Master's Thesis

LTE video streaming in real networks

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By

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Abstract

The growing popularity of smartphones has led to a sharp increase of video traffic over mobile networks. In contemporary wireless networks, video streaming sessions are typically treated as best effort traffic, which implies poor user experience when packets are not delivered on time. Another issue with the video streaming is, users' frequently abandon watching a video before play-out is completed. This may result in significant amounts of unnecessary data sent.

The majority of video downloads on the internet are video clip services like YouTube, where the content is pre-recorded and stored on a server. Different video clients download these media files from server using several different video algorithms. Therefore, it is necessary to understand the implications of such video downloading algorithms over a mobile network.

For performance evaluation of video streaming over an LTE network, radio propagation characteristics of a real city in North America are considered. Performance of video services is quantified by the number of satisfied users. Proportional fair scheduler is found to be more suitable in a real LTE network. The performance gains of frame bundling and buffer multiplier are not as large as it was previously reported for hexagonal cells. On the other hand, higher pre buffering time increases performance of the network. The impact on the network capacity and the network burden in terms of unnecessarily sent data is also investigated in case of user abandonment. Moreover, the performance of video service, when user with FTP service co-exists in the network as well as admission control is examined. Finally, a novel algorithm is designed to achieve significant performance gain by reducing inter cell interference.

Acknowledgments

The successful completion of my thesis in wireless technologies in pursuance of the Master's degree in Science is not only a product of the academic insight gained but also the fruition of two wonderful years in one of the best universities of the World for Wireless Communication. The erudition imparted here has honed my skills as a Wireless Communication Engineer while the socio-cultural experiences gathered in the course of my stay has enriched my life in myriad ways. I would like to express my gratitude to a few persons who have been a part of this beautiful journey in Sweden.

First and foremost I would like to thank Lund University, all its professors and their lectures at the department of Electrical and Information Technology for helping me expand and fortify my knowledge domain, required for a promising future. The continuous guidance of Fredrik Rusek, my academic supervisor at Lund University remains unparalleled.

This thesis is the result of extensive research in my desired field of wireless technologies at Ericsson, Kista, Sweden. In this regard, I am extremely grateful to Dirk Gerstenberger, Manager, System and Technology, Development Unit Radio for giving me the opportunity to pursue my research here. I express my heartfelt gratitude to Gunther Auer, System Manager at Ericsson for his continuous help, support and guidance.

I am also thankful to my friends, family and colleagues without whose love, good wishes and unflinching support, my academic endeavors would not have been successful. I would like extend my sincere thanks to my parents for their blessings and my beloved wife Punya Pallabi who has been a constant pillar of support and understanding throughout these years.

I dedicate my MSc. degree to my daughter, Rheanna.

Smruti Ranjan Panigrahi

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Preface

I along with Gunther Auer, System Manager at Ericsson, Kista, Sweden have applied for a patent on our designed algorithm for Inter cell interference coordination for wireless networks. The patent application ID is US61/902930.

CHAPTER 1

1 Introduction

1.1 Background

Wireless communication has been seeing a rapid technological development within the last 20 years. A subscriber was only able to make a voice call or send an SMS in second generation mobile technology (2G). With the latest cellular technology like long term evolution (LTE), other than voice calling or short messaging service (SMS), a variety of other activities like accessing high speed internet, online gaming, video calling, and video conferencing are possible. Continuous demand to perform personal as well as business activities while on-the-go, fundamentally fuels the popularity of today's mobile communication.

Data traffic in mobile communication has grown tremendously in recent years. This is achieved due to the developments of latest mobile terminals which support internet based applications, deep penetration of mobile internet across the globe, and high speed internet access over wireless. A significant portion of this data traffic comes from the video services. According to the Ericson mobility report [18], 90% of total network traffic will originate from video services by the year 2018.

The growing popularity of video services over cellular network is fueled by the latest smart phones and tablets, which are able to provide better display, better sound quality, large screen size, and easy to use application on touch. Moreover, developers are also creating applications which mostly use video services like video telephony, conferencing, and online video streaming. To summarize, growth in data traffic fuelled by video services, faster wireless networks, and powerful user friendly devices have created a burgeoning market for video services and telecom service providers are putting their best effort to capitalize this opportunity. This is why it becomes so important to understand the implication of video services on cellular network.

The majority of video download on the mobile internet are the video clip services from the content provider like YouTube, DailyMotion, SVT Play where the content is pre-recorded and stored in a server. The clients download the video file to view the content and different clients use different request algorithms. In this thesis, the implication of different video algorithms over real LTE mobile networks is studied.

In previous work at Ericsson, the behavior of different video algorithm was analyzed in artificial networks with regular hexagonal cell layout. It was seen, features like frame bundling and pre-buffering time improves the network performance of hypertext transfer protocol (HTTP) streaming video algorithms. However, the choice of network protocol either TCP or UDP/RTP has negligible impact on the performance. For frame bundling server merges more than one video packet to form a bundle, whereas pre buffering refers to storing few seconds of video content before play out. Readers are advised to visit section 2.3.2 to learn more about HTTP streaming, frame bundling, and pre buffering time.

In this thesis, the performance of different video algorithms is compared in real LTE networks. This shall allow for an assessment on how the network capacity and user's perceived quality are affected by the characteristics of real network.

1.2 Study Purpose

The objective behind this thesis to verify the conclusions drawn from previous work on video streaming algorithm in regular hexagonal networks are also hold valid for the real urban network. In abstracts, the following issues are addressed.

- The performance is quantified as network capacity in terms of active and satisfied users per cell. User satisfaction is calculated in terms of frame freeze.

- Performances of different schedulers are evaluated to know which scheduler suits most in real LTE network.

- Performances between different video algorithms in real LTE network are compared and identified most suitable video request algorithms.

- The effect of frame bundling, bundle size and buffer multiplier on video service is also analyzed.

- Burden on network resources when users abandon watching a video in terms of unnecessary data sent is also studied.

- Performance of video service is evaluated, when FTP service co-exists along with the video service.

- Effect of admission control on scheduler performance is also analyzed.

- Finally, performance improvement due to inter cell interference coordination is evaluated.

1.3 Research Approach

The activities of this thesis are divided into four stages: literature survey, understanding the simulator, feature implementation, collection and evaluation of the result.

The first stage of this thesis is a literature study. There are few internal studies in Ericsson already conducted on the performance of the video service on regular hexagonal cells. These reports give good amount of knowledge about the objective behind this thesis. Apart from this, different scholastics papers are studied to gain knowledge about different video models, schedulers in LTE, admission control functionalities, and Interference handling [3], [4], [5], [6], [7], [9], [11], [14], [16], and [17].

The simulation is carried out in a Matlab based simulator, which is internally developed and maintained by the Ericsson, because the simulator is allowed to evaluate major issues reported for video streaming algorithm. Various aspects of physical layer of LTE are implemented. Few of the important implemented functionalities are evolved NodeB (eNB) scheduler, queuing at eNB, interference handling, users' distribution across different cells of the real network, calculation of signal strength from path loss, and traffic generation for different applications.

For the performance evaluations conducted within this thesis a number of features have been implemented to the simulation tool. In contemporary wireless networks, video streaming sessions are typically treated as best effort traffic, which implies poor user experience. Therefore, different schedulers are implemented to investigate its effect on performance of the video services. Proportional fair (PF) and maximum carrier to interference power ratio (MaxCI) schedulers have been implemented so that performance of video service for these schedulers can be compared with a round robin (RR) scheduler. Though a higher performance improvement is observed for the MaxCI scheduler, it is not suitable for a real cellular network as many users with poor radio channels do not get the scheduling opportunities. On the other hand, the PF scheduler maintains fairness while selecting the users. It also achieves 11% better performance than the RR scheduler.

Admission control is also implemented to see its impact on video performance. A proactive measure is taken by considering average utilization of physical resource blocks. In this case, though the numbers of satisfied user counts increases, some of the users with good channel conditions are abstained from being served. Moreover, removing some of the dissatisfied users with poor radio channel from the network is found to be a better choice.

The simulator is also extended to handle user abandonment and inter cell interference coordination. The user abandonment scenario is broken into two different problems, user abandonment due to poor radio channel and user abandonment due to undesired video content. Previous studies at Ericsson have proposed to use higher buffer multiplier[1] to achieve better performance. However, we see, lower buffer multiplier is comparatively better by taking the amount of

[1] Please visit section 2.3.2.1 to know about buffer multiplier.

unnecessary sent data into consideration. A novel algorithm is implemented to improve the network performance by handling the inter cell interference in a better way. In the urban cellular network, the satisfied user count is improved to 37.4%. Even in some of the cells, the performance is enhanced up to four times.

During fourth stage, execution is carried out for different traffic loads and results are saved in the local server. Then these results are then processed to generate different Matlab plots for performance analysis and also Google earth is used to visualize the network performance.

1.4 Thesis Outline

This thesis is organized as follows.

- Chapter 2 provides background knowledge about different kind of scheduler used in this thesis and importance of admission control in LTE. Details about various video algorithms and concepts of inter cell interference co-ordination (ICIC) are also described in this chapter. Finally, this chapter ends with the concept of service abandonment and its implication on a cellular network.

- Chapter 3 starts with a description of the methodology used in the study. There are few major assumptions made during simulation by considering characteristics of a real LTE network and limitations in the simulator. Finally the real network is described in a pictorial way for the reader to visualize cellular network in urban and sub-urban areas.

- Chapter 4 starts with the definition of satisfied user. In-depth analyses of the results are conducted for various issues, which are mentioned in the section 1.2. Google earth is also used to visualize the performance at different cells of urban cellular network.

- Chapter 5 summarizes the thesis and briefed about the important findings of this thesis.

- Since demand for the video service in cellular network is growing continuously, there are many important issues still left to be addressed. The last chapter of this thesis, Chapter 6 highlights some of these issues, which could be addressed in future work.

CHAPTER 2

2 Background Studies

This chapter provides all the details about the theoretical knowledge required to understand this thesis. This chapter starts with the description of different types of scheduler considered like, round robin (RR), proportional fair (PF), and Maximum carrier to interference power ratio (MaxCI). Importance of admission control in LTE is also described. Different video model and concepts of inter cell interference co-ordination are also described in details. Finally this chapter ends with a short description of user service abandonment.

2.1 Scheduler

The scheduler in LTE resides in evolved Node-B (eNB). The MAC protocol stack has the responsibility for scheduling. The data transfer in LTE uses shared physical channel. This makes scheduler an important entity in LTE [10]. The primary function of a scheduler is to select different users in the time domain and assign different physical resource blocks (PRBs) in the frequency domain. The scheduler considers radio channel conditions, quality of service (QoS), mobility, terminal capability, and bandwidth requirement to choose a suitable user while ensuring fairness, stability, and throughput [1] and [3]. Scheduling algorithms differentiate among themselves either in terms of complexity, delay constraint or fairness [2]. RR, PF and MaxCI schedulers are considered in this thesis.

2.1.1 Round Robin (RR) scheduler

The RR scheduler is the simplest scheduler. It assigns the PRBs cyclically to users, those have data to transmit, ignoring their instantaneous radio channel conditions. Physical resources are allocated fairly among the users. As different users see different channel conditions in a real network, overall throughput of the system is not optimal in case for the RR scheduler. However, none of the users suffers starvation from being scheduled.

2.1.2 Proportional Fair (PF) scheduler

The PF scheduling maintains a good trade-off between spectral efficiency and fairness. It achieves these by taking advantages of user's varying radio channel conditions. The scheduling metric of user *i* is given by [2], [3], and [4],

$$P_i = \frac{r_i(t)}{R_i(t)} \tag{1}$$

Where, P_i, r_i and R_i is the weighted scheduling priority, the instantaneous bitrate per PRB, which depends upon signal to interference plus noise power ratio (SINR) observed by the user at the time of scheduling, and the historical average bitrate of the i^{th} user, respectively. The user with highest instantaneous bitrate relative to its historical average bitrate is scheduled at time instant *t*. The PF scheduler also does not suffer starvation from being scheduled. The overall cell throughput is also better than that of the RR scheduler.

2.1.3 MaxCI scheduler

The MaxCI scheduler is alternatively known as MaxSIR scheduler. This scheduler will pick the user for which

$$i = \arg\ \max_i \{S_i\} \tag{2}$$

S_i is the momentary signal to interference ratio (SIR) of the i^{th} user. This scheduler hence selects the user with good radio channel conditions [2]. Though this scheduler achieves highest spectral efficiency, user with poor SIR may get starved.

Fig. 1 gives an intuitive idea about how different scheduler selects user of different radio link quality. The upper part of the figure shows the variation of radio link quality for the different users, while the lower part of the figure shows which user is chosen at different time instances. Red, blue, and black color signify whether user 1, 2, or 3 is selected, respectively. In this figure, it can be seen in case of the MaxCI scheduler user 3 suffers from starvation as the users with best instantaneous channel conditions are served. On the other hand, the RR scheduler maintains fairness among the users and the PF scheduler is exploiting short term channel variations in its scheduling while maintaining the long term average user data rate [5].

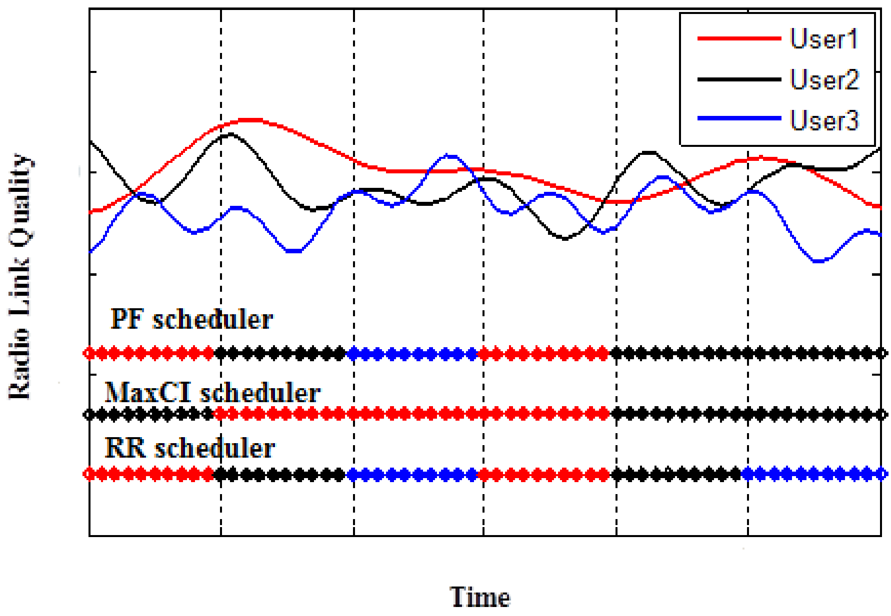

Fig. 1. Operational principle of scheduling algorithms

2.2 Admission Control

The admission control (AC) functionality is located in the layer 3 protocol stacks of the eNB [6]. The task of admission control is to admit or reject a new connection request depending on whether the QoS of a new user can be fulfilled without compromising the QoS of all users in progress in that particular cell [7]. Without admission control, the eNB keeps on adding new users and beyond a certain limit, it cannot satisfy desired QoS for all served users. This results in more and more unsatisfied users. Admission control can take into account resource situation in the cell, the QoS requirement for a new user, priority of the user and its requested service, as well as QoS of the active users in the cell [8].

