Industrial Scenario using LTE Cellular Network

ANTHONY OWONDO
JAVAD BLOUCHI
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DEPARTMENT OF ELECTRICAL AND INFORMATION TECHNOLOGY
FACULTY OF ENGINEERING | LTH | LUND UNIVERSITY

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By
Anthony Owondo
an0543ow-s@student.lu.se

Javad Blouchi
ja0810bl-s@student.lu.se

Department of Electrical and information Technology
LUND UNIVERSITY

Supervisors: Emma Fitzgerald (EIT)
Oskar Drugge (Ericsson)
Emma Wittenmark (Ericsson)
Examiner: Christian Nyberg (EIT)
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Abstract
This Thesis project used an event-based simulation tool written in MATLAB that modelled a factory scenario. Multiple base stations and a varying number of nodes were modelled. The nodes send data to the base stations and the simulation tool calculates the SINR of the received data and uses this SINR to model a probability of error. Latency statistics were then created using the time it took for the data generated to be received correctly at the base station.

The aim of this master's thesis work was to investigate the performance of an industrial scenario implementation of LTE. Data was generated periodically at the sensors and a scheduling request was sent to the base stations which in turn, according to LTE allocation standards, scheduled resources to the nodes in time and frequency. Link adaptation was performed by the eNodeBs whereby the modulation scheme and coding rate of the error correction was adjusted depending on the quality of the radio link.

Power control was then implemented to adjust the output power at all the nodes so that their respective received powers at the base station were the same. Simulations were done with the aim of optimizing the link adaptation and scheduling to determine which users to serve and how much resources to allocate to them.

Acknowledgements

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List of Acronyms

3GPP	3rd Generation Partnership Project
FDD	Frequency Division Duplex
LTE	Long Term Evolution
MCS	Modulation and Coding Scheme
MNO	Mobile Network Operator
OFDM	Orthogonal frequency-division multiplexing
PRB	Physical Resource Block
PUSCH	Physical Uplink Shared Channel
PUCCH	Physical Uplink Control Channel
RF	Radio Frequency
RLC	Radio Link Control
SR	Scheduling Request
SINR	Signal to Interference Plus Noise Ratio
SIR	Signal to Interference Ratio
SPS	Semi-Persistent Scheduling
SRS	Sounding Reference Signal
TDD	Time Division Duplex
TTI	Transmit Time Interval
UL	Uplink
WCDMA	Wide Band Code Division Multiple Access
ARQ	Automatic Repeat Request
HARQ	Hybrid Automatic Repeat Request
TPC	Transmitter Power Control
VOLTE	Voice over LTE
PLC	Programmable Logic Controller

1 Introduction

1.1 Project Specification

The aim of this Thesis was to investigate the performance of an Industrial scenario implementation of an LTE network. A simulator was used to model the scenario which is a factory floor with users modelled as nodes and base stations modelled as access points. The simulator has been in use with specific settings of parameters that was changed with an aim of improving the industrial network's performance. This investigation was divided into three parts.

- Link Adaptation
- Power Control
- Scheduling

Industrial applications target robust communication with low probability of error for each transmission, therefore an SINR estimation was set to select the worst of the last 20 SINR estimates of the previous 20 transmissions to minimize the interference that would otherwise be experienced if a higher SINR estimate was used for a transmission that did not require as much SINR. As shown in Figure 1.1, when the 34th packet is to be sent, the Simulator checks the last 20 transmissions and selects the smallest value of -2.692dB and uses this for the next transmission.

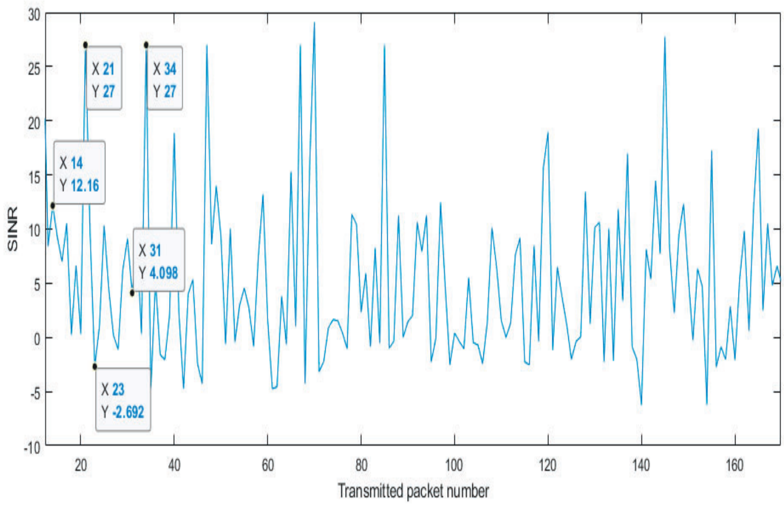

Figure 1.1: SINR selection for Link Adaptation

In the first task we changed this setting to different values with the aim of finding better settings. All the nodes in the factory model were transmitting data with their full output power. In the second task, we implemented power control as it is the case in real LTE setting where each node transmits using different power so that those nodes that are nearer to the eNodeB use lower power than those which are at a greater distance from the eNodeB. This is done so that the eNodeB receives all data with the same receive power to minimize interference.

The scheduling function used in the simulator was allocating the same amount of resources to each of the scheduled users. Our third task was to change the scheduling function by modifying the resource allocation such that more efficient scheduling could be achieved.

