.9.

The allocation amount of RB for UE is 9. Without signal power enhancement, the data bandwidth of DASH UE is 2.67 Mbps. The throughput increased to 3.38 Mbps after power enhancement. According to figure 5.9(b), the quality reach convergence at about 60 seconds in default scheme. The stable growth of buffer size also happened after 60 seconds (figure 5.9(a)). In our server-aided rate selection, server help UE select video quality to fill the bandwidth perfectly and directly converged in initial.

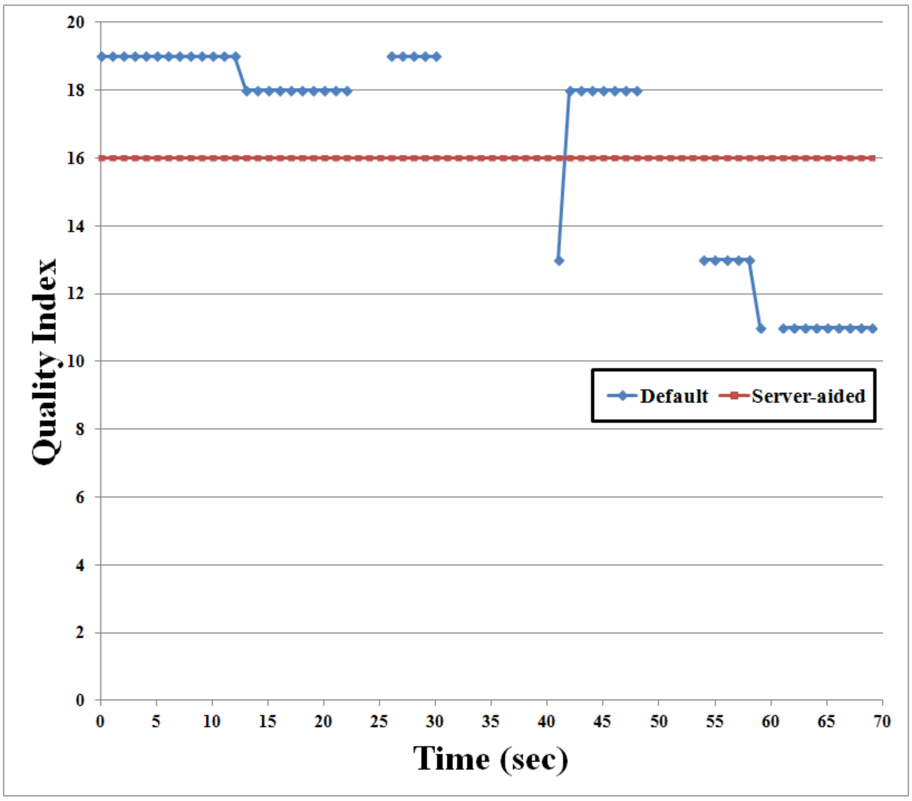
Table 5.6 is the DASH utility score results. Our approaches in power enhancement and server-aided rate selection prevent stall and choose the best quality perfectly using bandwidth. Also, we beat the default scheme in final utility score.

Table 5.6: DASH UE utility scores in scenario 4

	Default	**Server-aided**
Impairment of Initial Delay	5.088	4.1856
Impairment of Stall	66.3337	0
Impairment of Quality Variation	2.1641	0
Final Utility Score	26.4142	95.8144



(a) Buffer size time traces in default and server-aided



(b) Video quality time traces in default and server-aided

Figure 5.9: Time traces of buffer size and video quality in scenario 4

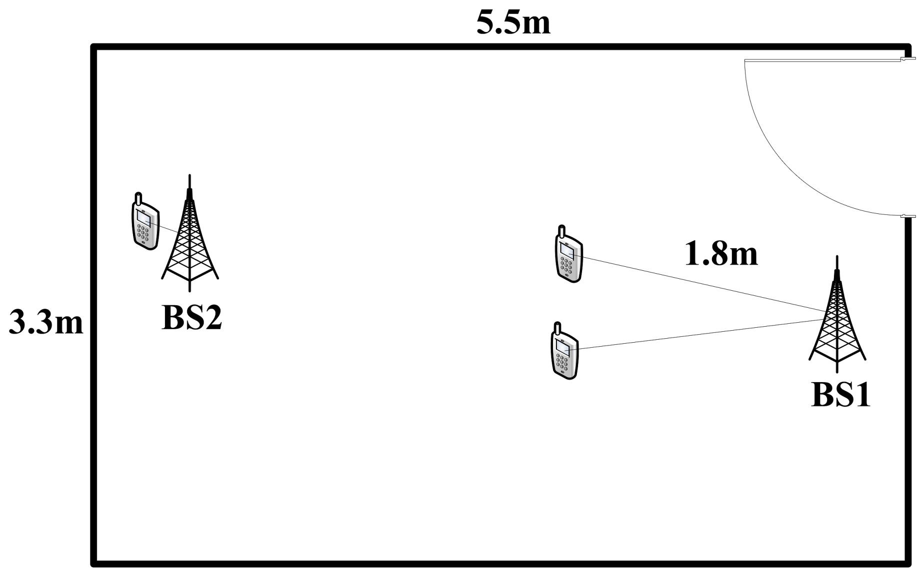
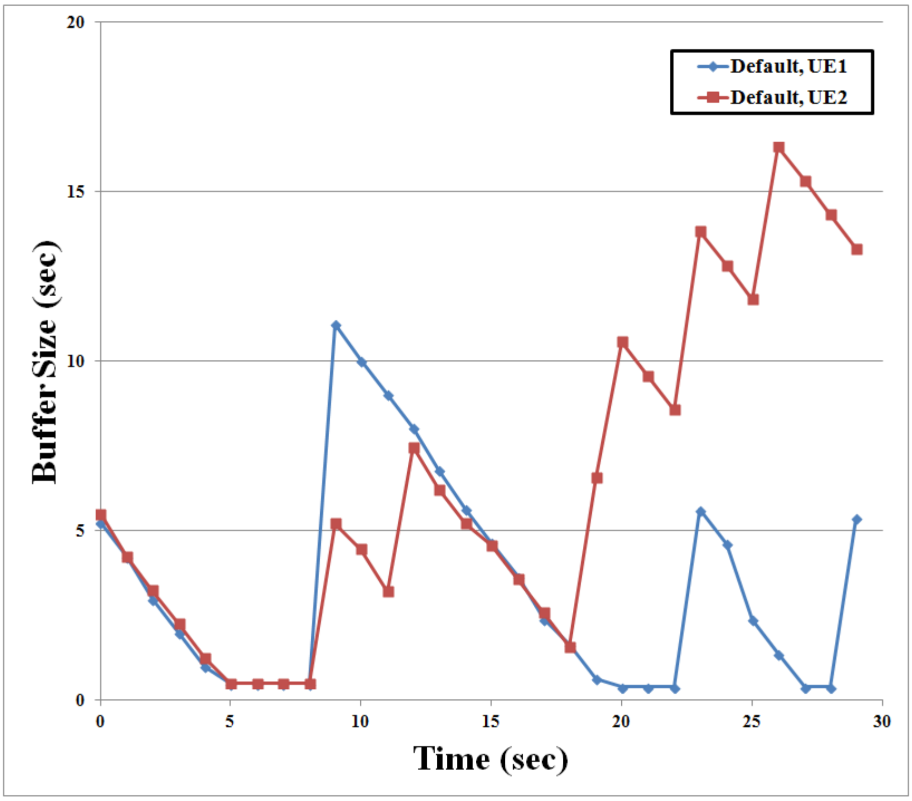