In this thesis, the admission control decision is based upon average utilization of PRBs. This algorithm is partly motivated from [6] and [9]. A new user will be admitted if the following condition will be satisfied.

$$N_{avg} + N_{new} \leq N_{tot} \tag{3}$$

Where, N_{avg} is the average utilization of the PRBs in a particular cell. N_{new} is the number of PRBs requested by new users to have adequate QoS. This depends upon the SINR observed by that user. N_{tot} is the total number of PRBs in the system bandwidth , e.g. 50 PRBs in case of 10 MHz system bandwidth.

2.3 Video Models

2.3.1 Real time (RT) Streaming

Real time (RT) streaming is a video model which is mostly used in mobile TV or real time streaming services, which use protocols such as real time streaming protocol (RTSP), real time messaging protocol (RTMP), and Microsoft media service (MMS) [11]. Upon reception of an initial request from the client to the server, the server then sends out one video frame at a time with equal time interval. If the video is encoded with 25 frames per second (FPS), then the server sends one video frame in every 40 ms. Here, the server initiates the conversation with the client. Then, there are two separate communication channel set up in between them for data and control messages. The control messages include the commands like ‘play’, ‘pause’, ‘stop’ and ‘seek’ [11].

2.3.2 HTTP Streaming

Video contents are delivered over hypertext transfer protocol (HTTP) in this video model. This is also called as progressive download. HTTP streaming is the most popular video algorithm used in cellular networks with over 98% of total video services [12].

This is due to the popularity of the YouTube, which supports progressive download to watch video online.

Video file is not considered as real time streaming anymore; rather it is downloaded from a web server. The video is temporarily buffered at the local computer or mobile devices. The media player can start playing the video as soon as some seconds of video data is available at the local buffer, which is configured by the video server. User can view the video again and again within the same user session without downloading it one more time [11].

In case of HTTP streaming, the video file is segmented at the server. Media player at the client first downloads the manifest file which contains the information about the URLs of all the available media segments. The media segments are much smaller than the actual media file and contain often around 10 s of media data. The duration of the media data per media segment is described in the manifest file. The media player then downloads all the media segments one after another using HTTP. Those received media segments are concatenated at the play-out buffer of the client.

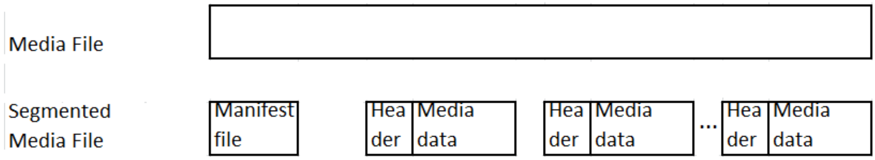

Fig. 2. Segmentation in HTTP streaming

The HTTP streaming is more robust towards the radio channel variations. It is possible to watch 500 kbps encoded video in a 256 kbps connection, which is otherwise not possible in case of the RT streaming. It is obvious in this case, it will take a longer time to download the file and viewer will also experience frequent interruption during the video session. However, buffered data in case of HTTP streaming helps to overcome the above problem, if the period of low bandwidth is temporary.

Progressive download possibly uses either chunk based video model or full file download based video model or Throttling based video model or some variations of these three models.

2.3.2.1 Chunk based video model

In the chunk based video model, the server sends a chunk of data, consisting of many video frames, in response to a request from the client instead of sending these frame by frame at a regular interval.

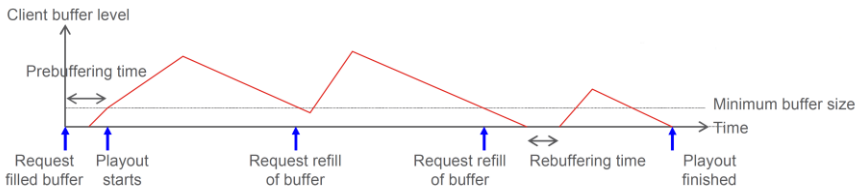

Fig. 3. Chunk based video model

The concept of the chunk based video model is shown in Fig. 3. First, the client sends one request to download the video file to the server via TCP. The client waits for some time before playing the video so that it can buffer the manifest file and also some seconds of media data. This initial waiting period is the pre-buffering time. Refill of the buffer is requested when the data in the local play-out buffer at the client goes below a minimum buffer level. It may happen that the local buffer at the client becomes empty during the video session and the client experiences a frozen image. This situation is called frame freeze. Re-buffering is needed before the client again start watching the video. The time taken for re-buffering is called as re-buffering time. Too many frame freezes during the video session may cause the user to stop watching the video and leave the system.

The Minimum buffer level is configured by the pre buffering time and the buffer multiplier. The buffer multiplier is assigned by the video server. Multiplication of these two parameters gives the minimum buffer level in terms of video play-out seconds. For example, 1 second of the pre buffering time and the buffer multiplier as 3 gives 3 seconds of video play-out seconds as the minimum buffer level. If the video file is encoded with 1 Mbps, then the minimum buffer level is 3 Mb.

In the chunk based video model, server uses frame bundling to form a chunk of data. The server bundles a number of video frames into a media segment, where each bundle consists of a number of consecutive video frames. The client finds out about bundle structure from the information in manifest file. Server sends one bundle of data for each request from the client.

The server can configure different bitrates for each bundle, which gives the client opportunity to improve or degrade the video quality in one session. This rate adaptation is proved to be beneficial in current cellular technology, where radio link quality changes continuously.

2.3.2.2 Full file download (FFD) based video model

The concept of FFD is shown in the Fig. 4 with the line marked in red. In case of FFD, first the client sends one request to download the video file to the server and then whole video file is downloaded via TCP. Then the client waits for pre buffering time to expire before starts playing the video so that it can buffer manifest file and some seconds of media data. In Fig. 4, play out starts at t1 and the client completes downloading whole video file at t2.

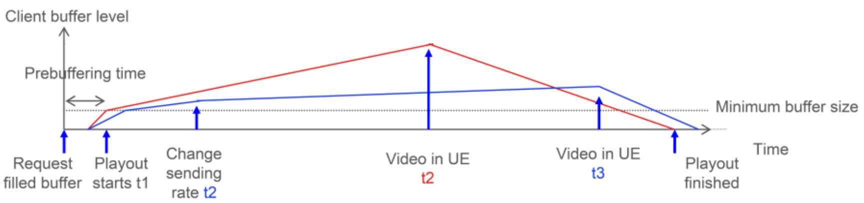

Fig. 4. Video file buffer status in FFD and Throttling based video model

2.3.2.3 Throttling based video model

The concept of the throttling based video model is also shown in Fig. 4 with the line marked in blue. For the throttling based video model, the client sends only one request to download the whole video as in case of FFD download. However, the server sends it in the beginning at 3 time higher bitrate than the actual video bit rate. After some time, the video server decreases the sending rate to 1.5 times higher compare to the actual bitrate. In Fig. 4, change of bitrate occurs at t2 and the video file is downloaded completely at t3.

2.4 User Abandonment

A viewer abandons watching a video on a mobile device either the video has boring and unorganized content, poor quality or frequent frame freeze due to poor received signal power. Visible Measures carried out an online research and found, 20% of the audiences abandon the video within first 10 sec. of playback and 60% of the audiences stop watching the video within first 120 sec., as shown in Fig. 5[2] [17].

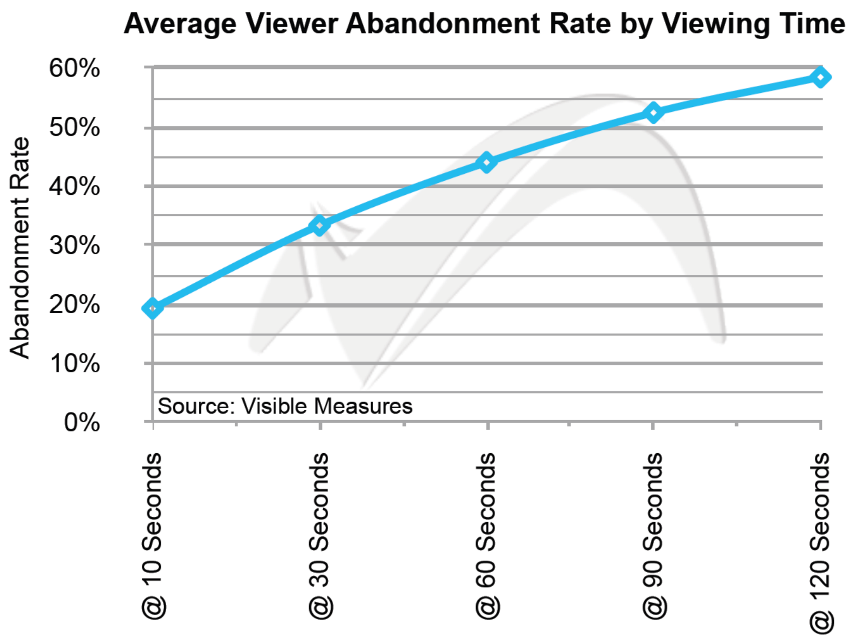

Fig. 5. Average viewer abandonment rate by viewing time

In a cellular network, the operator is concerned about this abandonment of video service as unnecessary sent data create a burden on the network resources. The unnecessary sent data utilize many resource blocks which otherwise could serve other users so that performance improvements in terms of more satisfied users could

[2] This picture is imported from 17

also be achieved. This abandonment also creates a false impression on the operator in terms of actual traffic load in an area and operator possibly set up additional base stations to handle the extra traffic load. On the other hand, most of the subscribers agree with a data plan with the operator, e.g. 2 GB of data usage per month. Subscriber needs to pay more for consuming additional data. Therefore, subscriber is also interested to minimize the volume of unnecessary data due to the abandonment. It is therefore become a topic of interest for the operator to understand implication of user abandonment to keep its subscriber base strong.

2.5 Inter-Cell Interference

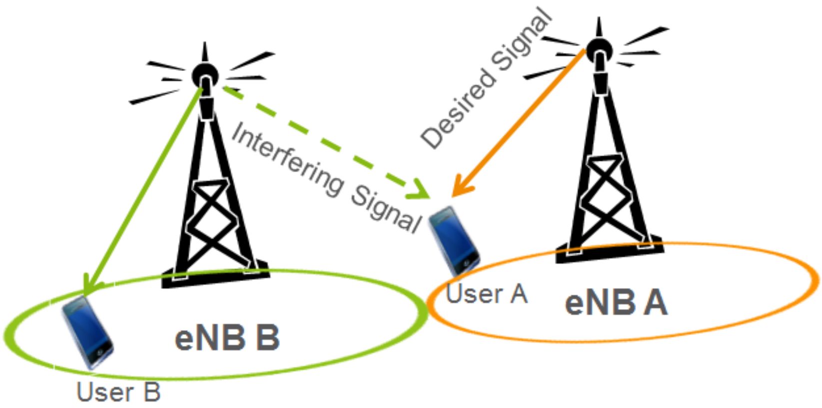

Fig. 6. Principle of interference in LTE

LTE uses frequency re-use factor of one. This means that the same frequency band is used in all cells. In cellular systems like LTE, which reuses frequency across different cells, users observe interference from neighboring eNBs as shown in Fig. 6. Cell edge users may have very low received signal power due to path loss. In this case, the interference from neighboring cells is at par with the received signal and hence, the observed SINR is very low. As a consequence of this, the data rate offered to cell edge users will be very low. Video services, which demands relatively high bit rate, are affected very much. Hence, the cell edge users do not experience a good quality video and frequent interruption might occur while watching the video. It is important to design a cellular system, which can take care of inter-cell interference [13], [5].

In this thesis, inter cell interference scenario is considered for the macrocells. Macrocellular networks fundamentally consist of operator installed base stations where typical cell range varies from a few hundred meters to a few kilometers. These macrocells typically emit a signal power of 46 dBm (40 watts) or higher. They are deployed to serve thousands of customers in a wider area [14], [15].

2.5.1 Inter cell interference coordination

Though the LTE standard does not specify how an eNb should mitigate interference, it facilitates inter cell interference coordination by defining set of messages exchanged via the X2 interface.

- Relative Narrowband Transmit Power (RNTP): RNTP is exchanged to handle interference in downlink. It used by a particular cell to inform its neighboring cells whether transmit power of specified resource block should kept below a certain threshold value [15].

- Overload Indicator (OI): OI is exchanged to handle interference in uplink. It contains the information about the average interference plus noise power (low, medium high) for each resource block. A neighboring eNb. Who receives this message, changes its scheduling behavior to mitigate interference [5], [15].

- High Interference Indicator (HII): HII is exchanged to handle interference in uplink. A cell signals HII to inform neighboring cells that one of its cell edge user is going to schedule in near future and neighboring cells may experience a higher interference from the resource blocks used by that particular cell edge user [5], [15].

As the latency of exchanging the messages over X2 is in the order of tens of milli-seconds, any updates in ICIC messages are relatively infrequent [14].

CHAPTER 3

3 Simulation and parameters

This chapter starts with the study methodology, where it is described how the considered LTE network is simulated. There are few major assumptions made considering a real LTE network and the corresponding limitations in the simulator. This chapter ends with the information about important network parameters and a Google earth view of a real city and cells of urban and suburban area.