1.2 Motivation

4G LTE technology was developed with the aim of meeting the need for increased capacity. It was developed only for packet switched data without support for circuit-switched data [3]. This technology has the advantage of having high data rates, low latency, high capacity spectrum flexibility and enhanced commonality between TDD (Time Division Duplex) and FDD (Frequency Division Duplex) [2]. Improvements in LTE have enabled its use in not only mobile broadband based services but also support for device to device and machine type communication.

1.3 Contributions

The Simulator has been used for a long period of time with specific parameter settings that define its operation. This is implemented in MATLAB code that has many functions simulating an LTE network. We were thus tasked to modify the code in some parts, add our own code in other parts of the code. We made the following contributions during our Thesis;

- When we did link adaptation in task one, we obtained a better throughput using a different setting than the one that was used before.
- There was no power control in the model and our implementation of it in task two using a link budget improved the throughput achieved by each user setting.
- The amount of frequency resources allocated to every user was fixed when we started but we changed this in task three to the buffer-based allocation which assigns resources based on the knowledge of buffer statuses when each node was scheduled to send data.

1.4 Limitations

Over the duration of the Thesis, we encountered several limitations that are listed below.

- Time limitations on the Thesis project did not allow us to carry out extensive investigation on all the workings of the simulator and the code used.
- Modelling of ARQ retransmissions in the simulator. When a transmitted subframe for a user is incorrectly received at the eNodeB, HARQ would normally transmit to the user using multiple HARQ processes until the packet is successfully decoded or until a maximum retransmission limit is reached [10]. The Simulator however stalls a user that is retransmitting a subframe as though it only had a single HARQ process which may lead to pessimistic results.
- We had hoped to make Wi-Fi simulations for comparison with our results but the time available was not adequate to do this.

The second chapter outlines the background of communications, data transmissions in LTE and power control for uplink traffic that will be the focus in the Thesis. Chapter three covers the model used, its implementation and a description of the data collected. The fourth chapter includes the results obtained and an analysis of these results.

2 Background

2.1 Industrial Revolution

Mobile communications have been categorized into generations each of which was associated with specific technologies. The first was the first-generation systems which were analogue mobile telephone systems that were country based and thus had limited, if any, international roaming services. The second-generation systems introduced in the early 1990s were digital based systems that supported voice services. Some were later extended to support packet-switched data and these are categorized into 2.5G technology [3]. They had higher capacity than 1G systems and are still in use around the world.

In the late 1990s the need to support data services necessitated the development of 3G technologies and industry players decided to form the Third Generation Partnership Project for global standardization (3GPP) and to ensure that the 3G technologies would have a global reach. 3GPP's first major release was WCDMA which used voice and video services that were circuit switched and data services that were circuit and packet switched. 3GPP2 was thereafter formed and it developed competing technologies to those made by 3GPP. As this was going on, there was a rapid increase in the use of mobile smart phones with a subsequent use of services based on packet data which translated to an increasing need for capacity and spectral efficiency [4].

Technological advancements in industry have been categorized according to the technologies that were in use at the time. The first industrial revolution was initiated by the mass extraction of coal and the invention of the steam engine. This enabled the process of mechanization and hence industry to be the base of societies economic structure, taking over from Agriculture. At the end of the 19th century, the discovery of oil, gas and electricity enabled the development of the combustion engine that fully utilized these energy sources. Mass production through the assembly line was also introduced which considerably reduced the time of production and increased the production volume. Telephone and Telegraph were the modes of communications used in this stage.

The third industrial revolution began in the 1960s triggered by the emergence of nuclear energy, the rise of electronics, computers and telecommunications with the transistor and microprocessor at the center of it all. These devices combined with integrated circuits gave rise to the partial automation using memory programmable controls (PLCs) which enabled miniaturization of machines and automation of in some cases entire production processes. When the internet came in the 1990s, it facilitated connectivity of computers, PLCs, sensors, machines and people all over the world and in industry, automation became computerized.

The fourth industrial revolution has already started with the introduction of Cyber-Physical Systems (CPS) that integrate computation, networking and physical processes through the internet of things (IoT). CPS monitor physical processes, make virtual copies of the physical environment and communicate with each other and with human operators in real-time. This has created the concept of the smart factory which will require wireless networks. Unlicensed spectrum was the obvious option for many of these industries given the demands that unlicensed spectrum is globally available free of charge. Wi-Fi is being used in many industries and recently a new standard called MulteFire has been developed for hyper dense environments to increase network efficiency when compared to Wi-Fi by using the signals and channelization of the LTE radio link although it is yet to be seen if the equipment for access points and stations will be available on the market. Recently, private LTE networks have emerged as an option for industries. The premise for this is that an industry would set up a local LTE network say, in a factory and since LTE requires licensed spectrum, the industry would have to gain LTE access through cooperation with a mobile network operator (MNO) or by acquiring access to licensed spectrum from a national spectrum regulator.

Currently, there are initiatives from certain countries to allocate dedicated licensed spectrum for industries. As an example, authorities in Germany and Sweden are discussing the allocation of 100 MHz in the range between 3.7 and 3.8 GHz to be available for local licenses to be used by industries. The two other options have been Dedicated licensed networks which were obtained through auctions to gain rights to frequencies and Shared Spectrum Access where multiple users gained access to a given band with separation, fairness and manageability mechanisms were enacted.