Figure 5.10: [Scenario 5] Congestion in edge

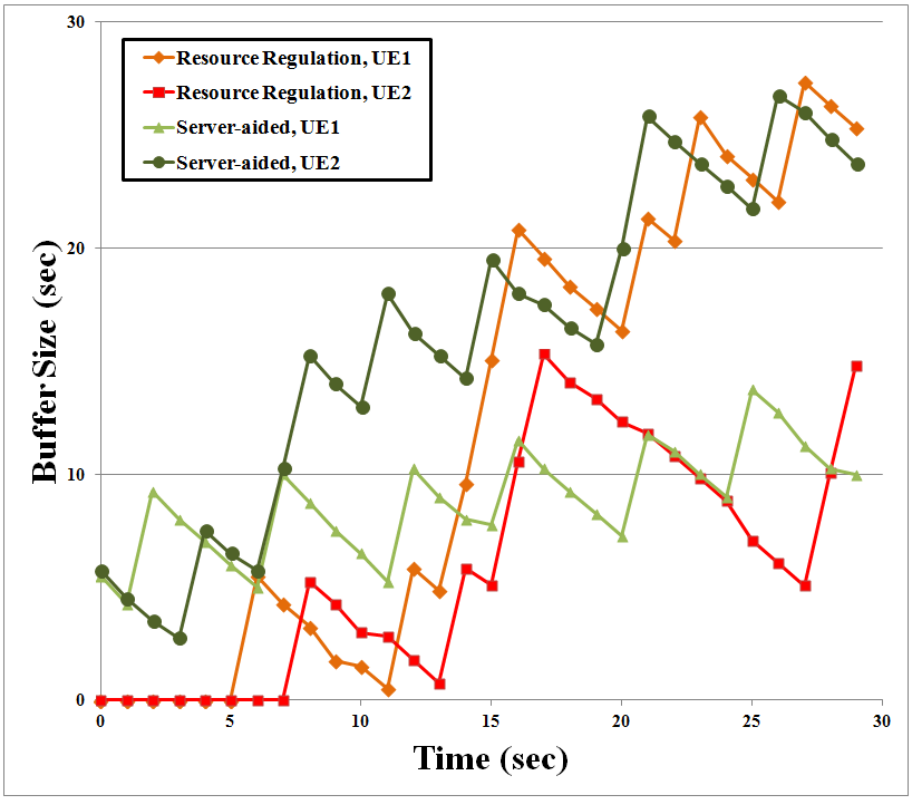
5.5 [Scenario 5] Congestion in edge

The fifth scenario we considered is congestion in edge. There are two edge UE requesting DASH service in base station 1 and a center UE in base station 2 acts as interference source. The signal power is -4 dBm and the interference power from base station 2 is -11.77 dBm. In this scenario, we conducted three schemes in analysis. Except for default setting and our server-aided approaches, we implemented a resource regulation scheme to avoid resource contention problem. We only regulated the resource allocation amount for UE in order to observe the effect of our rate selection. The time traces of buffer size and video quality are referred to figure 5.11 and 5.12.

Figure 5.11(a) and 5.12(a) are the default scheme plots. Two UEs struggled to resources which leads to low quality level and stall. In resource regulation scheme, it prevent the resource contention, so no UE suffered from stall impairment. However, without server-aided rate selection by server, the UE selected the highest quality leading to tremendous initial delay time. Besides, the choosing of quality did not respond to channel capacity in time. Referred to figure 5.12(b), the quality selection of two UEs fluctuated in the duration between 10 to 25 seconds. Default scheme suffered from stall impairment and resource regulation scheme suffered from initial delay and quality variation impairment. By our server-aided rate selection and resource allocation, the UE would not suffer