3.1 Study Methodology

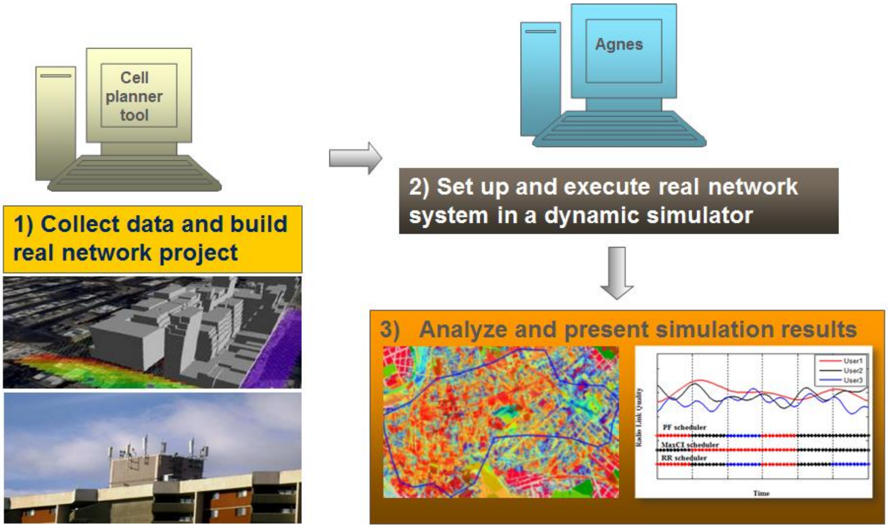

Fig. 7. Study Methodology

This study includes several tasks. As shown in Fig. 7, first a project file of path loss matrix of a particular city is generated by using a cell planner tool. To get as detailed path loss prediction as possible, the project file contains details about building structure with a 5x5 meter resolution of the city. It has information about the path loss from different base stations, location of buildings in the city and also network site data (e.g. antennas, feeder, tilt, power). These parameters are then exported to Matlab. A dynamic network simulator in Matlab, called Agnes is used for simulation. This simulator is modeled as an LTE FDD system. Finally, the saved result is processed in terms of different plots to evaluate the system performance. Google earth is also used to visualize the performance in different areas of the city.

TABLE 1. Important system parameter

LTE 2x2 MIMO	
Bandwidth	**10 MHz**
Carrier Frequency	**740 MHz**
Base station Transmission Power	**2x30 Watts**
Multiple Antenna configuration	**2x2 MIMO**
Video	
Bitrate	**1000 kbps**
Frame size	**40000 bits**
Frame rate	**25 frames/sec**
Session length	**30 sec**
HTTP Streaming	
Pre buffering time	**1 sec**
Buffer Multiplier	**3**
Re-buffering time	**1 sec**
Bundle size	**25 frames**

3.2 *Assumption in Simulation*

- New video sessions are randomly dropped within the considered network following a Poisson distribution. New users are distributed uniformly in each cell. It is also assumed, 80% of the total users are indoor. Each video session is associated with one user.

- Packets are arrived at the eNB according to the chosen video request algorithm. All packets have constant length with equidistant transmission intervals.

- The simulator is not modeled to handle various control and user plane protocol aspects of LTE. Even, some of the physical layer functionalities like channel coding, rate matching, DFT and IDFT are also not modeled. However, all the major issues reported for video streaming those are mentioned in the section 1.2 can be reproduced.

- The radio propagation characteristics of the considered cellular network are imported from a cell planning tool. The propagation characteristics are derived from a map with 5x5m granularity. The map contains building information, such as location and height. There is no explicit modeling of walls inside building but a dedicated indoor path-loss model is employed, which adds a path-loss of 0.8 dB per each meter the radio waves penetrate into the building. The penetration loss of the outside walls of the buildings is also assumed 12dB.

- Although Agnes is a dynamic simulator, a static model is implemented. Thus, the channel gains, which are derived from the imported path-loss coefficients, are frequency-flat and time-invariant. However, the radio channel variations is generated through the inter cell interference.

3.3 Real Network

Fig. 8 depicts a Google earth plot of a real city in North America and the location of cells and the eNbs. The area circumscribed by the green line is the area whose LTE network is interest of our study. The center of this figure, which has very densely situated buildings, is the downtown area. Readers can observe that base stations are also placed more close to each other in the downtown area. This is due to the higher demand for data traffic per area unit in the urban cellular network. The remaining area is sub urban. The position of the base stations in this figure is marked by the yellow colored map pin and cell numbering is with the red color.

The aim of this thesis is to understand implication of video services in the urban area of real LTE network. Still, networks in the sub urban area are also considered in the simulation, as these cells create interference on the urban area networks. To limit interference from sub urban cell to urban network, admission control is always adopted for the new users of the sub urban cells in the simulation.

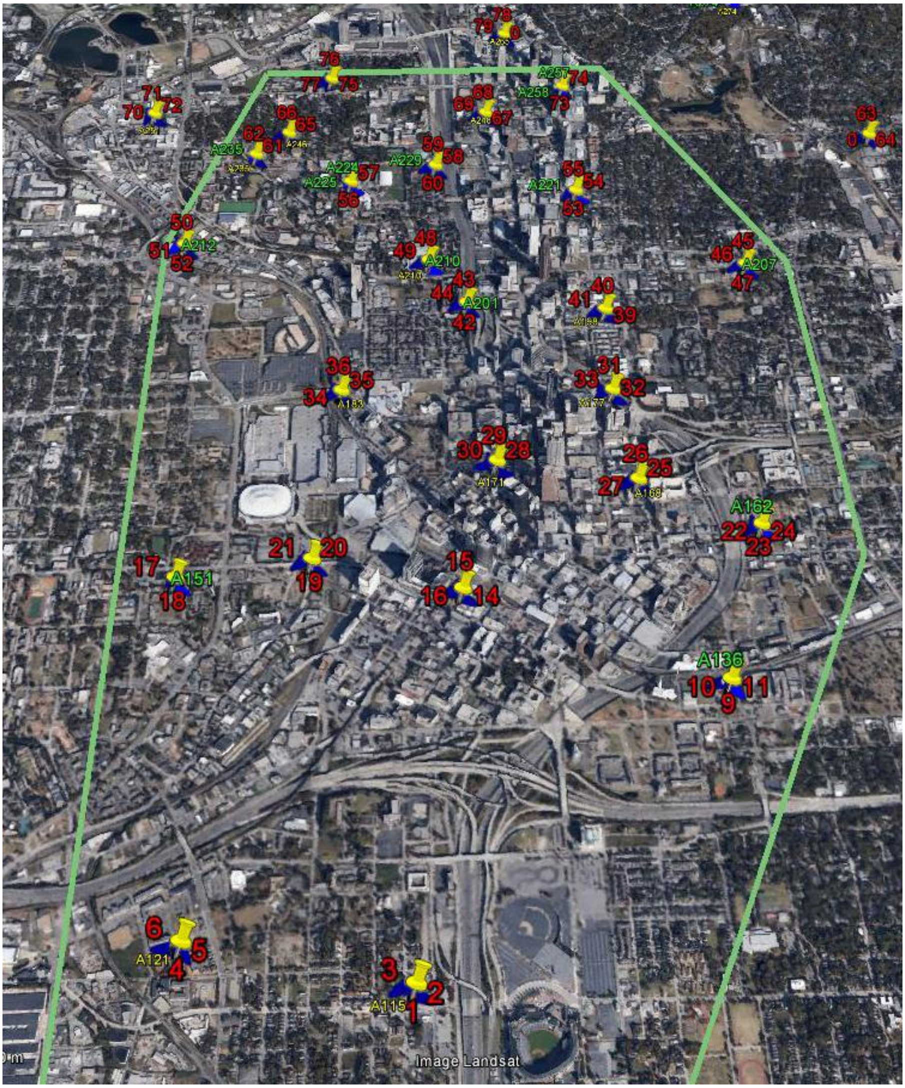

Fig. 8. Google earth view of a real city

The same network inside the green line of Fig. 8 is drawn with Matlab in Fig. 9. Here, the area circumscribed by the red curve is the urban area and rest area is the sub-urban area. In this figure, different areas inside the black curves are different cells and their cell number is also mentioned there. The brown spots are the different buildings according to their sizes. It is necessary for reader to understand distribution of the buildings in different cells as in the simulation it is assumed that 80% of the users are indoor.

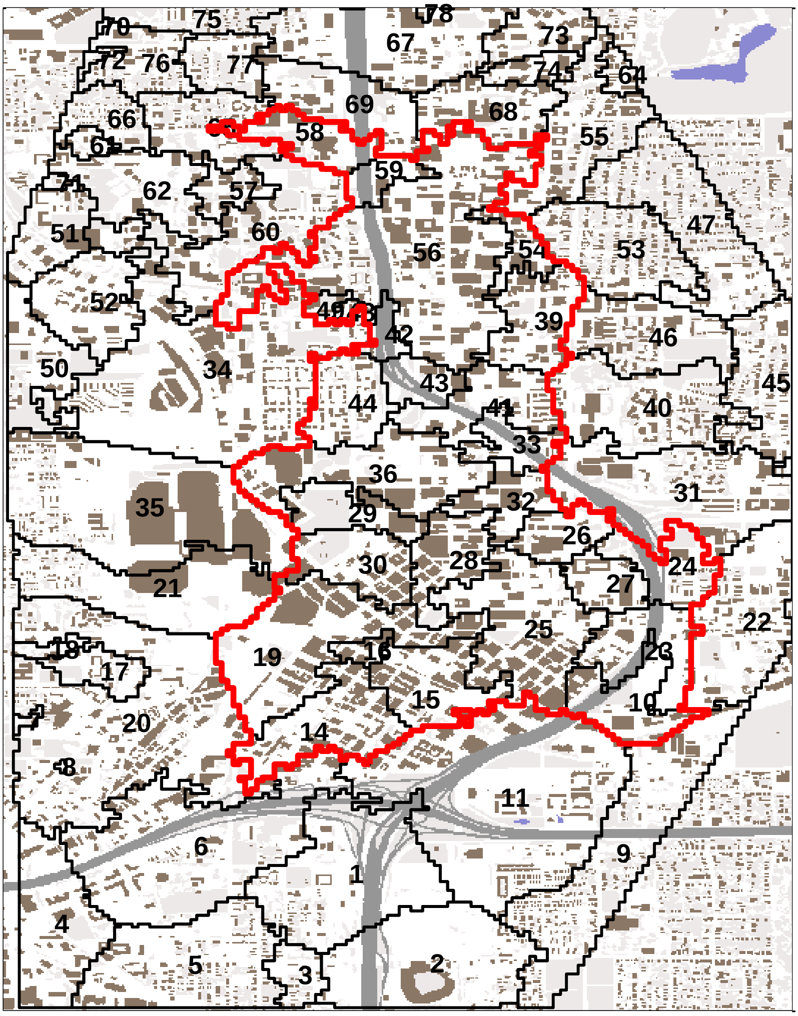

Fig. 9. Matlab plot of the real network

CHAPTER 4

4 Results and Discussions

This chapter starts with defining criteria for the user satisfaction. In-depth analyses of the results are conducted for various issues, which are mentioned in the section 1.2, with the help of different Matlab plots. Google earth is also used to visualize the performance at different cells of the urban cellular network.

4.1 User Satisfaction criteria

Empty data in the client's local play-out buffer causes frame freeze. The user satisfaction is quantified in terms of number of frame freezes. In our simulation, a user is considered happy if the following two conditions are satisfied.

1. A user completes watching the whole video clip, whose total play-out time is thirty seconds.

2. There is a maximum of one second of frame freeze.

4.2 Performance comparison between schedulers

The performance between the Max CI, the PF and the RR schedulers is compared in terms of number of active watchers and number of satisfied users per cell at different traffic loads. The simulation time span is 10 minutes and it has a warm up period of 1 minute. The users, which are created during the warm up period, are excluded from the performance analysis. The configured traffic load determines the number of active watchers in a cell.

Fig. 10 shows the performance of the investigated schedulers in terms of the number of users, who have completed their sessions and the number of satisfied users. The performance of these schedulers is almost identical at lower traffic loads but as the traffic load increases, a difference in the performance between these schedulers is observed. The MaxCI scheduler outshines the PF and the RR schedulers at higher traffic loads as the MaxCI scheduler has almost twice as much as satisfied users in comparison to the RR and the PF scheduler. However, a Max CI scheduler may not be preferred in a real LTE network. A constant video bit rate of 1 Mbps is considered for all the users in our simulation. This is why; the Max CI performs better here. However, presence of different user equipment categories and the large range of requested video bit rates leads to an unfair allocation of resources. User equipment with the better hardware can support higher video rate and hence, it consumes more bandwidth. These users possibly cause starvation to the other users present in that cell that experience less favorable channel conditions. Also in this work, it has been seen that some of the users with poor radio link quality are not scheduled at all.

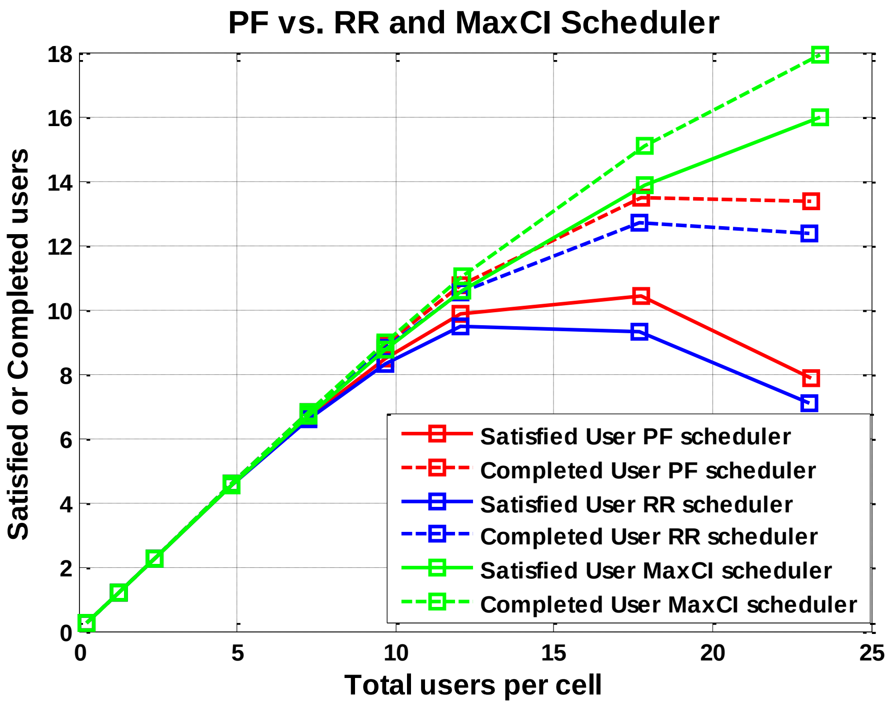

Fig. 10. Performance Comparison between PF vs. RR and MAX CI

Fig. 10 also depicts the performance of the PF and the RR scheduler at different traffic loads. All the users who have completed their session are satisfied at lower traffic loads. However, the difference between the numbers of users who have completed their session and the number of satisfied users starts to widen as the traffic load increases. The performance of these schedulers starts to worsen as number of users in the cells increases. This is due to more number of users are competing to access same set of physical resources. Even the inter cell interference also increases along with the traffic loads and hence the SINRs observed by the users' decrease.