2.2 Data Transmission in Mobile Communications

One of the main targets of using LTE in industries is to provide high data rates. For cyber physical systems to efficiently work, there must be high data rates with very low latency in the LTE systems. When communication is done over a channel where additive white Gaussian noise is the limiting factor, the channel capacity is given by the expression below where BW is the available bandwidth, S is the received signal and N the white noise [3].

$$C = BW \times \log_2\left(1 + \frac{S}{N}\right)$$

As can be seen from the above, the achievable data rate depends on the signal to noise ratio and on the available bandwidth [9]. According to [2], expressing the received signal power as $S = R \times E_b$ and the noise power as $N = N_o.BW$, (where R is the data rate, N_o is the noise spectral density and the bandwidth utilization as $\Upsilon = R/BW$, the required received energy per information bit thus has a lower bound defined as:

$$\frac{E_b}{N_O} \geq min\left(\frac{E_b}{N_O}\right) = \frac{2^{\Upsilon} - 1}{\Upsilon}$$

From figure 2.2 below, an increase in the available bandwidth in the power limited region has little impact on the received signal power required for a certain data rate [2]. On the other hand, in the bandwidth limited region, where data rates are of the same order as or greater than the available bandwidth, an increase in the data rate requires a much larger relative increase in the receive signal power unless the bandwidth is increased proportionally with the increase in data rate [9].

The Transmission Time Interval (TTI) in LTE is set to 1ms [4]. Consider an example where a device is to transmit a packet of 115 bytes = (115×8) = 920 bits over a duration of 1ms. The communication rate becomes roughly 1Mbps. Assume that the device is allocated 1MHz for the transmission, with a resulting bandwidth utilization of 1.0, which is at the border of the power limited region and the bandwidth limited region in Figure 2.2 below. Assume further that the energy per bit in the example is fixed e.g. because the transmitter is already using the maximum power available. Increasing the bandwidth will decrease the bandwidth utilization which will move us to the left into the power limited region where the system can handle more noise and interference although as can be seen the curve is relatively flat, so the gain in terms of resilience to noise is limited. At the same time increasing the bandwidth for one user means that there will be less spectrum available for other users. If we reduce the bandwidth, the bandwidth utilization will increase, and this will move us into the bandwidth limited region to the right where the noise tolerance will decrease. In this example, it is therefore likely that the performance in terms of capacity i.e. the number of users that can be served with low latency will suffer if the bandwidth for the individual user in the example is increased beyond 1MHz.

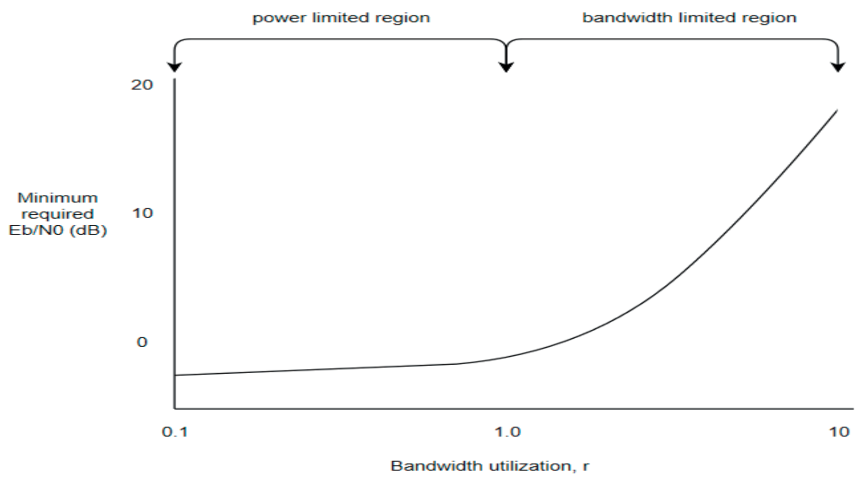

Figure 2.2: Minimum required Eb/No at the receiver as a function of the bandwidth utilization [1]

2.3 Duplexing in LTE

LTE is specified to use both Frequency Division Duplex (FDD) and Time Division Duplex (TDD). In FDD two separate RF carriers are used for uplink and downlink data transmission [5]. It uses frame structure type 1 that consists of 10 subframes of 1ms within a 10ms frame [2]. Each of the subframes has 2 slots of 0.5ms. Since transfer of data can be continuous in both uplink and downlink direction, FDD offers higher throughput because two carriers offer greater capacity than a single carrier. No synchronization between the eNodeBs is required in FDD systems unlike for TDD where eNodeBs that are close to each other must be time synchronized to limit the interference between uplink and downlink transmissions [5].

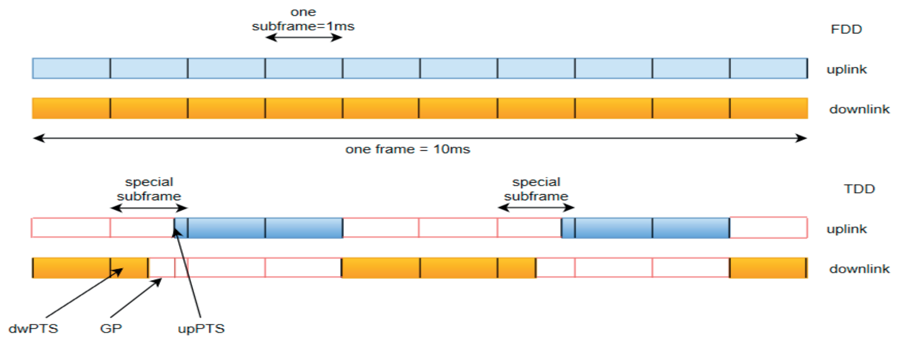

Figure 2.3: FDD and TDD frame structures [4]

TDD on the other hand uses only one RF carrier for both uplink and downlink data transmission. This means that at each point in time either the UE or the eNodeB will be transmitting data but not both. TDD uses frame structure type 2 consisting of one 10ms frame that that has two 5ms half frames [5]. Each half frame has five subframes. The subframes can be uplink, downlink or special [3]. The special subframes have a downlink pilot time slot (dwPTS), a guard period (GP) and an uplink time slot (upPTS) as shown in the figure 2.3 above [2]. They are used when switching from DL to UL transmission but not from UL to DL [5]. The Simulator has support for TDD and FDD, but the scope of the Thesis only covers FDD.