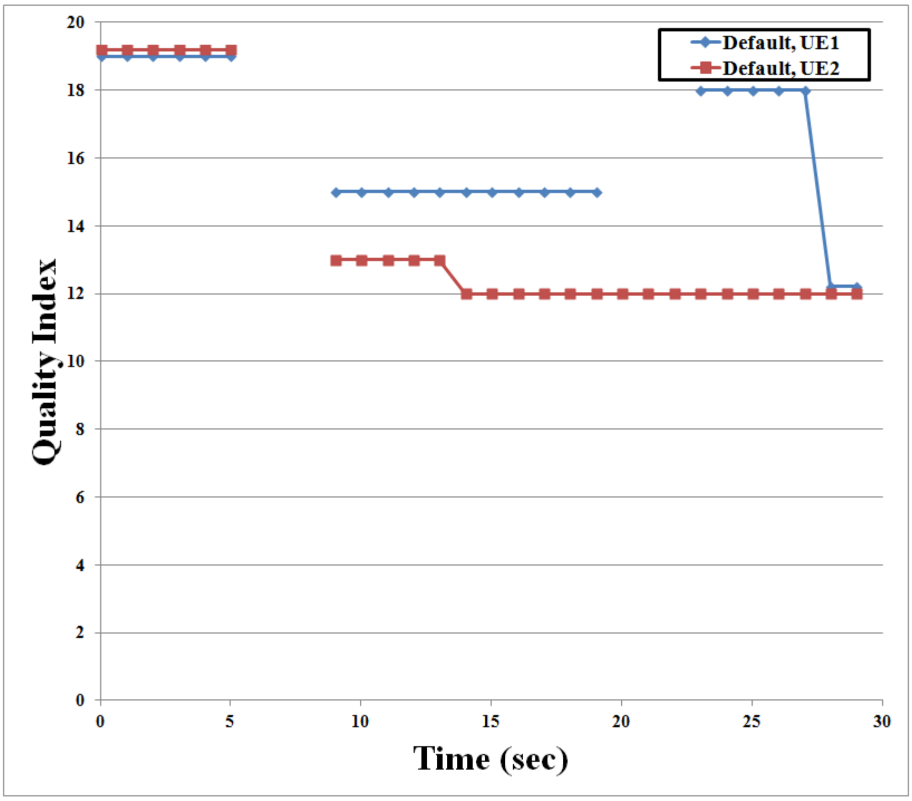


(a) Buffer size time traces of each UE in default

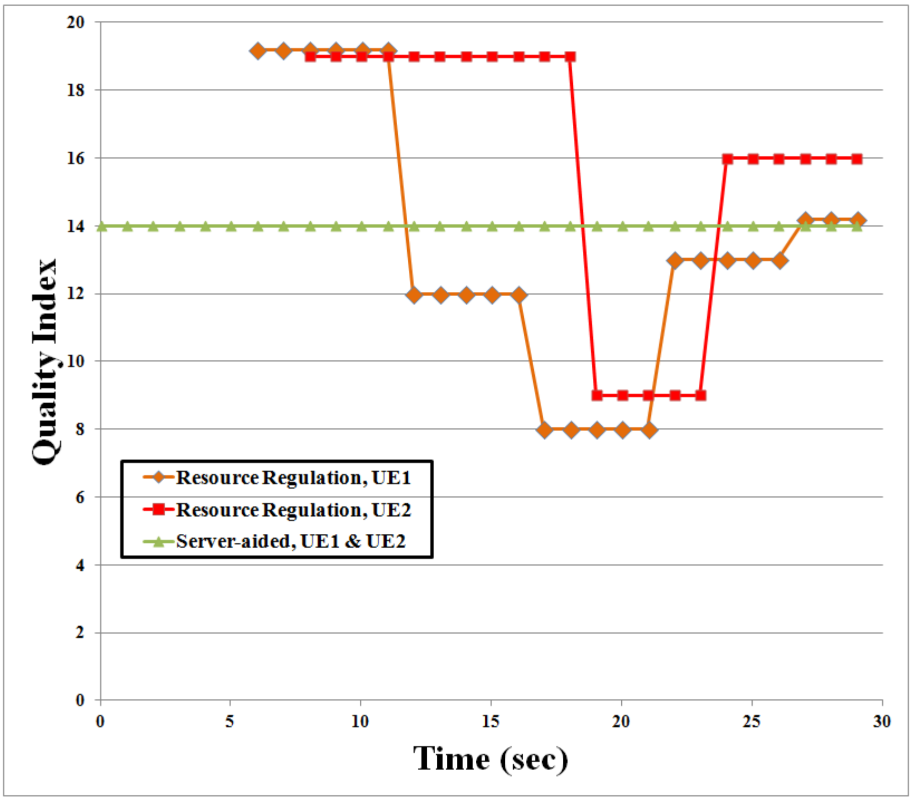


(b) Buffer size time traces of each UE in resource regulation scheme and server-aided rate selection and resource allocation triggers

Figure 5.11: Time traces of buffer size in scenario 5



(a) Video quality time traces of each UE in default



(b) Video quality time traces of each UE in resource regulation scheme and server-aided rate selection and resource allocation triggers

Figure 5.12: Time traces of video quality in scenario 5

from long initial delay and the buffer growed up stably.

Table 5.7: DASH UE utility scores of default setting in scenario 5

	UE1	UE2	Avg.
Impairment of Initial Delay	5.2544	6.6048	5.9296
Impairment of Stall	22.1933	13.4313	17.8123
Impairment of Quality Variation	0	3.7026	1.8513
Final Utility Score	72.5523	76.2613	74.4068

Table 5.7 and 5.8 showed the utility score of default scheme and resource regulation scheme. Resource regulation scheme can avoid the stall and quality variation but the initial delay causes the great deduction. As a result, the utility scores are lower than default scheme. Table 5.9 showed the utility score of our approaches. We beat the other two in every terms and final utility scores.

Table 5.8: DASH UE utility scores when server only regulates the resource allocation amount for each UE in scenario 5

	UE1	UE2	Avg.
Impairment of Initial Delay	22.8512	30.224	26.5376
Impairment of Stall	0	0	0
Impairment of Quality Variation	6.7867	4.8422	5.8145
Final Utility Score	70.3622	64.9338	67.648

Table 5.9: DASH UE utility scores when server-aided rate selection and resource allocation triggers in scenario 5

	UE1	UE2	Avg.
Impairment of Initial Delay	5.2096	3.9904	4.6
Impairment of Stall	0	0	0
Impairment of Quality Variation	0	0	0
Final Utility Score	94.7904	96.0096	95.4

5.6 [Scenario 6] Uniform distribution using 4K video content

The sixth scenario we considered is uniform distribution. There is no missing type of UE in each base station and the UE distribution is referred to figure 5.13. All UEs in base station 1 request DASH service and base station 2 acts as interference source. In this