Among the PF and the RR schedulers, the PF scheduler outperforms the RR scheduler in terms of number of satisfied users as the waiting period for a user to get scheduled is found to be less in case of the PF scheduler. The PF scheduler has 11% more satisfied users than the RR scheduler at higher traffic loads, as shown in Fig. 10. The advantage of the PF scheduler is, it enhances the chances of scheduling to users with good channel conditions, without ignoring the users with poor radio channels.

An in depth analysis is carried out across the cells of the considered urban network, in order to understand distribution of users' average SINR and its variations throughout a video session, which causes the difference in the performance among the cells either for a particular scheduler or between the different schedulers. Fig. 11 shows the performance comparison in terms of satisfied users for the PF as well as the RR schedulers for the cell IDs 15, 16, 43, and 59 at medium and high traffic loads. These four cells are chosen because each of them shows different performance behavior. The number of satisfied users in cell 16 and 59 for the PF scheduler is comparatively better than the average performance of the overall network (Fig. 10). On the other hand, satisfied users counts are significantly lower in case of cell id 43. While the performance difference among the PF and the RR schedulers in cell 59 is quite large, both of these schedulers have similar performances for the cell 15, 16 and 43. Readers are advised to see Fig. 8 and 9 in Chapter 3 to know the location of these cells in the real urban network.

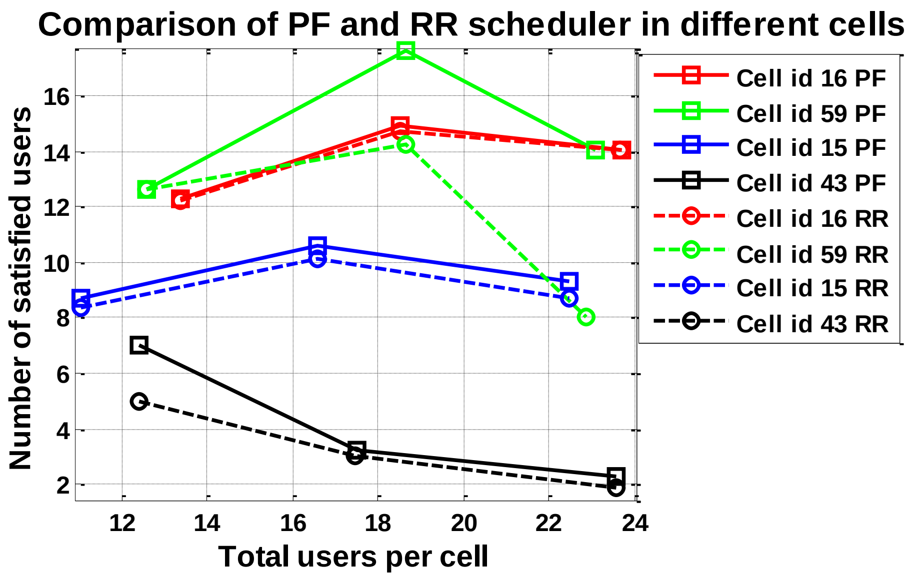

Fig. 11. Comparison of PF and RR scheduler in different cells

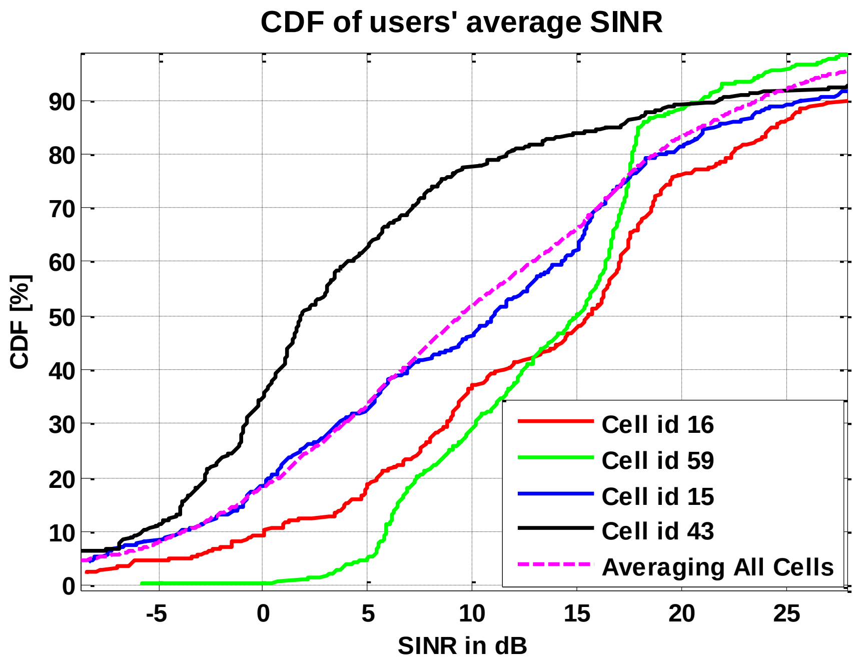

Fig. 12. Cdf plot of users' average SINR

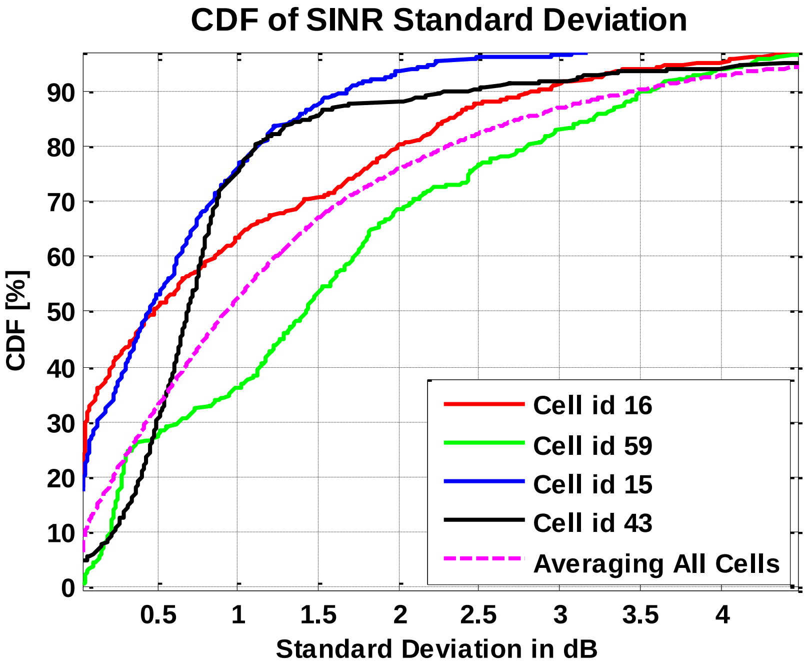

Fig. 13. Cdf plot SINR standard deviation

The average SINR and the SINR standard deviation are plotted in Fig. 12 and 13, to further understand the above performance differences among those cells. Fig. 12 represents the cumulative distribution function (cdf) of the average SINR for the PF scheduler at 100 Mbps/km^2 traffic load, e.g. 23.7 active watchers per cell. The number of dissatisfy users in a particular cell mostly depends upon the percentage of users with poorer SINR. The cells that have more number of users with less average SINR have in general more dissatisfied users. For instance, Fig. 12 shows that the cell ID 16 and 59 have the less users at the lower SINR region in the cdf plot of the average SINR, while the cell 43 has more users with poor SINR. Therefore, the cells 16 and 59 have higher number of satisfied users in the considered urban network.

The performance difference between the RR and the PF scheduler in a real cellular network fundamentally depends upon both the average SINR and the variations of users' SINR during the video session. Cells with SINR standard deviation, comparable with respect to users' average SINR have shown the performance difference between the PF and the RR scheduler. This is because, in these cells, the average waiting period for the users to get schedule is less in case of the PF scheduler. Fig. 13 shows the cdf plot of the standard deviations of users' average SINR seen during their video sessions at 100 Mbps/km^2 traffic load. Cell 59 has a mean of users' average SINR of 14.1 dB and mean of SINR standard deviation is 1.66dB. Therefore the PF scheduler performs a lot better than the RR scheduler in this cell (Fig. 11). On the other hand, the mean of user's average SINR is 14.7db and the mean of SINR standard deviation is 1 dB in cell 16. Hence, the PF and the RR scheduler perform identically in this cell (Fig. 11). Moreover cell 15 has a lower average SINR and SINR standard deviation in comparison to cell 16. Still small performance difference between the RR and the PF scheduler can be observed as the variation of SINR is comparable to users' average SINR in this cell.

Therefore, we find the PF scheduler more suitable for the considered urban network.

4.3 Comparison between RT and HTTP streaming

Fig. 14 shows the performance comparison in terms of number of completed and satisfied users between the RT and HTTP streaming video algorithms for the PF scheduler. The performance difference between the RT and the HTTP streaming video algorithm is insignificant. The RR scheduler also shows similar results. However, the HTTP streaming algorithm is found to have a bit higher user satisfactions in comparison to the RT streaming in some cells at higher traffic load. This is due to the packet bundling and the initial pre buffering in case of the HTTP streaming maintain a higher buffer fill level at the client, which helps the client to survive the temporary poor radio channel conditions. Packet bundling in the HTTP streaming algorithm also leads to a better utilization of the available frequency resources as more bits can be transferred per scheduling instances. For Example in Fig. 15, the HTTP streaming video algorithm has 5.25% more satisfied users in cell 16 at 100 Mbps/km^2 traffic load.

As 98% of the total video traffic in a cellular network is contributed by the HTTP streaming video algorithms, here onwards performance of the video service is only analyzed for the HTTP streaming.

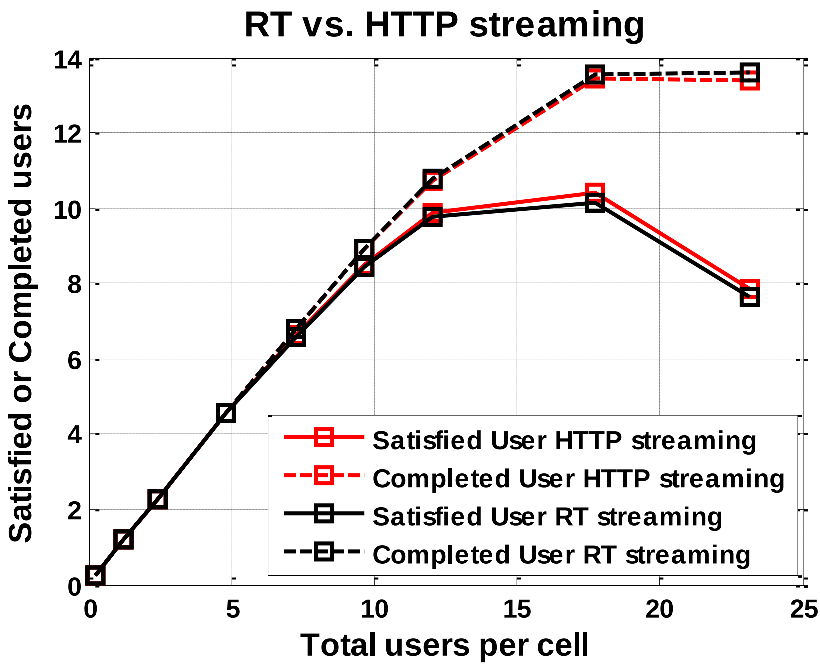

Fig. 14. RT vs. HTTP streaming video algorithm

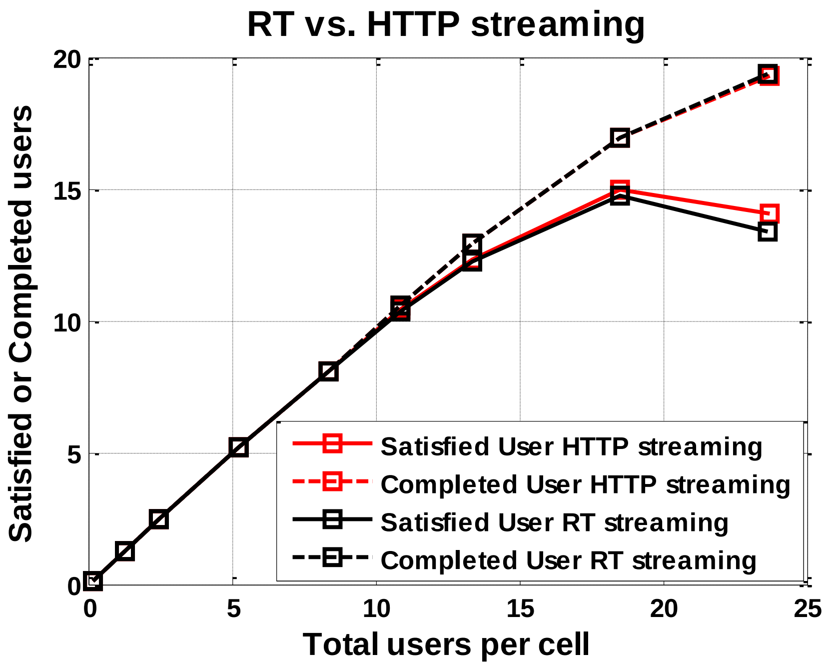

Fig. 15. RT vs. HTTP streaming video algorithm in cell 16

4.4 Effect of pre buffering time and bundle size

As described in section 2.3.2.1, pre buffering time is the time taken between initial buffer fill request to server and start of video play-out. Increasing pre buffering time (PBT) gives a performance improvement at higher traffic load. A client maintains a higher average buffer fill level due to initial pre loading of the video data. This reduces the possibility of frame freezing and hence, the number of satisfied users increases. Fig. 16 shows the performance improvement in terms of number of satisfied users when pre buffering time is increased from 1 to 5 second. At a higher traffic load of 100 Mbps/km^2, the pre buffering time of 5 second has 20% more satisfied users. On the other hand, increasing the buffer multiplier (BMUL) does not improve the network performance (Fig. 16) as this does not give any advantage to the average buffer fill level.