2.4 Transmission Resources

A resource element is the smallest physical resource defined for LTE [3]. It consists of one subcarrier during one OFDM symbol. Resource elements are grouped into resource blocks which are defined both in the time and frequency domain. A resource block is a grouping of 12 consecutive subcarriers in the frequency domain and one 0.5ms slot in the time domain [2]. The 0.5ms slot is divided into 7 OFDMA symbols in the normal cyclic prefix and into 6 OFDMA symbols in the extended cyclic prefix [5]. In the frequency domain, the resource block occupies 12*15=180kHz. Using the extended cyclic prefix, the resource block configuration has 3 symbols in the time domain and a subcarrier spacing of 7.5kHz is used thus 24 subcarriers are contained within the 180kHz bandwidth.

Using the normal cyclic prefix, a resource block contains 84 = (7×12) resource elements and in the extended cyclic prefix, 72 = (6×12) resource elements are used [4].

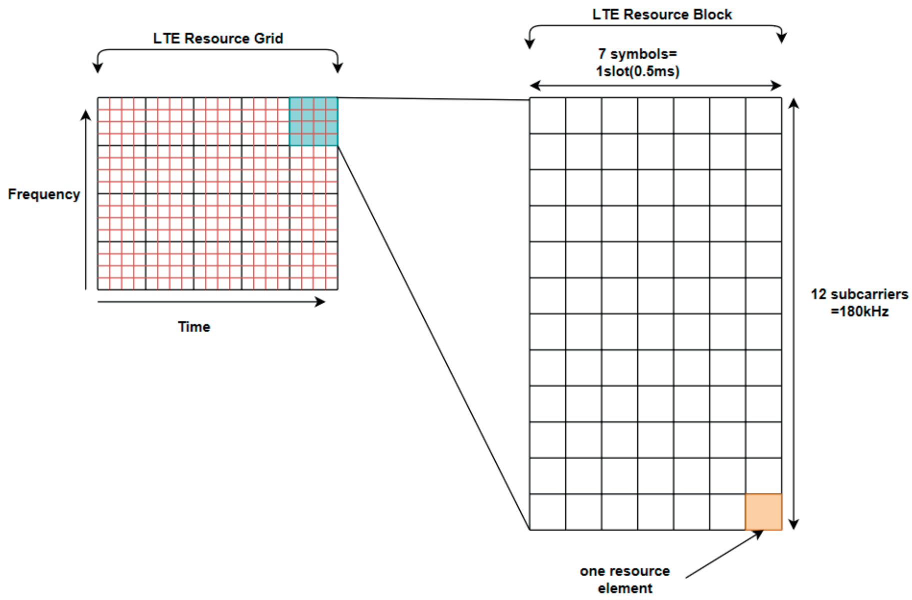

Figure 2.4: LTE physical time-frequency resource [4]

2.5 Uplink Power Control

LTE power control is the configuration of output power levels of transmitters, nodes in uplink and eNodeBs in downlink with the aim of improving system capacity, user quality and coverage and to minimize power consumption [12]. The required demodulation can only be done if the signals are received with enough power. To reduce inter-cell interference, the transmit power at the UE should not be unnecessarily high [3]. Uplink power control is done to reduce UE power consumption and to limit intra cell and inter cell interference.

In LTE, the power control combines both open loop power control and closed loop power control [9]. The UE transmit power depends on estimates of the downlink path loss and a closed loop mechanism meaning the network can directly modify the transmit power using explicit power control commands that have been transmitted in the downlink. For LTE release 10 and beyond [2]:

- Carrier aggregation is possible whereby multiple Physical Uplink Shared Channel (PUSCH) can be transmitted in parallel on different component carriers. PUSCH is used to carry data traffic in the uplink and when signaling and data is being simultaneously transmitted, it carries signaling traffic.

- Simultaneous transmission of PUSCH and PUCCH is possible on the same carrier and on separate carriers.

In LTE the power control specified for PUSCH, PUCCH and SRS can be considered as a summation of two factors:

- Basic open loop operating point for the transmit power per RB which has a semi static base level P_O that enables the eNodeB to correct for systematic offsets in a UEs transmission power setting and an open loop path loss compensation component that is based on the UEs estimate of the downlink path loss.
- Dynamic offset part of the power per RB that has a component dependent on the MCS (Δ_{TF}) which allows the transmitted power per RB to be adapted subject to the transmitted information data rate and an explicit Transmitter Power Control (TPC) command component.

According to [13], for the PUSCH and SRS, the total transmit power of the UE in each subframe is linearly scaled up from the power level derived from the semi-static operating point and dynamic offset according to the number of RBs that are scheduled for transmission from the UE in the subframe. This leads to the following overall power control equation:

$$\text{UE transmit power} \ = P_o + \alpha PL + \Delta_{TF} + f(\Delta_{TPC}) + 10log_{10}M$$

Where $(P_o + \alpha PL)$ is the basic open loop control point, $(\Delta_{TF} + f(\Delta_{TPC}))$ is the dynamic offset and $10log_{10}M$ is the bandwidth factor. Δ_{TPC} denotes a TPC command, $f(.)$ Represents accumulation in the case of accumulative TPC commands and M is the number of allocated RBs. This formula allows the UEs transmit power to be controlled with a granularity of 1dB with a range of -40dBm to +23dBm.