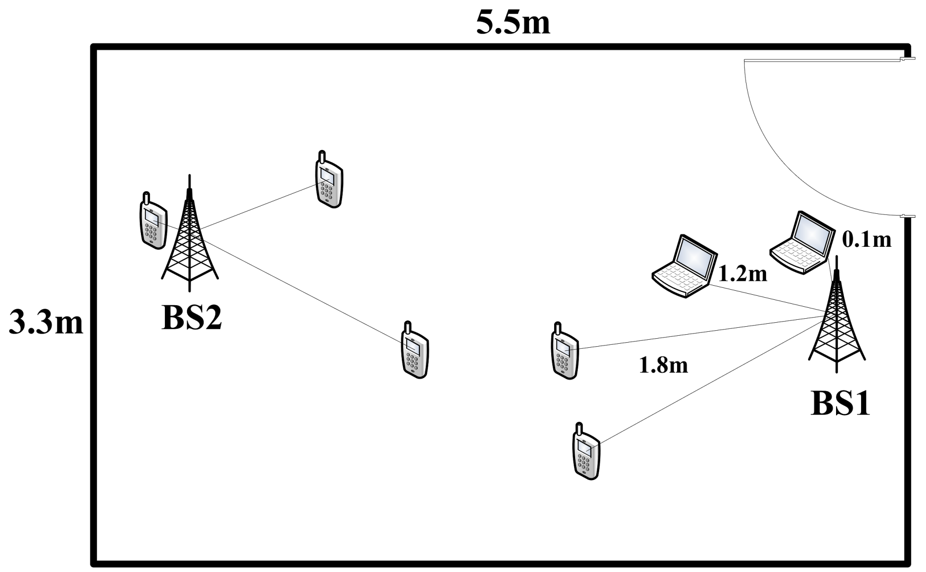


Figure 5.13: [Scenario 6] Uniform distribution

scenario, we used the DASH video data set with resolution up to 4K (3840×2160) to fill the bandwidth in a easier manner. In our approaches, the signal power for center, middle and edge UE is -11.77, -8.77 and -4 dBm respectively. The resource block amount in each region is 12. As a result, the amount of resource block that center and middle UE can acquire is 12. The two edge UEs can acquire 6 resource blocks respectively. The corresponding data bandwidth of center, middle and two edge UEs is 13.3, 5.82, 2.36, 2.28 Mbps respectively. The comparison scheme is no power control, no resource amount regulation and no server-aided rate selection. The transmitting power is -11.77 dBm and total resource block amount is 36. The throughput comparison of two schemes is as following table 5.10. We used *iPerf* to generate full traffic in duration of 100 seconds and returned the throughput values. The throughput of center has no difference since the signal is good enough. By our interference management manner, the average overall enhancement of two base station's throughput in middle and edge is 34.25% and 62.67% respectively.

The time traces of buffer size and video quality of two schemes are referred to figure 5.14 and 5.15. The behavior of center UE had no obvious difference in two schemes. The buffer variation and quality are nearly the same. The middle UE in default scheme selected improper initial video quality which caused long initial delay and the quality

Table 5.10: Throughput comparison in two schemes

Scheme	Default	Our Approaches	Throughput Enhanced
BS1 Center Throughput	13.3 Mbps	13.3 Mbps	-
BS2 Center Throughput	13.3 Mbps	13.3 Mbps	-
BS1 Middle Throughput	4.28 Mbps	5.82 Mbps	35.98%
BS2 Middle Throughput	4.48 Mbps	5.94 Mbps	32.59%
BS1 Edge Throughput	3.17 Mbps	4.84 Mbps	52.68%
BS2 Edge Throughput	2.67 Mbps	4.66 Mbps	74.53%

drasticly dropped down when it tried to correct delay.

The edge UE1 in default scheme suffered from two times of stall which is caused by the interference and resource contention. In our approaches, the guaranteed resources are given for UE, so UE would not suffer from stall impairment. The buffer size of each UE in our approaches growed up stably and the quality had no fluctuation.

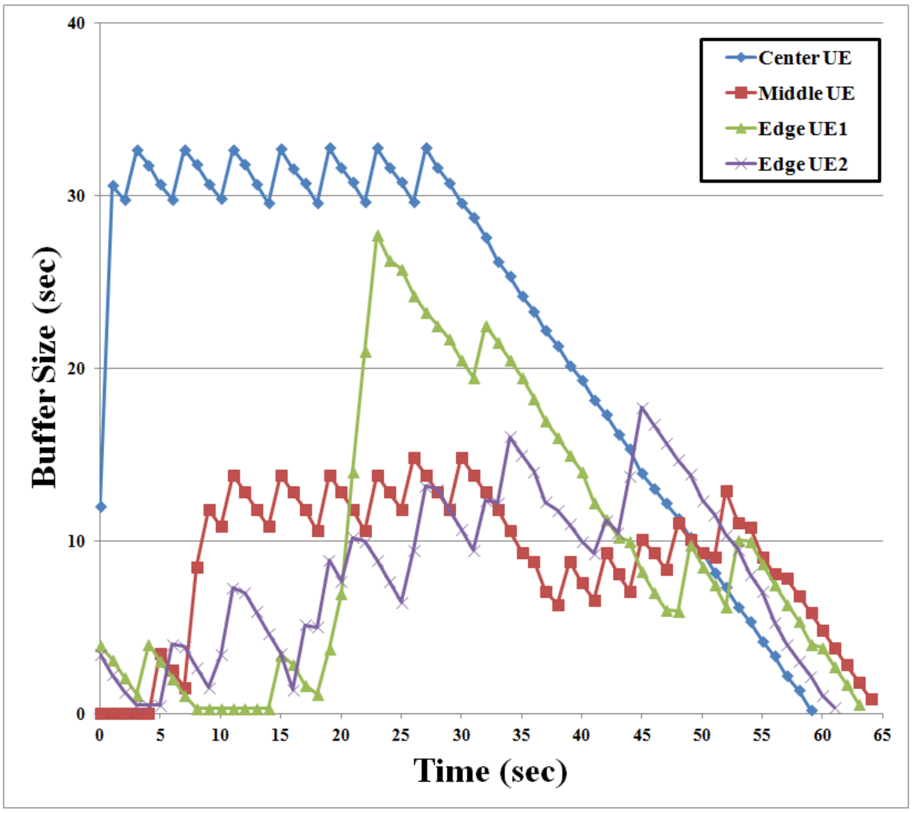
Table 5.11 and 5.12 are the DASH utility score results of default and our approaches respectively. Our approaches prevent stall and quality variation. The final utility scores beat the default scheme in all UEs.