Fig. 17 shows the distribution of the average buffer level of different users at 100 Mbps/km^2 traffic load. A similar pattern is also observed for other traffic loads. For a pre buffering time of 1 sec only 34.5% of the users are satisfied. Users with lower average buffer level are mostly dissatisfied. In this Fig. 17, the curves with buffer multiplier as 3 and 5 overlap till the average buffer level approaches 2000 kbits. Almost 65% of the users have buffer fill level less than 2000 kbits and they are mostly the dissatisfied users. However, users' with pre buffering time of 5 sec have a higher average buffer fill level than users' with pre buffering time of 1sec. This proves, why there is no performance gain in case of different buffer multiplier with same pre buffering time. Moreover, the number of satisfied users increases in case of a higher pre buffering time.

Although there is a performance improvement observed in our simulation, previous studies on artificial hexagonal network within Ericsson show that the pre buffering time does not improve the performance. One of the possible reasons behind this difference in the observations might be due to criteria considered for user satisfaction. It is also found that [19] viewers, connected to faster devices or networks are less tolerant towards the startup delays and so abandons sooner. Therefore, it is not a good idea to increase the network performance just by increasing the pre buffering time.

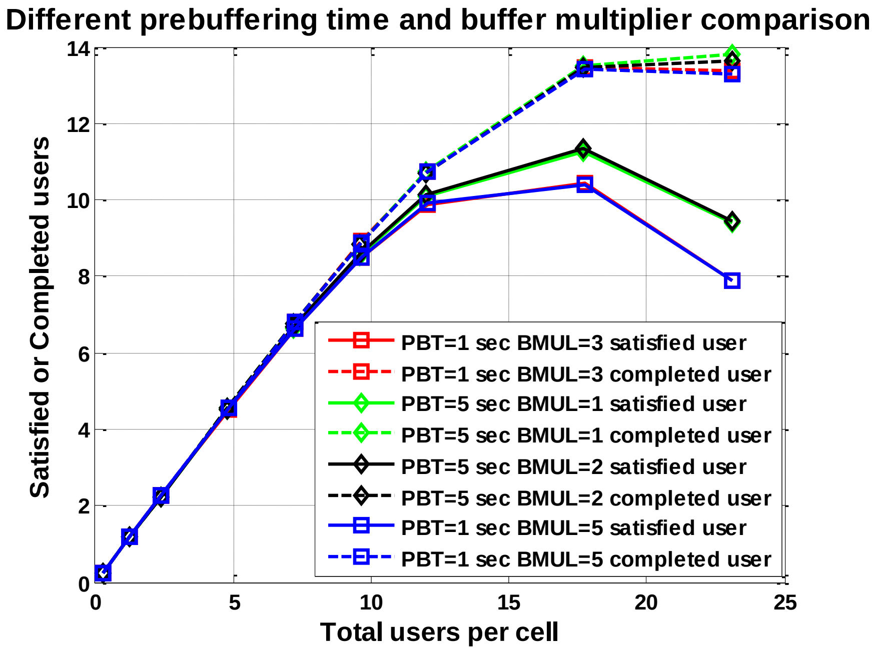

Fig. 16. Comparison between different PBT and BMUL

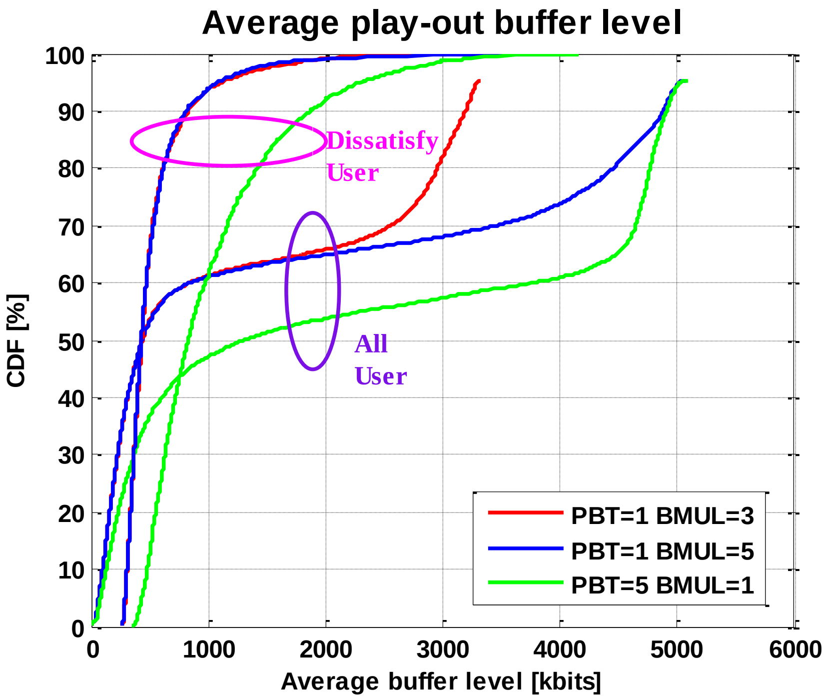

Fig. 17. Average play-out buffer fill level at 100 Mbps traffic load

As described in section 2.3.2.3, in case of frame bundling in HTTP streaming, the server bundles a number of video frames and sends one bundle of data per buffer fill request. Simulations are carried out for bundle sizes of 10, 25, and 50 with pre buffering time of 1 second and buffer multiplier of 3. Network performance does not vary much for different bundle sizes. Fig. 18 gives a performance comparison in terms of satisfied users and it can be observed that satisfied user count is almost constant for bundle sizes 10, 25, and 50 at all traffic loads. This observation also contradicts with the earlier findings of artificial hexagonal network, where it was concluded, higher bundle sizes give better performance.

However, performance in some cells at higher traffic load, like cell 59 for bundle size 10 is slightly better than bundle size 25 and 50 as shown in Fig. 19. The SINR variations in radio channels are higher in this cell due to inter cell interference, as seen in Fig. 13. Average SINR and PRBs utilization is similar in all the three bundle sizes. The average buffer fill level is somehow higher in case of bundle size 10, which gives better performance.

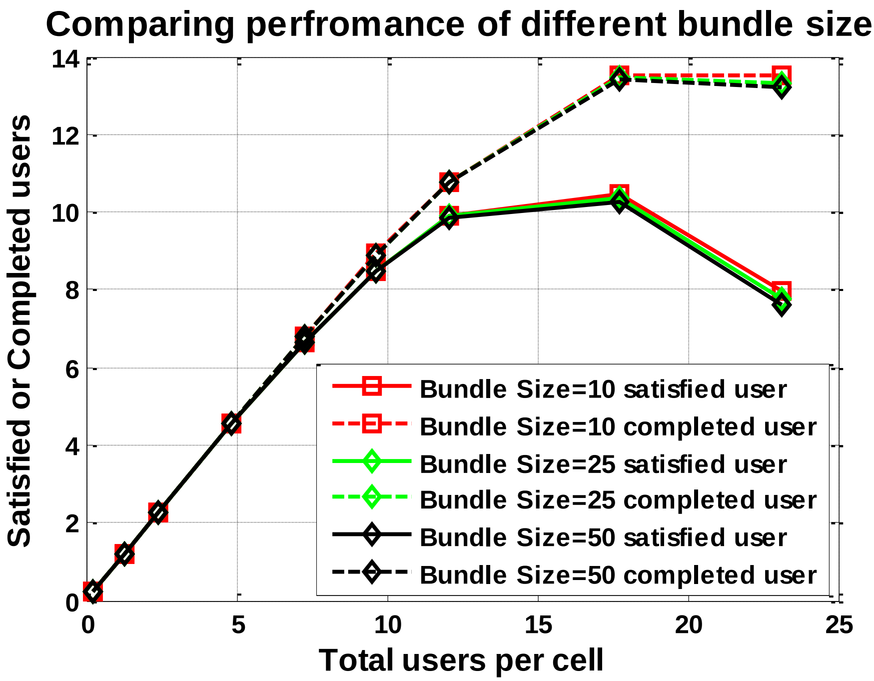

Fig. 18. Performance comparison between different bundle sizes

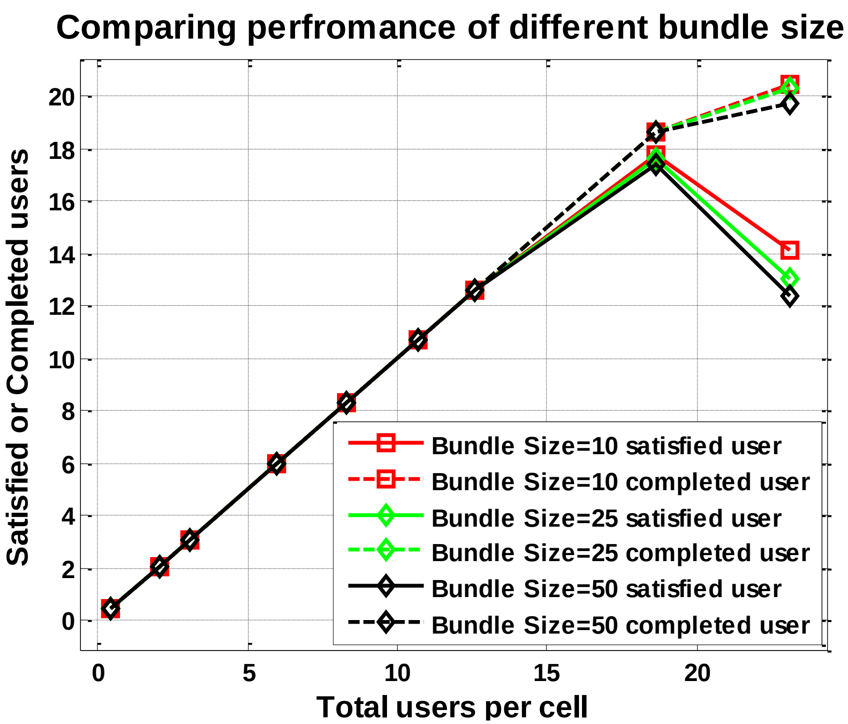

Fig. 19. Performance of different bundle size in cell 59

4.5 User abandonment

4.5.1 Abandonment due to poor video quality

Frequent frame freezes during the course of video session causes user dissatisfaction. It possibly pushes user to stop watching the video after a certain number of frame freezes. Four frame freezes are considered enough for a user to abandon watching the video in our simulations.

There is a performance improvement observed in case of user abandonment due to poor video quality. Those users, who stop watching the video and leave the network, mostly have poor SINR. These users demand more PRBs when scheduled. The remaining users observe better SINR and hence, utilize less number of PRBs for the same amount of data transfer. Lower resource utilization by the remaining users results in a performance gain in case of user abandonment. This can be verified from Fig. 20 and Fig.21. Fig. 20 compares the system performance in terms of number of satisfied users for both with and without user abandonment. Fig. 21 shows the difference in average resource utilization for both cases. Average resource utilization is less in case of user abandonment. Number of abandoned users increases with increasing traffic load, as seen from Fig. 22. It is seen that a growing number of users increases interference and hence, more PRBs are needed for data transfer. It can be observed from Fig. 22 that only 1.88% of total users abandon their call at 100 Mbps/km^2 traffic load. On the other hand, the number of satisfied users becomes almost doubled as seen from Fig. 20.

Fig. 23 shows the amount of abandoned data, which was in the play-out buffer before the user abandons the video service. The amount of abandoned data increases with the traffic load as more and more users quit watching the video. Only 0.47% of data is abandoned out of the total sent data at a traffic load is 100 Mbps/km^2. Service abandonment due to poor radio quality is found to be beneficial for the cellular network.