UE maximum power

Power control uses the UE configured output power P_{CMAX} as its upper limit. 3GPP specifies that the UE sets its own maximum power to satisfy [5]:

$$P_{CMAX\_L} \leq P_{CMAX} \leq P_{CMAX\_H}$$

where P_{CMAX_L} is the lower limit of the maximum power that the UE can transmit and P_{CMAX_H} is the upper limit of the maximum power that the UE can transmit.

Each physical channel is separately and independently power controlled but in the case of parallel transmission of multiple channels, the total power to be transmitted can exceed the maximum terminal output power P_{TMAX} that corresponds to the terminal power class [9]. In this case, the first task is to assign the needed transmission power to any L1/L2 control signaling transmission. The power that remains is then assigned to the remaining physical channels. Each terminals uplink component carrier has a maximum per-carrier transmit power P_{CMAXc} that can be different for different component carriers.

The sum of all P_{CMAXc} is usually greater than the P_{TMAX} because the terminal will not be scheduled for uplink transmission on all the component carriers that it has configured and in which case it should be able to transmit with its maximum output power.

Power scaling is usually applied to the transmitted physical channels to ensure that the total transmit power for all component carriers to be transmitted by the terminal does not exceed the maximum terminal output power P_{TMAX} . There are two methods of implementing power control in LTE uplink [2]:

1. Conventional power control where a constant Signal to Interference and Noise ratio is maintained at the receiver. The UEs fully compensate any increase in path loss by increasing their transmit power.
2. Fractional power control in which the received SINR is allowed to decrease as the path loss increases. Thus, as the path loss increases the UE transmit power decreases. Fractional power control enhances air-interface efficiency and increases the average cell throughput by reducing intercell interference.

2.6 Scheduling in LTE

A scheduler in the eNodeB determines to which user time-frequency resources will be allocated and the data rate that will be used in the transmission [3]. The scheduler's basic operation is dynamic scheduling where the eNodeB makes a scheduling decision in each 1ms TTI and sends scheduling information to the selected users [9]. Consequently, there is scheduling of both downlink and uplink transmissions by the downlink scheduler and the uplink scheduler respectively. The downlink scheduler dynamically controls the users to transmit to by providing each of the scheduled nodes with a scheduling assignment that has a set of RBs upon which the node's DL-SCH is transmitted and the associated transport format [3]. The uplink scheduler dynamically controls which devices are to transmit on their UL-SCH by providing each scheduled node with a scheduling grant that has the set of RBs upon which the device should transmit its UL-SCH and the associated transport format.

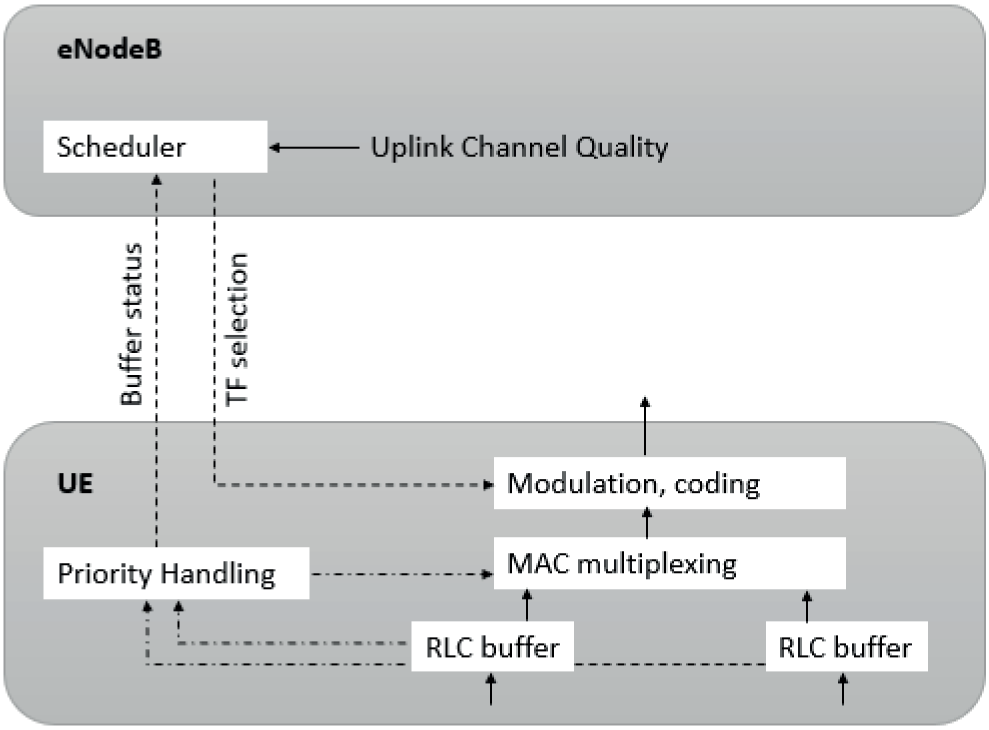

Figure 2.5: Transport-format selection in uplink [9]

The uplink scheduler has complete control of the transport format the device will use, and the logical channel multiplexing is controlled by the device as shown in Figure 2.5 above [9]. When a device has data to transmit, it sends a scheduling request to the eNodeB. The scheduling request is transmitted on the PUCCH because it still has no PUSCH resource [3]. When data with a higher priority than the data already in the transmit buffer arrives and the device has no grant with which to transmit data, the device transmits a scheduling request at the next possible instant [2] as shown in figure 2.6. A dedicated PUCCH which occurs every nth subframe can be assigned to every device. The eNodeB accepts the request by issuing a scheduling grant to the specific device. If a device is not issued a scheduling grant, the scheduling request is repeated up to a configurable limit above which random access will be resorted to for resource request from the eNodeB. A scheduling request is a simple flag (one bit) to keep the uplink overhead low as using multi-bit scheduling requests would require more resources [9].