Table 5.11: DASH UE utility scores of default setting in scenario 6

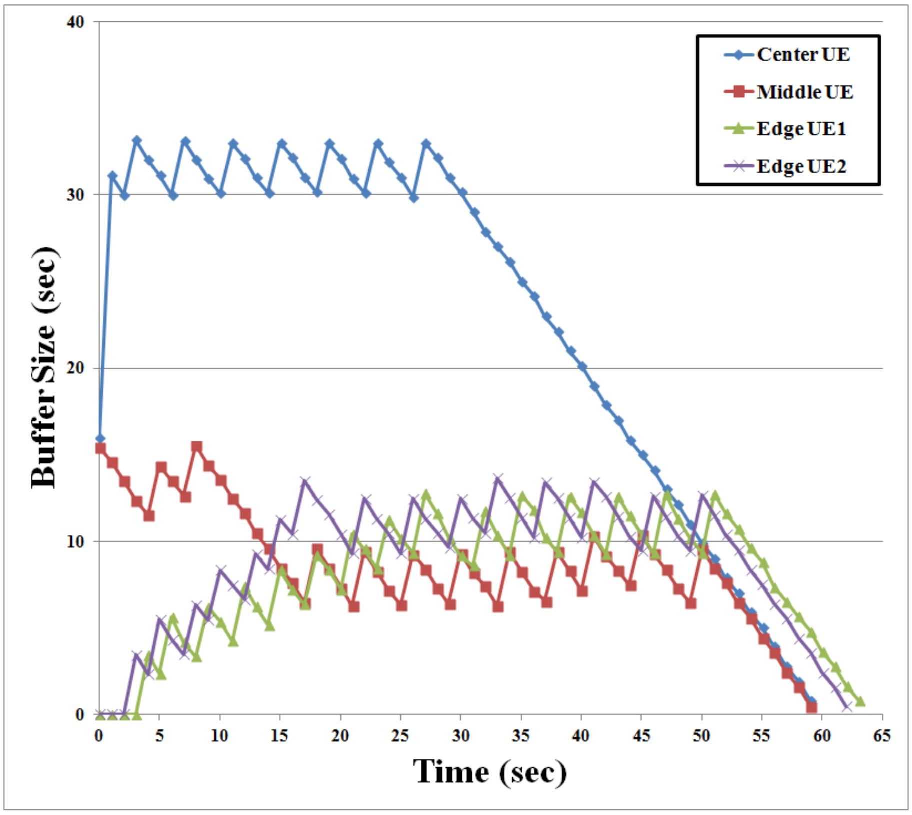
	Center UE	Middle UE	Edge UE1	Edge UE2	Avg.
Impairment of Initial Delay	4.2304	17.3248	5.1616	3.2224	7.4848
Impairment of Stall	0	0	20.6313	8.1231	7.1886
Impairment of Quality Variation	0	1.4906	13.5629	1.5707	4.1561
Utility Score	95.7696	81.1846	60.6441	87.0838	81.1705

Table 5.12: DASH UE utility scores when server-aided rate selection and resource allocation triggers in scenario 6

	Center UE	Middle UE	Edge UE1	Edge UE2	Avg.
Impairment of Initial Delay	2.6944	4.1408	14.4448	11.8912	8.2928
Impairment of Stall	0	0	0	0	0
Impairment of Quality Variation	0	0	0	0	0
Utility Score	97.3056	95.8592	85.5552	88.1088	91.7072