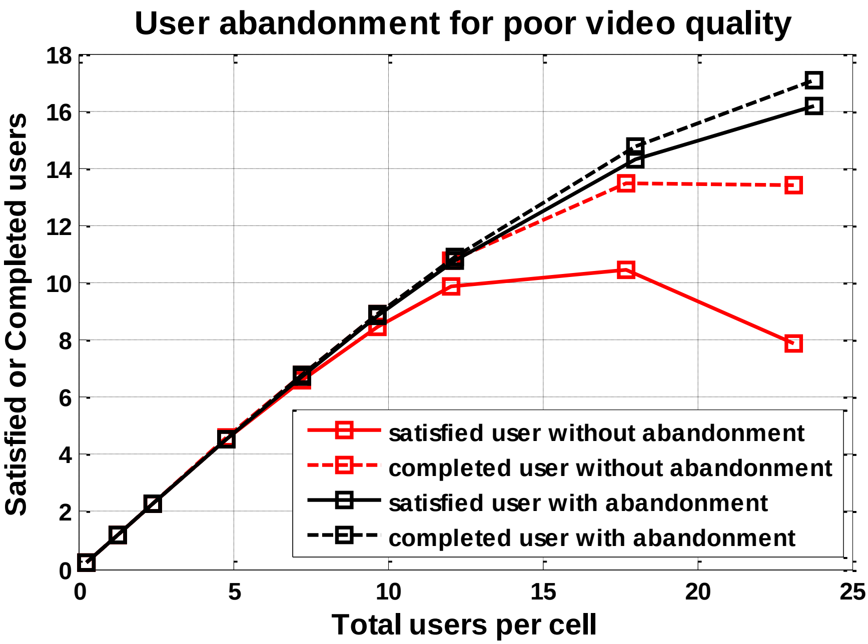

Fig. 20. Comparison between with or without abandonment

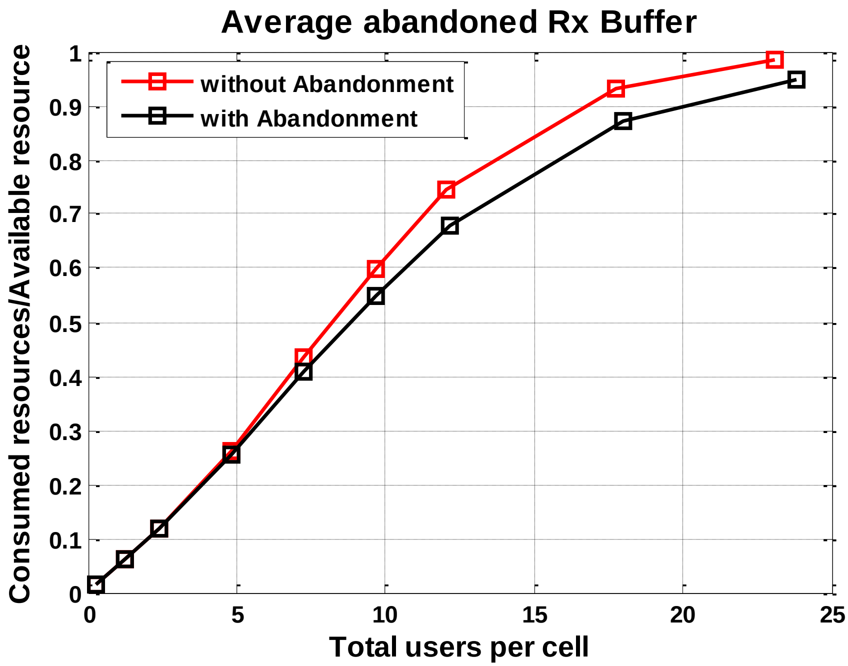

Fig. 21. Average resource utilization with and without abandonment

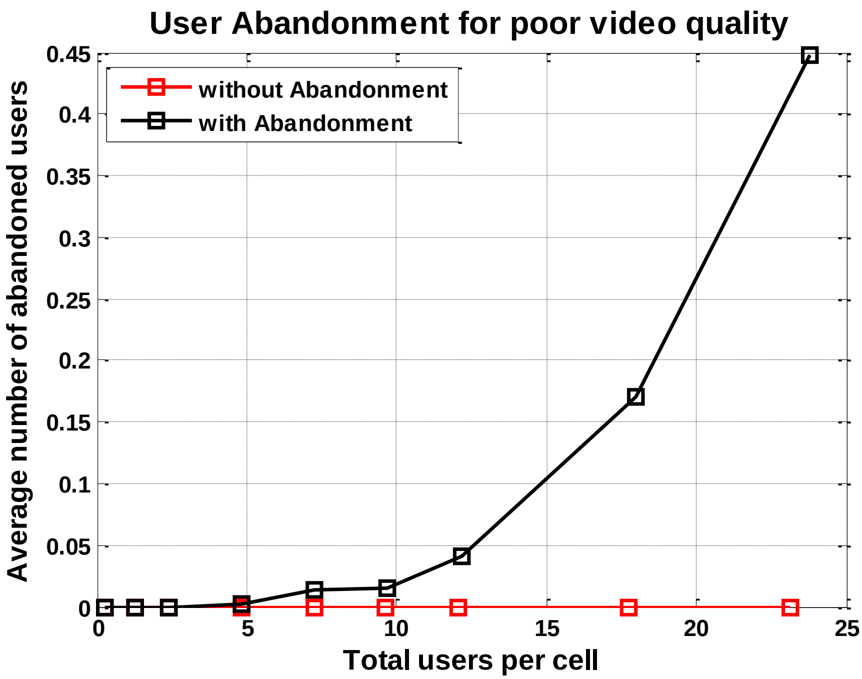

Fig. 22. Number of abandoned users at different traffic loads

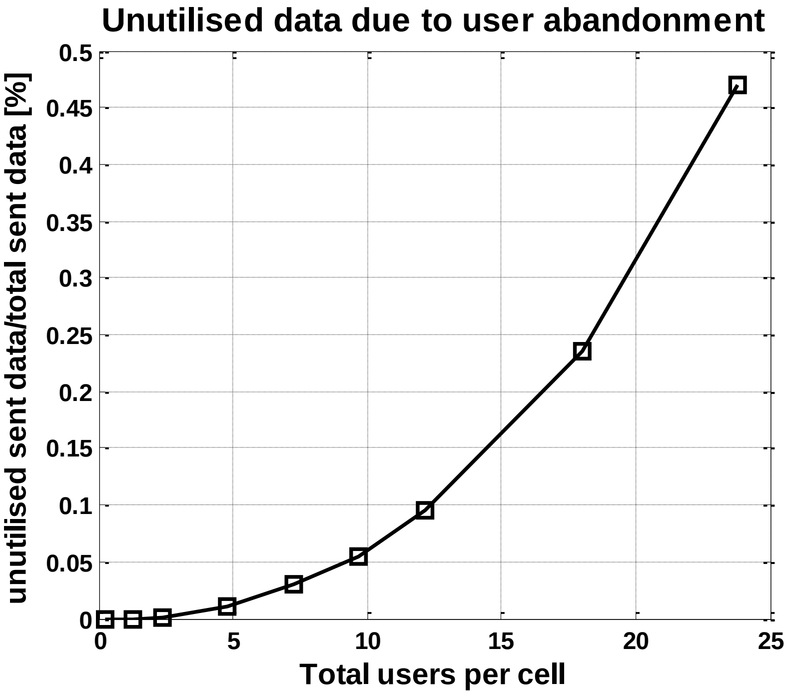

Fig. 23. Average Buffer content before abandonment

4.5.2 Abandonment due to undesired video content

If a subscriber does not show further interest in watching the video, he/she may occasionally stop watching and abandons the video session. As mentioned in the section 2.5, Visible Measures [17] carried out an online research and found that 20% of the audiences abandon watching their video within first 10 seconds of playback and within 30 sec, 35% of the audiences abandon the video session. The average users abandonment rate by viewing time, which are used in our simulations, is mentioned in TABLE 2. Performance evaluation are carried out with this assumption to estimate the amount of unnecessary sent data due to the user abandonment and to find out its correlation with the minimum buffer level. Therefore, performance is analyzed between different buffer multiplier when the pre buffering time (PBT) is 1 second. The simulation time span is considered as 1200 sec. and the warm up period is 60 sec. Video session length is considered as 30 sec.

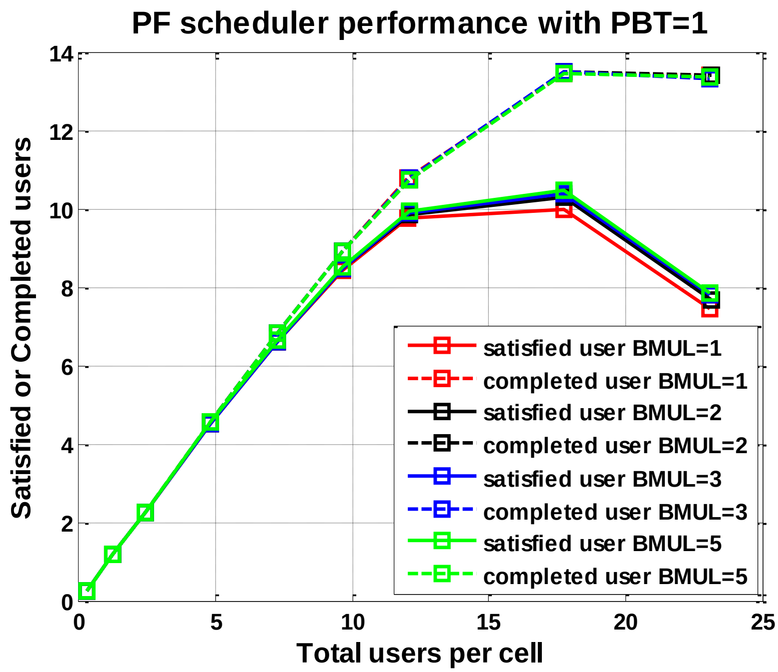

Fig. 24. PF scheduler performance with PBT=1

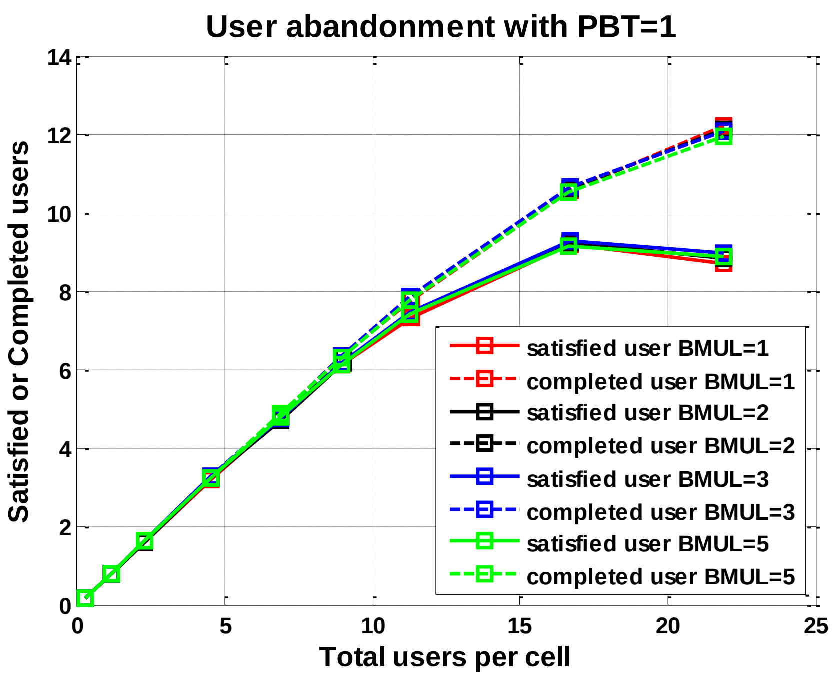

Fig. 25. User abandonment with PBT=1

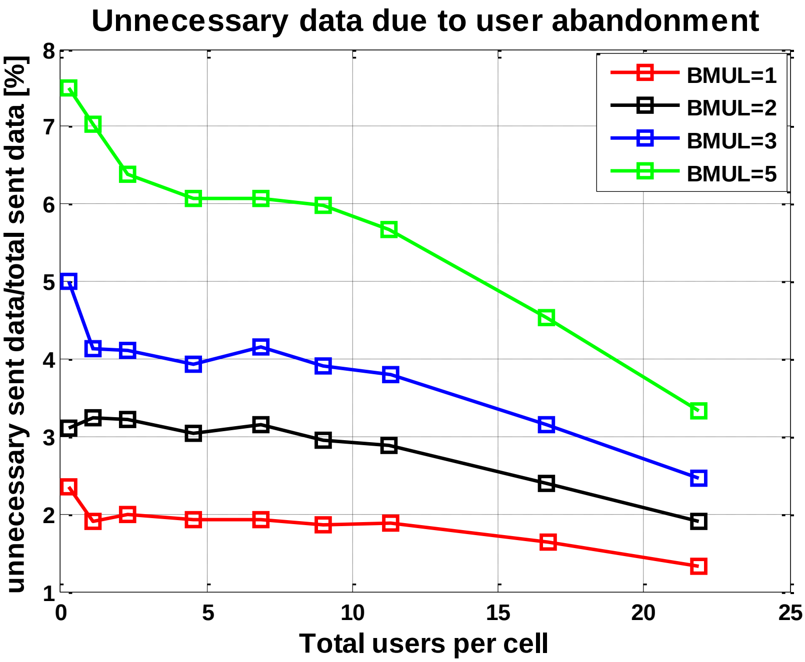

Fig. 26. Unnecessary sent data due to user abandonment

TABLE 2. Average user abandonment rate by viewing time

Maximum Playout time before abandonment	**Abandonment Percentage**
0-10 sec	**20%**
10-20 sec	**10%**
20-30 sec	**2%**

Fig. 24 represents a performance comparison between different buffer multipliers without user abandonment. The number of satisfied users is almost equal in case of buffer multipliers of 2, 3, and 5. However, the satisfied user count drops 4% to 6% at higher traffic loads for a buffer multiplier of 1.

Fig. 25 shows performance of different buffer multiplier in case of user abandonment. The satisfied user count increases 12.6 % with respect to the scenario without user abandonment. The improved performance is due to the presence of less number of users in the network. Moreover, the video performance is similar between different buffer multipliers.

As described in section 2.3.2.3, the buffer multiplier is an important parameter to configure the minimum buffer level, e.g. when the client sends a new request for another bundle of data. The lower the minimum buffer level, the less is the unnecessary sent data. Fig. 26 compares the percentage of unnecessary sent data with respect to total sent data for different traffic loads. The percentage of abandoned data decreases with increasing traffic load. At higher traffic loads, the eNBs have more users to schedule and overall performance of the system also decreases due to inter cell interference. Hence, lesser amount of data is abandoned as users' average buffer fill level is less at higher traffic load. From Fig. 26, a buffer multiplier of 1 has the lowest percentage of abandoned user data.

Previous studies at Ericsson on regular hexagonal cells concluded that video performance is better with higher buffer multiplier. In this study, we see that performance of video services is similar between different buffer multipliers and a smaller buffer multiplier is found to be beneficial in terms of less abandoned data.

4.6 Effect of Admission control on performance

Admission control (AC) is implemented in order to maintain a stable queue at eNB. AC compares the amount of PRBs, which a new user is anticipated to consume with the available resources in a given cell. Only if the available resources exceed the requested resources, a new user will be admitted.

The network performance improves, as less number of users is scheduled in case of the admission control. Fig. 27 shows the performance comparison of the network in terms of satisfied users between with and without admission control. The satisfied users count at higher traffic loads increases when the admission control is implemented. Even all the users, who are able to complete their video session, are also satisfied.