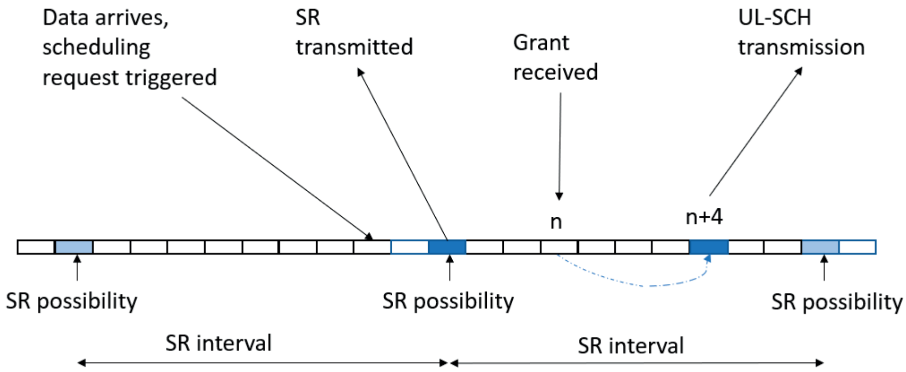

Figure 2.6: Scheduling Request Transmission [3]

2.7 Previous Work

According to [15], Rio Tinto, a mining conglomerate, developed a private LTE network in 2013 that covered 15 mines and other related facilities such as railways and offices in Australia. Rio Tinto had a special arrangement with the local regulator that allowed it to use 1800MHz spectrum. They had previously been using 30 Wi-Fi access points which they replaced with four LTE base stations. The network, which is managed from a single Network Management Center consists of an LTE core and various related applications that handle VoLTE, push-to-talk and unified communications. In 2014, another company called Enel Group that generates and distributes power implemented a private LTE network in one of the biggest power stations in Europe using TDD. Their aim was to support, among other functions, predictive diagnostics services, workforce management, machine automation and plant operations safety. The dedicated core network used provides integrated communications between the workers, machines, sensors and applications.

In [14], there is a proposed buffer based adaptive SPS scheme for the LTE uplink that increases or decreases the number of allocated radio resource blocks (RBs) according to the latest buffer status of the device similar to the investigation in our Thesis and this is later compared to the performance of a rigid fixed allocation SPS scheme. They assume the Machine to Machine (M2M) traffic to be grouped into three multi-service classes that belong to three different traffic patterns recognized by the eNodeB scheduler but in our case, all the nodes have the same traffic pattern. In their investigation, packets are generated in a Poisson process unlike in our Thesis where an exponential distribution is used. $N_{PRB\ (min)}$ which is the initial SPS transmission from the nodes when no prior knowledge about the nodes buffer is available is set to 1PRB but in our simulations, we use 6PRBs. Though they come to the same conclusion we did that the adaptive buffer-based scheme is better than the fixed allocation scheme, they used packet sizes of 32 bytes which is much smaller than the 115 bytes we used, and they also assumed that each uplink packet can be accommodated in exactly one PRB. Their periodicity ranged from 10ms to 100ms and the scheduler allocated less PRBs as the periodicity increased. In our case, the periodicity was from 10ms to 50ms and this had no correlation with the number of PRBs allocated which solely depended on the buffer status.

In [12], investigations are done for a scenario when no power control is implemented i.e. where all the users transmit with maximum power, and this is compared to open loop power control with full compensation (α=1) and with fractional compensation (α=0.7) and to closed loop power control. Their terminals are randomly positioned in the system area unlike our set-up where all the nodes are evenly placed on the factory floor. They recorded a significant improvement in the cell edge bitrate for the three settings described above as compared to using no power control. We used open loop power control with full compensation and similarly found this to yield better latency that when no power control was used.

3 Implementation

3.1 Technical Background

The aim of this thesis is to investigate the performance of a wireless network in a Factory implementation. Ericsson currently use a simulation tool that models a 90m by 180m by 20m factory as shown in Figures 3.1 and 3.2 below. The model is a room with five base stations that receive data transmitted by nodes which have six different settings of (98, 200, 300, 392, 648, 882) users. These numbers are chosen because they give an even distribution of the nodes on the factory floor.

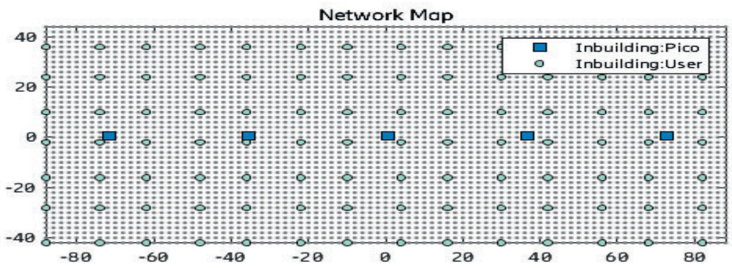

Figure 3.1: Modelled Factory Floor with base stations (Pico) and users

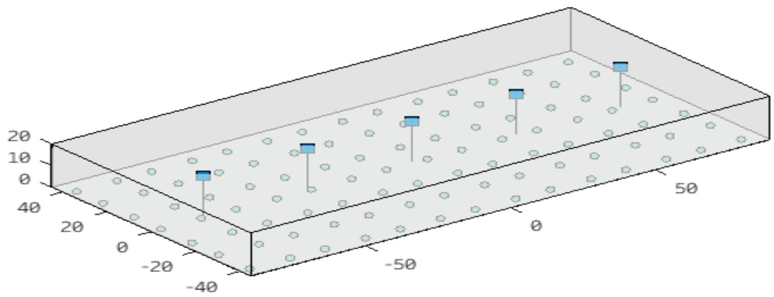

Figure 3.2: 3D view of the Factory Scenario (Dimensions in meters)