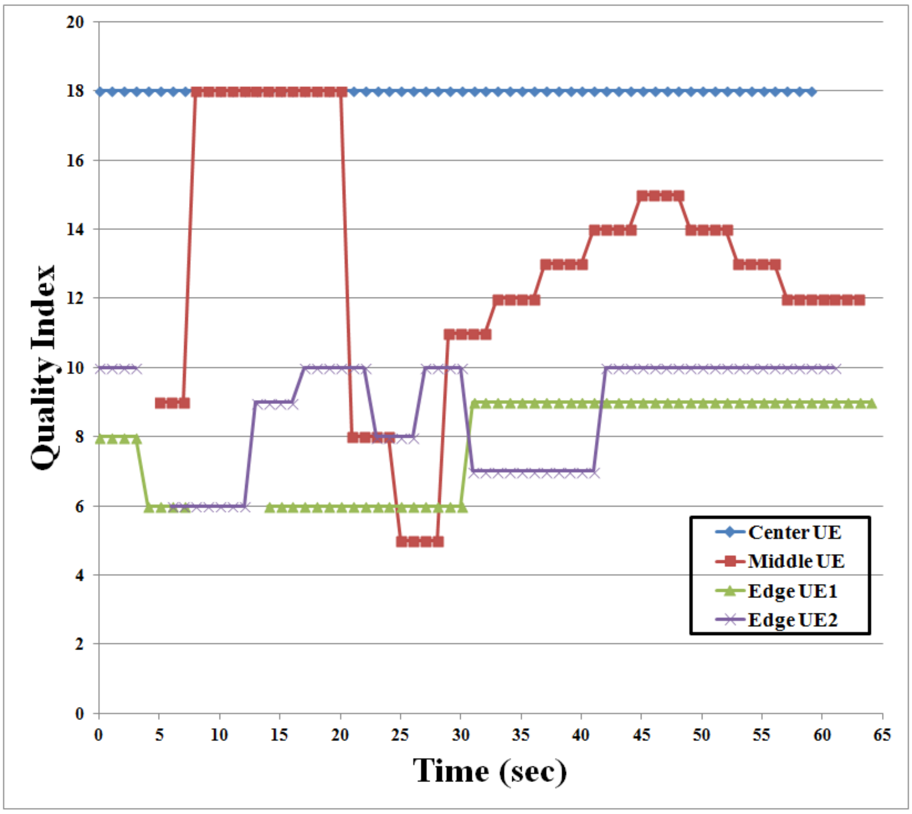


(a) Buffer size time traces of each UE in default setting

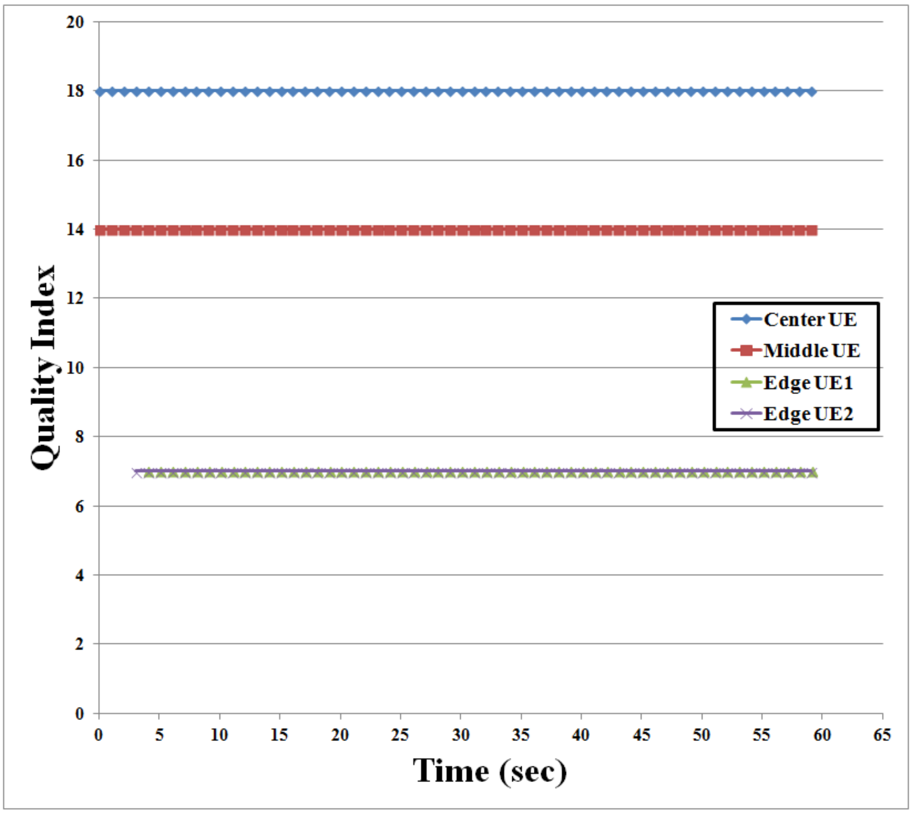


(b) Buffer size time traces of each UE when server-aided rate selection and resource allocation triggers

Figure 5.14: Time traces of buffer size in scenario 6



(a) Video quality time traces of each UE in default setting



(b) Video quality time traces of each UE when server-aided rate selection and resource allocation triggers

Figure 5.15: Time traces of video quality in scenario 6

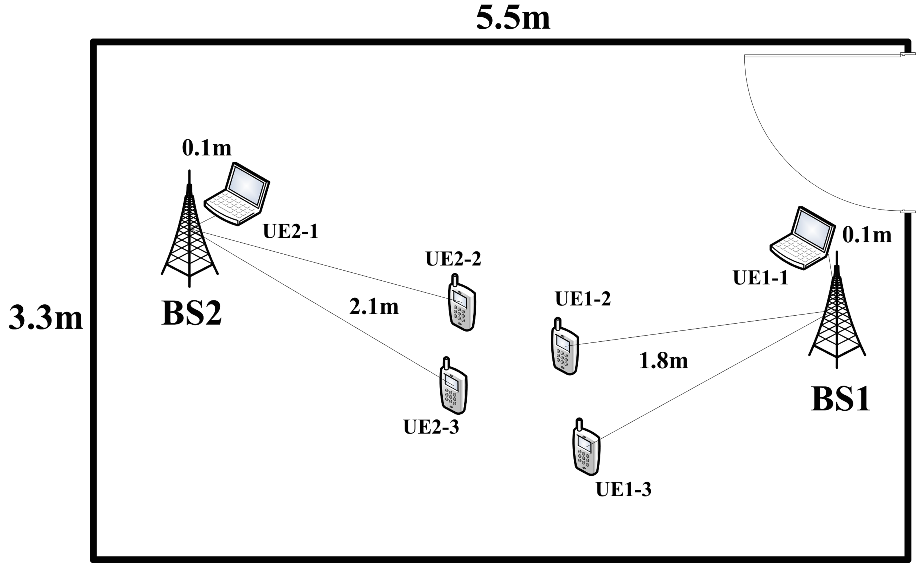


Figure 5.16: [Scenario 7] All UEs in DASH service

5.7 [Scenario 7] All UEs in DASH service

The seventh scenario we considered is all UEs in DASH service. The UE distribution is referred to figure 5.16. There are one center UE and two edge UEs in each base station. All UEs in this scenario request DASH service and the DASH video data set we used is also the resolution up to 4K (3840 $\times$ 2160) to fill the bandwidth in a easier manner. In our approaches, the signal power for center and edge UE is -11.77 and -4 dBm respectively. The resource block amount in each region is 12. As a result, the amount of resource block that center UE can acquire is 12. The two edge UEs can acquire 6 resource blocks respectively. The corresponding data bandwidth of center and two edge UEs is 13.3, 2.36, 2.28 Mbps respectively. The comparison scheme is no power control, no resource amount regulation and no server-aided rate selection. The transmitting power is -11.77 dBm and total resource block amount is 24. The throughput comparison of two schemes is as following table 5.10. We used *iPerf* to generate full traffic in duration of 100 seconds and returned the throughput values. The throughput of center has no difference since the signal is good enough. By our interference management manner, the average overall enhancement of two base station's throughput in edge is 62.67%.

Among all center UEs' performance, the UE2-1 in default scheme is different with others obviously. It lost the resources when its buffer size was enough, so the buffer was

Table 5.13: Throughput comparison in two schemes

Scheme	Default	Our Approaches	Throughput Enhanced
BS1 Center Throughput	13.3 Mbps	13.3 Mbps	-
BS2 Center Throughput	13.3 Mbps	13.3 Mbps	-
BS1 Edge Throughput	3.17 Mbps	4.84 Mbps	52.68%
BS2 Edge Throughput	2.67 Mbps	4.66 Mbps	74.53%

consumed continuously until the buffer size reached about 10 seconds. In our approaches, UE2-1 had enough resources amount to guarantee the download of video contents.