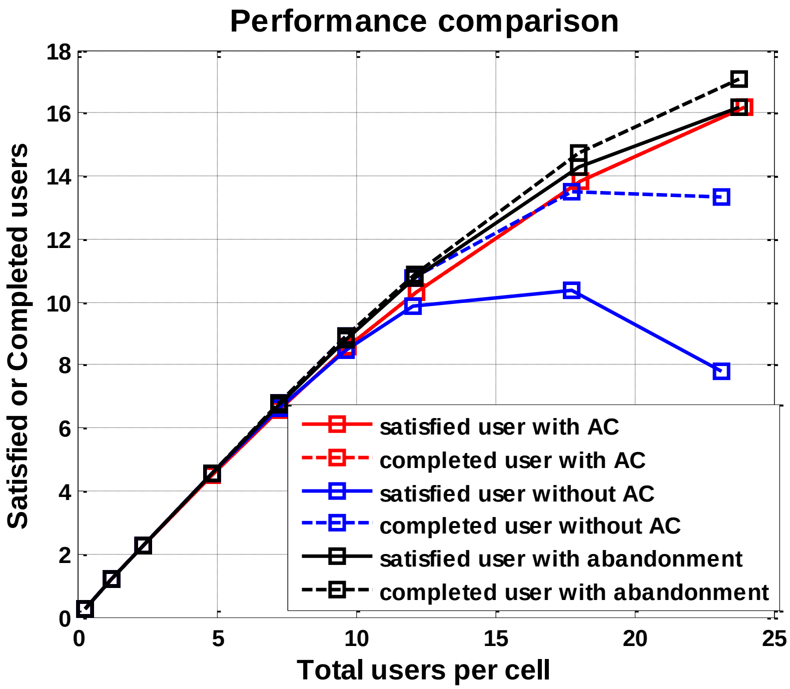

Fig. 27. Performance impact due to AC

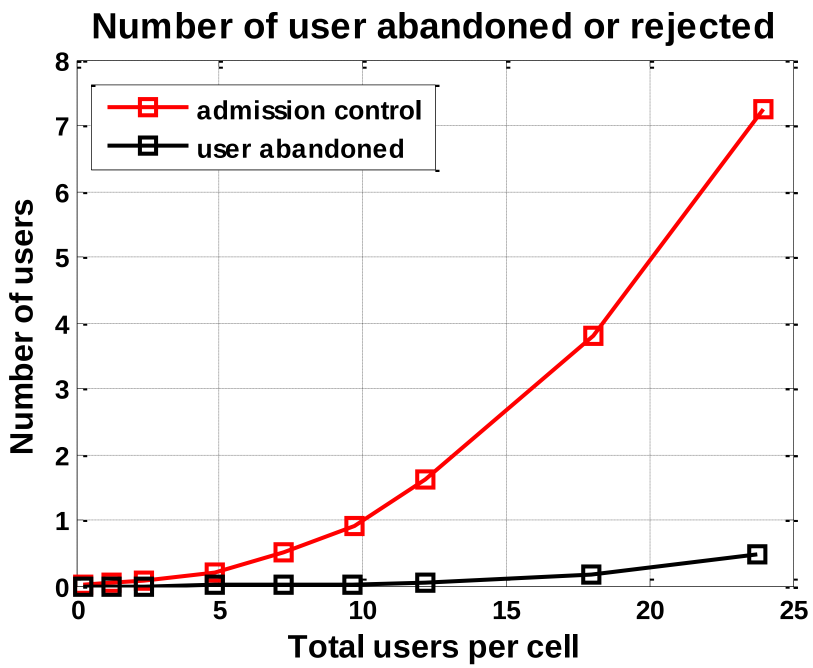

Fig. 28. Number of rejected or abandoned users

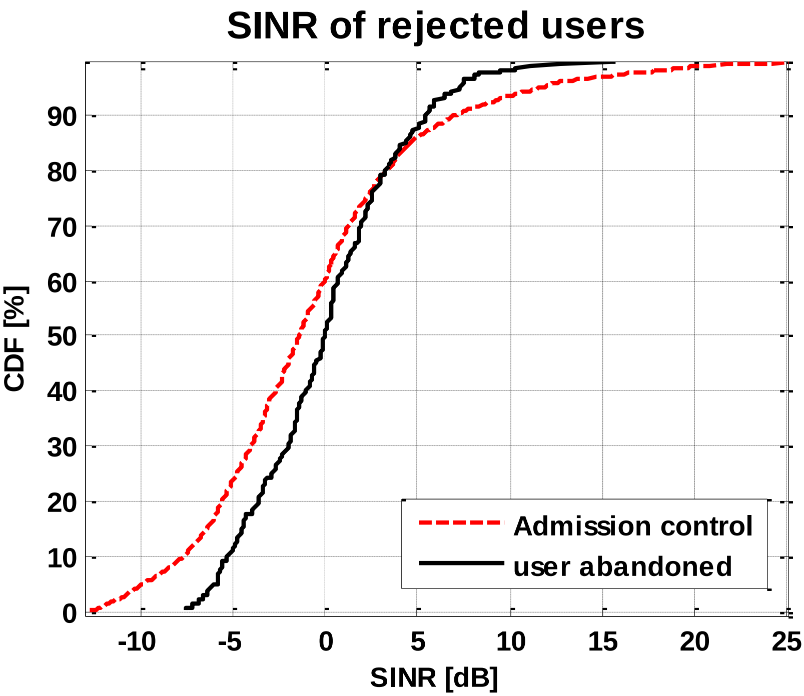

Fig. 29. SINR comparison between rejected users

Fig. 28 shows the number of users rejected by the admission control policy. The count increases with the traffic loads. Although number of satisfied user count increases, some of the new users do not get opportunity to get scheduled. In case of traffic load 100 Mbps/km^2, almost 30% of the users are rejected by the admission control. In Fig. 27, a comparison is also done between number of user rejected by the admission control and abandonment of users with poor radio channel. In our simulation, a user is abandoned from the service if four frame freezes would happen. The performance in terms of satisfied user is identical in both the case as seen from Fig. 27. However, admission control rejects more user than the abandonment technique.

Fig. 29 shows the cdf plot of SINR distribution of the users, which are rejected by the admission control policy at 100 Mbps/km^2 traffic load. 14 % of the users have the SINR more than 5dB. The users, who have significantly higher signal strength and also get rejected due to admission control, definitely bear a negative impression towards the operator. On the other hand, the users, which are preempted from their services, have much lower average SINR.

4.7 Coexistence of video and FTP service

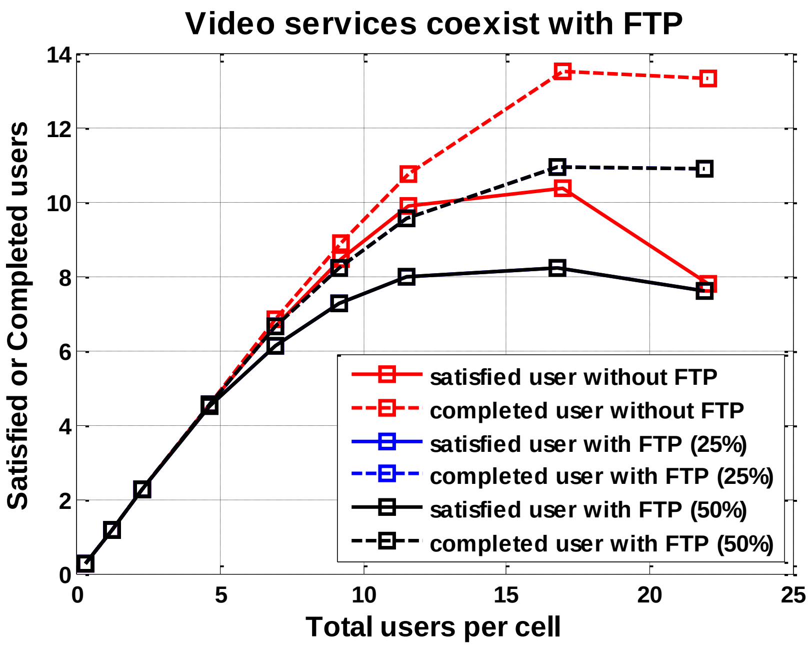

Fig. 30. Performance of video service co-exists with FTP

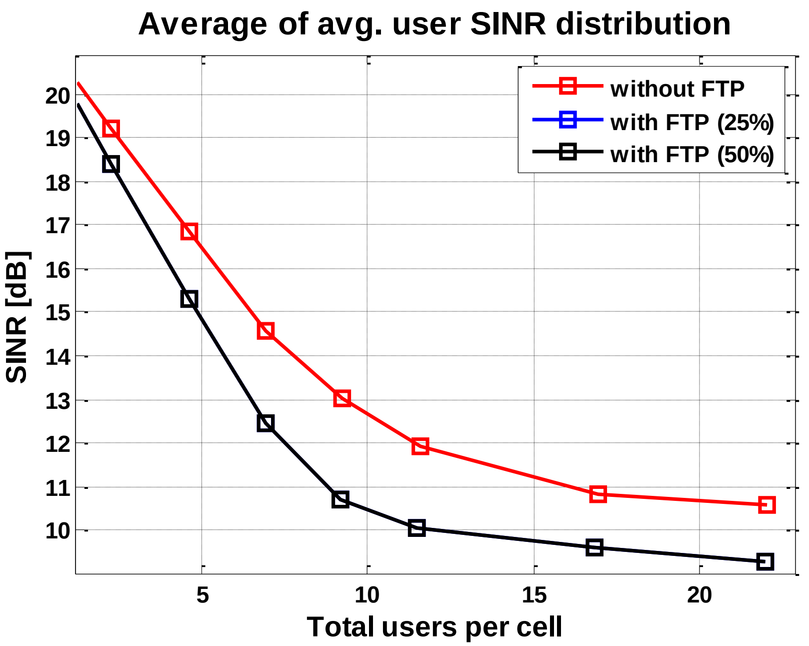

Fig. 31. Median of average SINR distribution

Although the traffic from the video services is growing tremendously in real LTE network, a significant portion of the traffic is also contributed by the FTP services, like web page browsing, emails, and file downloads. In this section, influence of these FTP services on the performance of video services is analyzed. In our simulations, we consider that 25% and 50 % of the total data traffic is contributed by FTP services and the remaining data traffic comes from video services. The eNB also uses the PF schedulers for the users of FTP services. However, the video services are given more scheduling priority over FTP.

The presence of the FTP services in the network reduces the system performance with respect scenarios without FTP service. However, the video service performance is not affected much by the amount of FTP traffic in the network. Fig. 30 shows the difference in performance in terms of satisfied users, which starts to show at medium traffic loads. Presence of additional users due to FTP services create extra load on the eNBs. The PRB utilization increases in case of FTP services co-existence. Inter cell interference also increases and hence, the SINR observed by the user decreases. Fig. 31 plots the median of SINR across different traffic loads. Users observe close to 2 dB decrease of average SINR when FTP services co-exist in the network.

4.8 *Effect of ICIC on Network performance*

Inter cell interference co-ordination (ICIC) is applied in the downlink in our simulation. It mitigates interference observed at user's device by either reducing the base station transmission power or avoiding scheduling users on some of the PRBs. In our simulation, few PRBs are reserved for those cell edge users, which are experiencing interference from the non-serving cells' eNBs. Interfering base stations must be abstained from scheduling those PRBs to their users. Rests of the available PRBs are free to use by other users present in that serving cell.

The algorithm, which is designed for the ICIC, is mentioned in the Appendix 1. In our simulations, we assume,

cellEdgeSinr = 3.1623 (5dB),

interferenceLevel = 3.1623 (5dB),
noOfReservedSubband = 10, and
ICICRefreshRate = 10 ms.

At a higher traffic load, user devices observe high interference from near-by eNBs. This scheme is designed to achieve higher performance gain by reducing the interference to cell edge users. A significant increase in the number of satisfied users is observed with the implementation of ICIC. 37.6% more satisfied users are observed in the network in comparison to without ICIC scheme at 100 Mbps/km^2 traffic load. It can be verified from Fig. 32, which shows comparison between with and without ICIC in terms of satisfied and completed users.

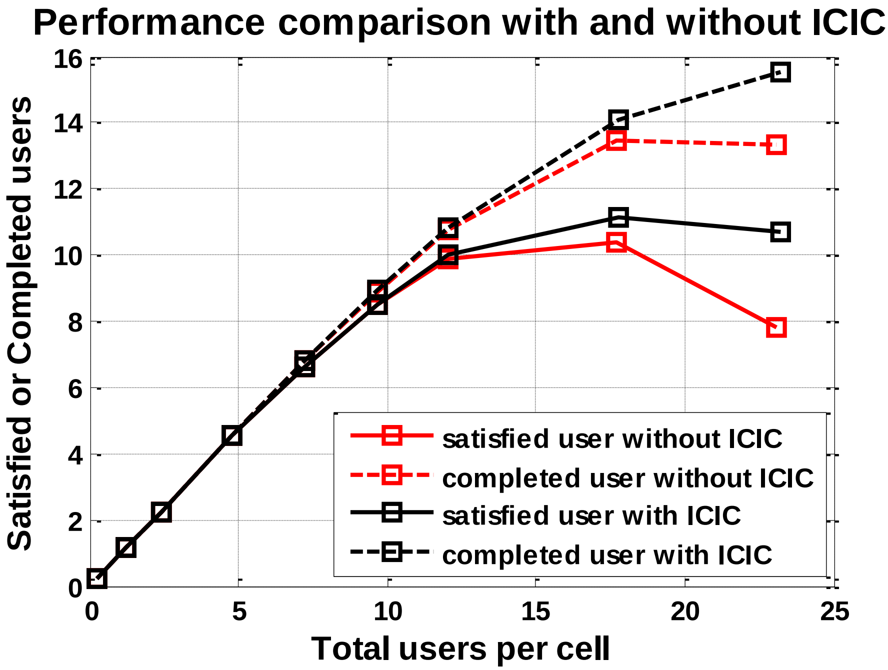

Fig. 32. Performance comparison between with and without ICIC

This improved performance is achieved without compromising performance of other users present in the same cell. This can be verified from the cdf plot of the frame freeze in Fig. 33 as the curve gets better with the implementation of ICIC. More users now have a lesser frame freeze seconds, which increases the satisfied user counts.

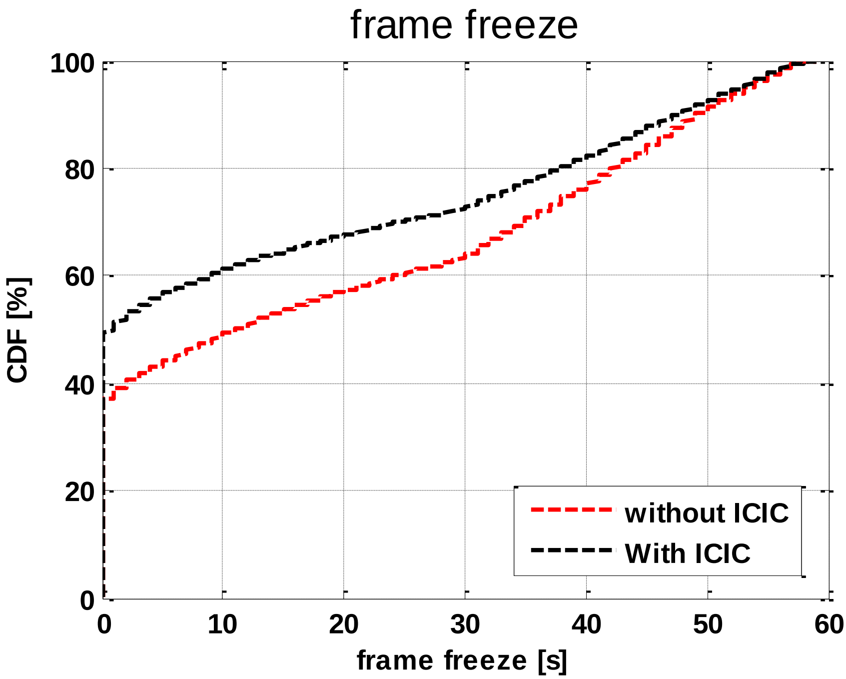

Fig. 33. Frame freeze difference between with or without ICIC

Fig. 34 and Fig. 35 are the Google earth plots of our considered cellular network. Here, a comparison is done between with and without ICIC schemes, in terms of percentage of happy users out of total active users in a cell. In our considered urban network, the cell edge users in some cells are hardly affected by the interference as interfering eNBs are far away from each other. The SINR observed by users in those cells are mostly noise limited. Benefits of ICIC are hardly observed in those cells. It can be seen from Fig. 34 and Fig. 35 that there is hardly any change of colors in some cells, e.g. any changes in the number of satisfied users. However in some areas, eNBs are closely placed. The observed SINRs in those areas are mostly interference limited. Implementation of ICIC enhances the capacity of these cells by increasing satisfied user counts and it is verified in our simulation. It can be seen from Fig. 34 and Fig. 35 that for cell 14, 58 and 59, there is a huge performance improvement. Cell 58 observes close to four times more satisfied users. The location of the cells can be found from the Fig. 8 and 9.