Each node that has data to transmit is scheduled by the eNodeB and sends a portion of the data during each TTI. Some of the data sent is not received because of interference in which case retransmission is necessary. The base station does link adaptation by selecting the modulation and coding based on an estimated signal to noise and interference ratio (SINR) of the transmission. The SINR of each transmission is calculated by the simulation tool which also keeps track of which nodes have simultaneous transmissions. A probability of error in reception that depends on the modulation and coding scheme (MCS) is modelled based on the previously calculated SINR. The simulator keeps track of all the received transmissions and calculates the SINR for each of these transmissions.

For analysis, the link adaptation algorithm uses a window parameter and an offset parameter to calculate an SINR which is used to select an MCS for the next transmissions. In the baseline simulator implementation, the window setting was 20, meaning that the worst SINR of the latest 20 transmissions was selected in the link adaptation and an offset of 3dB was used to decrease the SINR even more. To get reliable transmissions and avoid retransmissions as much as possible, this very conservative approach of selecting SINR was used. Data of 115 bytes is generated with a certain periodicity at each of the nodes. In each simulation run, the periodicity is a parameter that is varied from 10ms to 50ms with 10ms intervals and at each instant, the number of transmissions that arrive later than the threshold which is the same as the periodicity is recorded and compared to the total transmissions that have occurred. The outage probability is then calculated from the latency as the number of transmissions that arrive later than the periodicity at each instant. The base stations then schedule time and frequency resources to the nodes following LTE resource allocation.

3.2 System Model

The Simulator

The thesis project used an event-based simulation tool written in MATLAB that models a factory scenario. SimLibs is a platform which was developed at Ericsson to work with Radio Access. It enables library approach of accessing simulations tools, development of environments and a forum for discussion and information spreading. To access the SimLibs, we used a UNIX account. A Citrix Receiver enabled logging into the terminal servers of SimLibs.

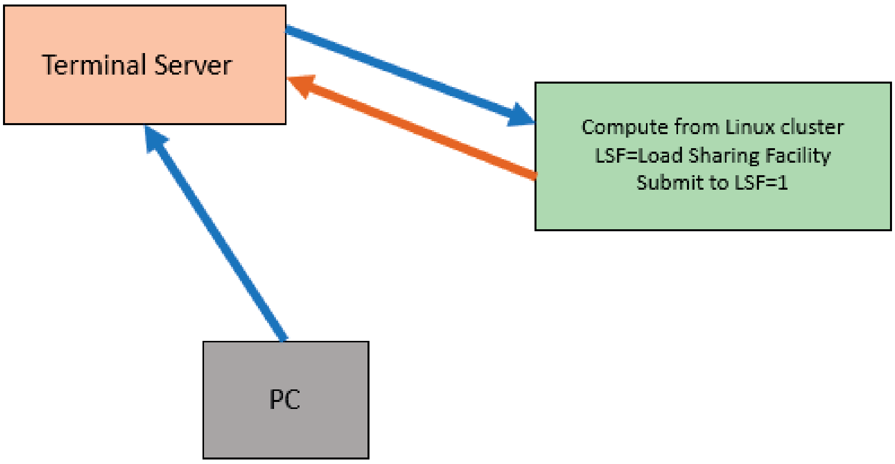

Figure 3.3: Simulator Interface

The Simulator is accessed by multiple departments and using Linux reduces the workload that would otherwise overwhelm personal computers if they were used to run big simulations. PCs can be used for running simple short simulations and for debugging the code. All results of the simulations in the Cluster are stored in the terminal server which can be accessed by a PC.