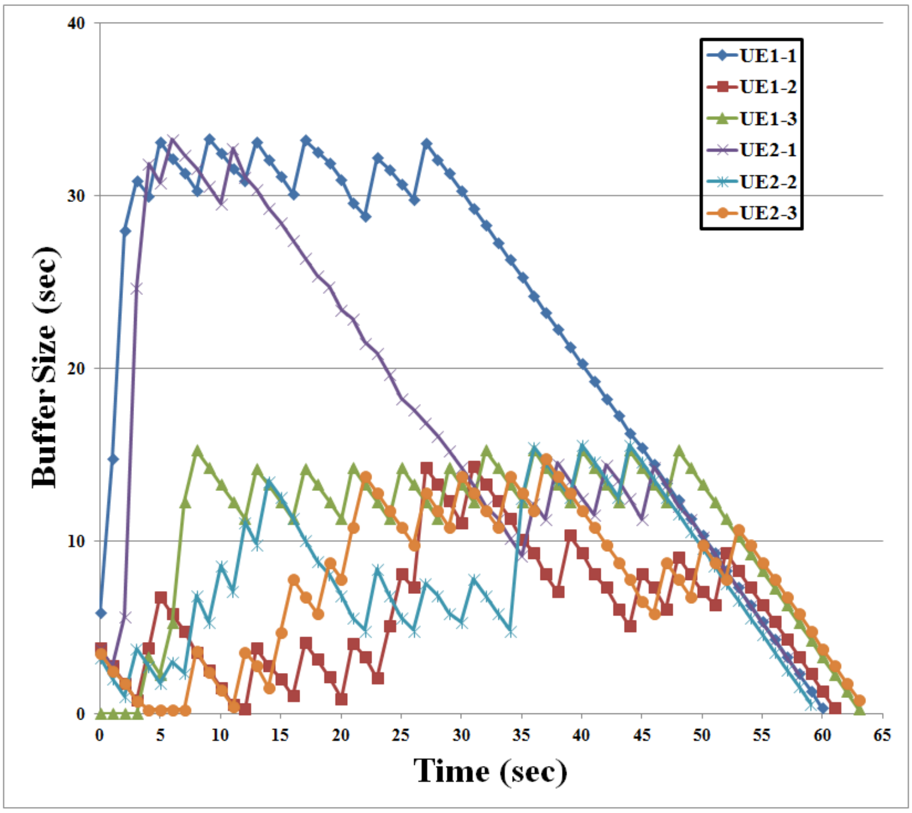
Among all edge UEs' performance, the UE1-3 in default scheme suffered from long initial delay which is caused by bad allocation of resources. The center UE1-1 occupied resources which made UE1-3 delay in initial. Furthermore, the edge UE2-3 in default scheme suffered from a long stall because of insufficient data bandwidth. In our approaches, the buffer size is greater in overall which make a smooth and great quality in video playbacks.

Referred to time traces of quality figure 5.18, the edge UEs had severe quality fluctuation and the qualiy reach stable at about 40 seconds finally. Contention caused stalls and low quality level in edge UE. In our approaches, we maintain the steady quality level of video playbacks.

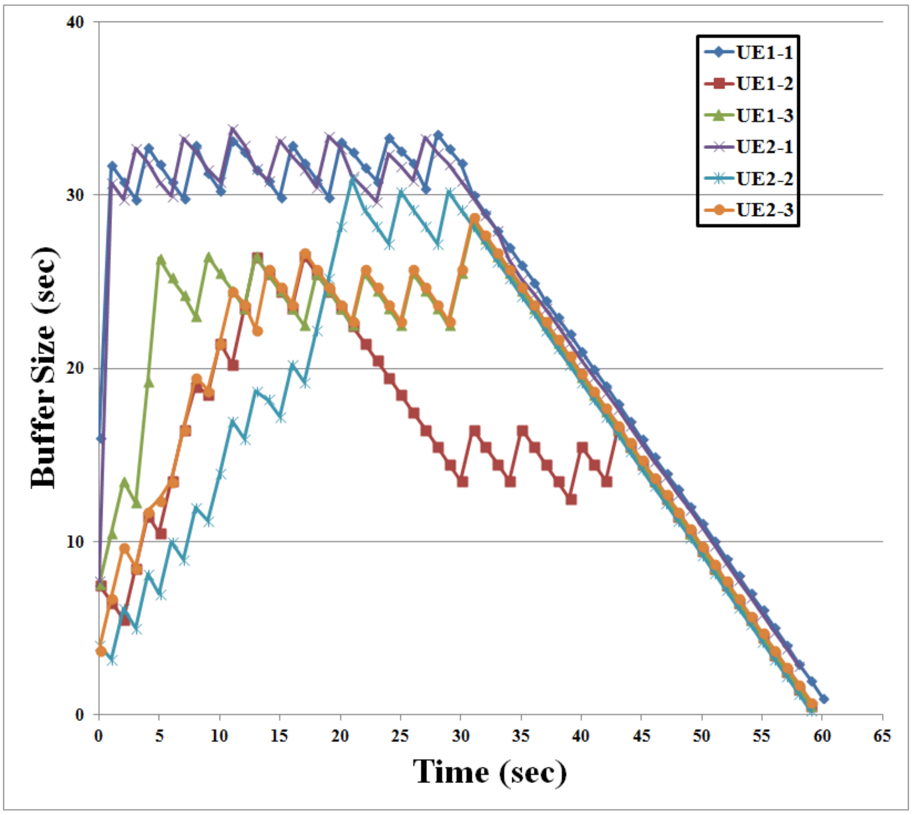
Table 5.14 and 5.15 are the DASH utility score results of default setting and our approaches respectively. Our approaches prevent stall and quality variation. The final utility scores beat the default scheme in all UEs.

Table 5.14: DASH UE utility scores of default setting in scenario 7

	UE1-1	UE1-2	UE1-3	UE2-1	UE2-2	UE2-3	Avg.
Impairment of Initial Delay	3.1904	5.7824	13.7696	1.6064	4.1664	6.0704	5.7643
Impairment of Stall	0	5.4	0	0	0	14.2	3.2667
Impairment of Quality Variation	0	14.9872	18.8695	0	0	0	5.6428
Utility Score	96.8096	73.8304	67.3609	98.3936	95.8336	79.7296	85.3263