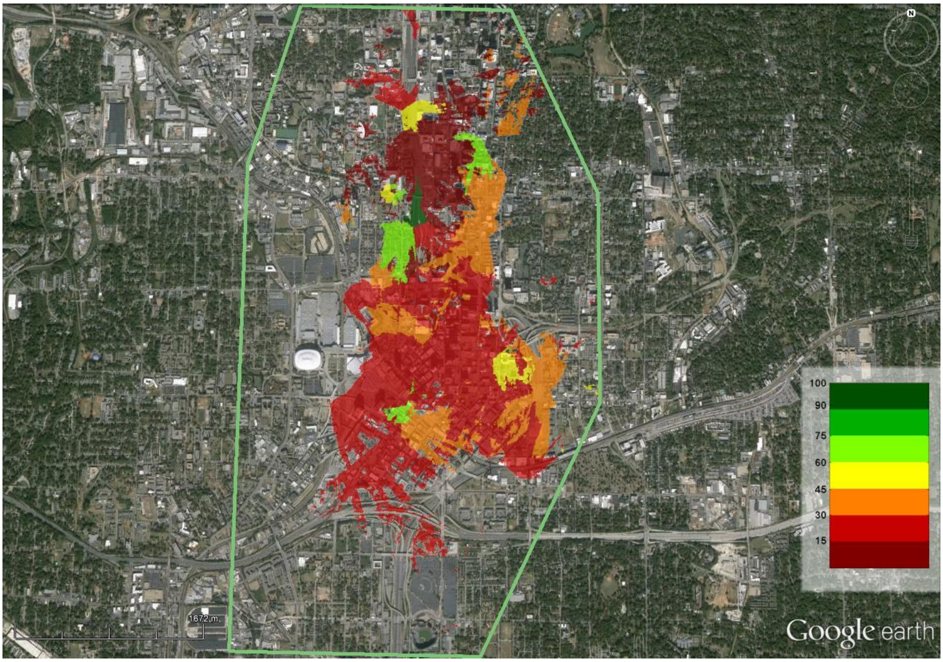

Fig. 34. Cell level performance without ICIC

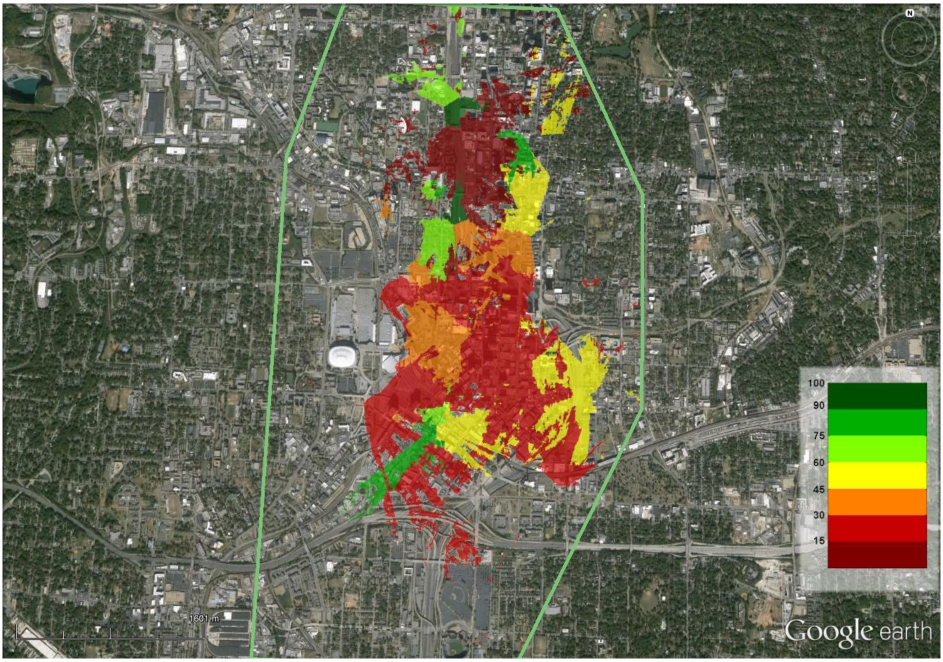

Fig. 35. Cell level performance with ICIC

CHAPTER 5

5 Conclusions

As mobile data traffic fuelled by the video services is growing tremendously over the years, it becomes essential to understand factors affecting performance of video services over a real cellular network. The objective behind this thesis is to assess how the network capacity and users' perceived quality are affected by the characteristics of a real network.

In this thesis, the performance of video services are analyzed between the proportional fair, the round robin, and the MaxCI schedulers to know out of these three schedulers, which one suits most for a real LTE network. Proportional fair scheduler is the most preferable scheduler. The MaxCI scheduler is not suitable for a real network as users with less favorable channel conditions are deprived of being scheduled. The round robin scheduler has the worst performance.

The performance is also compared between RT and HTTP streaming video algorithm and the number of satisfied users in both the cases are equal. However, due to the pre buffering time and the frame bundling, the HTTP streaming algorithm however shows a slightly better performance in some of the cells.

The effects of various features of the HTTP streaming like, pre buffering time, buffer multiplier, and bundle size on performance of video services are also investigated. The earlier studies within Ericsson suggest, higher bundle sizes and buffer multipliers increase the performance. Moreover higher pre buffering times do not increase the performance much. However, our observations contradict with the earlier conclusion derived from artificial hexagonal networks

User abandonment of video services is a burden on network resources due to unnecessary sent data at the clients' play-out buffer.

Abandonment, which is caused due to poor radio channel conditions, proves to be beneficial as number of satisfied user counts increases. Moreover, in this case, the unnecessary sent data is very less with respect to overall sent data by the system. However, when a user does not like the videos and abandons the service, a major chunk of data at the clients' play-out buffer remain unutilized. However, this unutilized data at clients' play-out buffer can be reduced by choosing lower buffer multipliers.

Although admission control gives an improved performance, the number of users rejected by the admission control is a matter of concern. It is seen; almost 30% of total users are not admitted to the network at the traffic load 100 Mbps/km^2. Even users with significantly better SINRs are also rejected. On the other hand, we propose a method, where users with poor radio channel are abandoned by the network, also gives us the similar performance. Moreover, the number of abandoned users is very less.

Finally, the implementation of inter cell interference co-ordination proves to be beneficial for the network performance. This feature does not sacrifice performance of other users. The overall network performance in terms of satisfied users increases up to 37.4%. Moreover, in certain cells, the number of satisfied users increases up to four times.

CHAPTER 6

6 Future Work

In this thesis, we address several different issues and its impact on the video service performance on a real LTE network. Data traffic contributed by video service has been growing tremendously. According to the information available in Ericsson mobility report, June 2013 edition [18], the smart phone users who subscribed to both music and video services, consume more than 2 GB of data per month now-a-days. Seeing the popularity of video services over cellular network, we firmly believe there are much more work still need to be done. Few of these future works are cited in this chapter.

In this thesis, the user satisfaction is quantified by the number of frame freezes. Mean opinion score (MoS) model which is prescribed by ITU-T, can give more realistic user satisfaction criteria. Several different video quality parameters like packet loss rate, frame rate, bit rate, end to end delay, display size, and video codec information are considered to calculate MoS [20].

To achieve high system capacity and higher per user data rate, Hetnet becomes essential to be deployed in an LTE network. ICIC gives improved performance in those cells, which are mostly affected by the inter cell interference. However, some of the cells in the considered urban network have very less satisfied users and they also do not see much performance enhancement by the implementation of ICIC, as cell edge users in these cells are basically limited by the low signal strength. Hetnet will bring performance improvement in these cells. Therefore, further research is required to understand, how Hetnet is beneficial for the video service performance.

In this thesis, users are assumed to be stationary and the radio propagation channel is frequency-flat and time-invariant. Analyzing video performance on a more realistic channel model will be more interesting. Even users moving between different cells generate several new issues for the future research.

Different smart phones are using different operating systems like, iOS and android. These operating systems differ in their video file download algorithm. It will be interesting to understand, implication of different mobile operating systems have on the video service performance over an LTE network.

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List of Acronyms

2G	Second Generation
3G	Third Generation
AC	Admission Control
BMUL	Buffer Multiplier
cdf	Cumulative Distribution Function
eNB	Evolved NodeB
FDD	Frequency Division Duplex
FFD	Full File Download
FPS	Frames Per Second
FTP	File Transfer Protocol
GB	Giga Byte
HetNet	Heterogeneous Network
HSDPA	High Speed Downlink Packet Access
HTTP	Hypertext Transfer Protocol
ICIC	Inter Cell Interference Coordination
Kbits	Kilo Bits
LTE	Long Term Evolution
MAC	Medium Access Control
MaxCI	Maximum Carrier to Interference Power
MB	Mega Byte
Mbits	Mega Bits
MOS	Mean Opinion Score
MUE	Macrocell User
PBT	Pre Buffering Time
PF	Proportional Fair
PRB	Physical Resource Block
QoS	Quality of Service
RR	Round Robin
RT	Real Time
SINR	Signal to Interference plus Noise Power Ratio
SIR	Signal to Interference Power Ratio
SMS	Short Messaging Service
TCP	Transmission Control Protocol

Appendix 1

A.1 Inter cell interference coordination algorithm the video services

Step 1: Define *cellEdgeSinr*, *interferenceLevel*, *noOfReservedSubband*, *noOfRequiredReservedSuband*, *actualNumberOfReservedSuband*, and *ICICRefreshRate*.

The *cellEdgeSinr* is the threshold use to define a cell edge user. SINR of the cell edge user must be less than or equal to the *cellEdgeSinr*.

The *interferenceLevel* is the threshold to define the cell edge users, who are heavily interfered by the neighboring eNBs. All the cell edge users are not always affected by the interference. The SINR of some of the users is limited by low signal strength due to the path loss and also some of the users are also receiving less interference. These users might not gain much in performance by the implementation of ICIC. Hence, the *interferenceLevel* is used to locate users observing high downlink interference. A user is heavily interfered, when

$$\frac{Interference\ Power + Noise\ Power}{Noise\ Power} \geq interferenceLevel$$

The *noOfReservedSubband* is used to define, maximum number of physical resource blocks (PRBs) per cell will be reserved for the allocation to the cell edge users, who are experiencing high interference in the downlink. Neighboring eNBs of the cell edge users must be abstained to use those PRBs.

The *noOfRequiredReservedSuband* is used to define, actual number of PRBs are needed to transfer the whole buffered data of a celledge user at the serving eNB within a period of ICICRefreshRate. i.e.

$$noOfRequiredReservedSubband = ceiling\left(\frac{Total\ buffered\ data\ at\ the\ eNB}{(amount\ of\ data\ carried\ per\ PRBs \times ICICRefreshRate)}\right)$$

The *actualNumberOfReservedSuband* is the minimum of the *noOfRequiredReservedSuband* and the *noOfReservedSubband*. Amount of data carried per PRB is estimated from the observed Signal to Noise Power Ratio (SNR).

ICICRefreshRate is used to define, how frequently one eNB send RNTP request to its neighboring eNB. Exchange of RNTP message are time synchronized among all eNB in the network. RNTP messages are not sent in every sub frame. A subframe is basic time domain unit for scheduling, consisting of two consecutive time slots. The time difference between two consecutive RNTP messages is equal to the *ICICRefreshRate*. If an eNB has a cell edge user experiencing high interference from a neighboring eNB, then only it will send RNTP messages.

Step 2: Find cell edge users and also users who see high downlink interference. Proportional fair scheduler is used to set scheduling priority irrespective of user location. Scheduling priority prioritized users in their respective serving cells.

Step 3: Sort the cell level scheduling priority of all the cell edge users, who are heavily interfered (as defined in Step 1) and also are requested for data at that moment.

Step 4: Initialize all the elements of *ICICMatrix* to zero. The *ICICMatrix* is a square matrix and its row and column has the size equal to the number of cells in the network. The *ICICMatrix* is used to define which serving eNB cell has asked its neighboring eNBs' cells to block the PRBs for its cell edge user. The *ICICMatrix* is initialized in every *ICICRefreshRate* period.

Step 5: Pick the cell edge user according to their sorted respective cell level scheduling priority. User with high priority is chosen first.

Step 6: Find serving cell and interfering neighboring cells for the selected users in Step 5. User possibly receives interference from more than one cell but not all cells have the strong interference. Pick those interfering cells, which are interfering more than the threshold *interferenceLevel*. This is done to avoid unnecessary blocking of PRBs.

Step 7: Update the *ICICMatrix* to 1 if following two conditions would satisfy. Row is the serving cell id. Columns are the interfering cell ids. First condition, interfering cells have not already requested to block PRBs to the current serving cell for their cell edge user. Second condition, the serving cell can only request to block PRBs for one of its cell edge users. The *ICICMatrix* is updated in every *ICICRefreshRate* period. This means the PRBs are reserved for only *ICICRefreshRate* period. The eNB will send another RNTP messages if it wants again to reserve the PRBs. e.g.

ICICMatrix[serving cell id, interfering cell id]=1 when
ICICMatrix[interfering cell id, Serving cell id]=0 for all the interfering cells and
ICICMatrix[Serving cell id, all cells]=0.

Step 8: The serving cell allocates the number of PRBs equal to the *actualNumberOfReservedSuband* from the available PRBs. The serving eNB should aware of the available PRBs at the interfering eNBs. It can be possible that interfering eNBs has reserved some of the PRBs for their cell edge users. It also informs the eNBs of the interfering cells not to use those PRBs to schedule its users of those interfering cells. The same cell edge user will be scheduled always throughout

ICICRefreshRate period, irrespective of scheduling priority in its camped cell.

Step 9: Nullify the interference from the chosen neighboring cells.

Step 10: Repeat the Step 5 to 9 for all the cell edge users at that scheduling moment.

Step 11: Repeat Step 2 to 10 for every *ICICRefreshRate* period

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