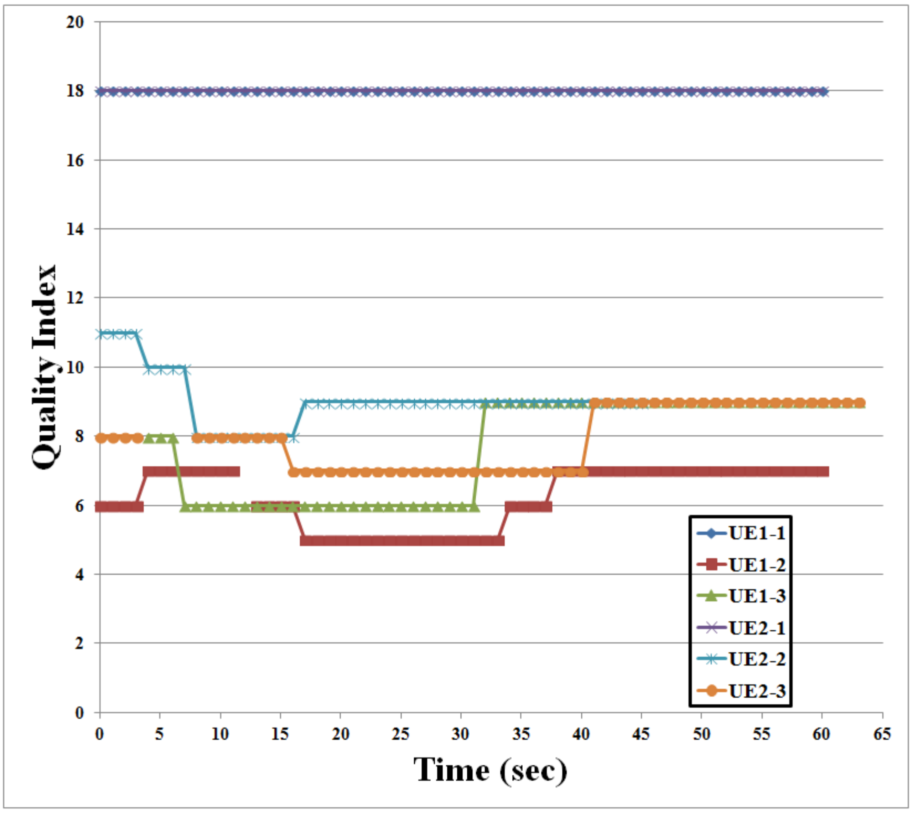


(a) Buffer size time traces of each UE in default setting

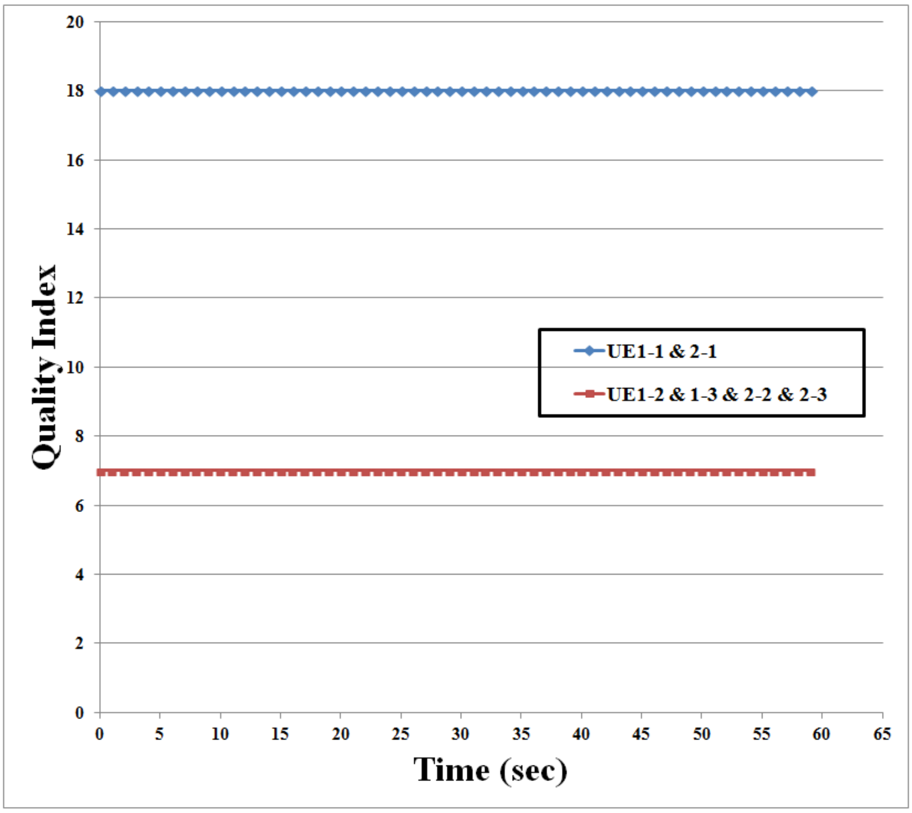


(b) Buffer size time traces of each UE when server-aided rate selection and resource allocation triggers

Figure 5.17: Time traces of buffer size in scenario 7



(a) Video quality time traces of each UE in default setting



(b) Video quality time traces of each UE when server-aided rate selection and resource allocation triggers

Figure 5.18: Time traces of video quality in scenario 7

Table 5.15: DASH UE utility scores when server-aided rate selection and resource allocation triggers in scenario 7

	UE1-1	**UE1-2**	**UE1-3**	**UE2-1**	**UE2-2**	**UE2-3**	**Avg.**
Impairment of Initial Delay	4.1792	4.8416	4.2912	2.016	4.1888	5.3248	4.1403
Impairment of Stall	0	0	0	0	0	0	0
Impairment of Quality Variation	0	0	0	0	0	0	0
Utility Score	95.8208	95.1584	95.7088	97.984	95.8112	94.6752	95.8597

Chapter 6

Conclusion

In this work, our goal does not tend to propose a method in theoretical. Instead, we want to solve real world problems with implementation. In order to implementation, our design accorded with testbed characteristics and followed 3GPP specification. In the begin, we took a lot time in familiar with testbed behavior by firmware code review and testing experiments. Construct solutions steps by steps. Test our methods with testbed experiments to ensure it workable. We improved system throughput by interference management in first. Next, we design a server-aided rate selection procedure. The rate adaption is notified by server rather than traditional client-only approaches. It helps UEs to have a better experience on video playbacks.

In performance analysis, we considered about seven kinds of scenario to cover as many situations in real world as possible. In each scenario, we got real gain in our approaches. The result showed we improve system throughput by interference coordination and we ensure the most proper segment can be downloaded in time for playing to reach a higher DASH utility score.

In this work, different from the previous ones, we design a cross-layer approaches on physical layer interference management and application layer rate selection to improve DASH services in ICI environment. With combination of two aspects, we have more insights on whole wireless network system and its provided services. Finally, we improved DASH services in ICI environment with testbed implementation in this thesis.

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