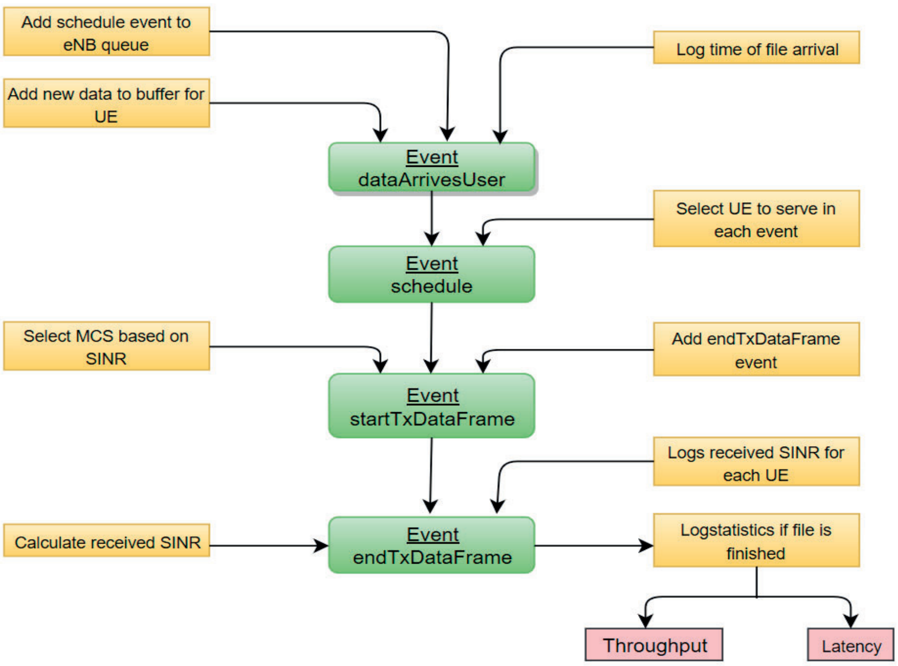

Figure 3.4: Core flow of events

The Thesis project used an event-based simulation tool called simMAC written in MATLAB that models a factory scenario. The simulator core is a loop that serves a queue of events as shown in Figure 3.4. Each event has a type and time stamp indicating when the model is to be executed. In addition to having a receiver ID and an embedded transmitter it has some information that collects statistics. First, there is initialization of the event queue followed by a *timeNow* state variable that keeps track of the time progress. A loop then starts processing x number of events. The event with the earliest time-stamp is fetched and processed in each iteration. At the end of the loop, *timeNow* is incremented by letting *timeNow* be equal to timestamp for the currently fetched event. Multiple base stations and a varying number of nodes are modelled. The nodes send data to base stations and the simulation tool then calculates the SINR of the received data and thereafter uses this SINR to model a probability of error. Latency statistics are then created using the time it takes for the data to be correctly received at the base station.

The simulation setup includes a gain matrix which is a square matrix that represents the pathloss between all pairs of eNodeBs and nodes that have already been generated using another simulation tool and imported to the simulator. A map over the location of all the nodes has been defined that includes radio propagation features and the Gain matrix is created using this information. Each node is associated with a specific eNodeB with which it has the lowest path loss and the output power statistics of each node are recorded. At the beginning of the simulation, a first SINR estimate for each node is initialized followed by initialization of the event queue in Figure 3.4. As part of the simulation, a link to system model is setup that includes a list of MCSs, a list of SINR to cover, a table of BLER vs SINR for each MCS and a list of the most suitable MCS selection for each SINR that can be used in the scheduler.

3.3 Objectives

The time taken from data transmission to correct reception was recorded by the simulation tool and this was used to create latency statistics. The latency statistics were used to calculate the outage which is the number of users (nodes) that the system could not serve i.e. the number of users that failed to meet the latency threshold. A latency target was set to be equal to the periodicity and the outage was calculated as the number of transmissions that had a latency greater than the latency target.

1. The SIR estimation was based on historic estimations from each user's previously received frames. The Window setting in use had been 20 meaning that the simulation tool was selecting the worst of the last 20 SINR estimates. The first task was to investigate different values of the setting and hence find which value would yield optimal results.
2. In the Simulator, all nodes transmitted data with a full output power of 0.1 Watts. The second task was to implement power control with the existing scheduling maintained and to compare the results with those of task one to see if any improvements would be achieved by the system. This was done by adjusting the transmit power of the nodes in a link budget such that at each base station, the received power was the same for all the nodes transmitting to it.
3. The Simulator was previously using fixed scheduling. This meant that equal resources were being assigned to all the nodes that had data for transmission. With power control implemented, the scheduling function was changed to different allocations in task three with an aim of getting higher efficiency.

3.4 Methodology

For each setting (of Window and offset), we ran two simulations. The first one that had a simulation time of 0.5 seconds in the simulator was done in the PC environment. When this was finished and confirmed to be working, we ran the same simulation with a bigger time of 10 seconds in the Linux cluster which would take approximately 3 hours to complete.

Parameter Investigation

The existing Window (Filter) Setting was 20 and an offset of 3dB. Since we wanted to investigate the performance when the maximum number of users are transmitting data, we included further statistics such as object delay, SINR values, CDF of SINR values, MCS selected and a histogram of the MCS values for 882 users using a very small Window value of 1. As can be interpreted from Figure 3.5 below, this means the simulator selects the previous SINR value. We also did simulations of a window value of 50 meaning the worst of the last 50 received values is selected.

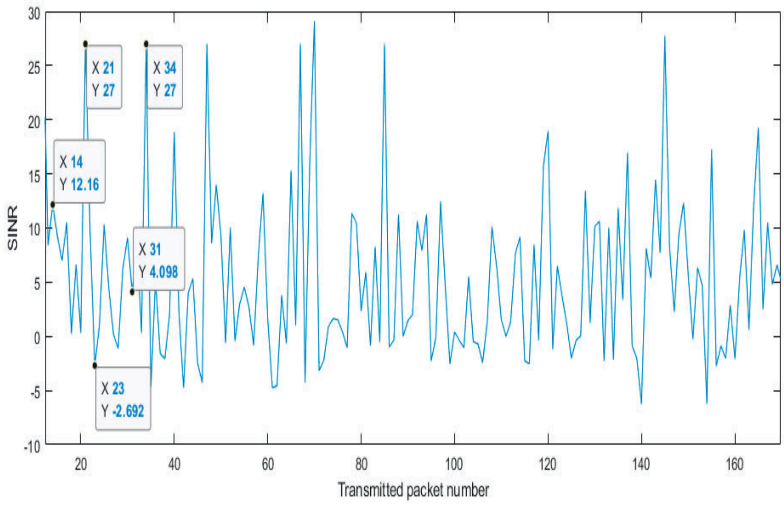

Figure 3.5: SINR selection for Link Adaptation

The object delay is a representation of the latency experienced by every transmitted data bundle. As can be seen in Figure 3.5 below, when the periodicity is small (10ms), the system is not able to handle all the received packets. By the time the next packet arrives, the last packet has not been fully received and processed and this builds up an increasing delay for the oncoming packets for the duration of the simulation. The x-axis represents the number of samples and the y-axis represents the delay. The delay of each sample is indicated in milliseconds.

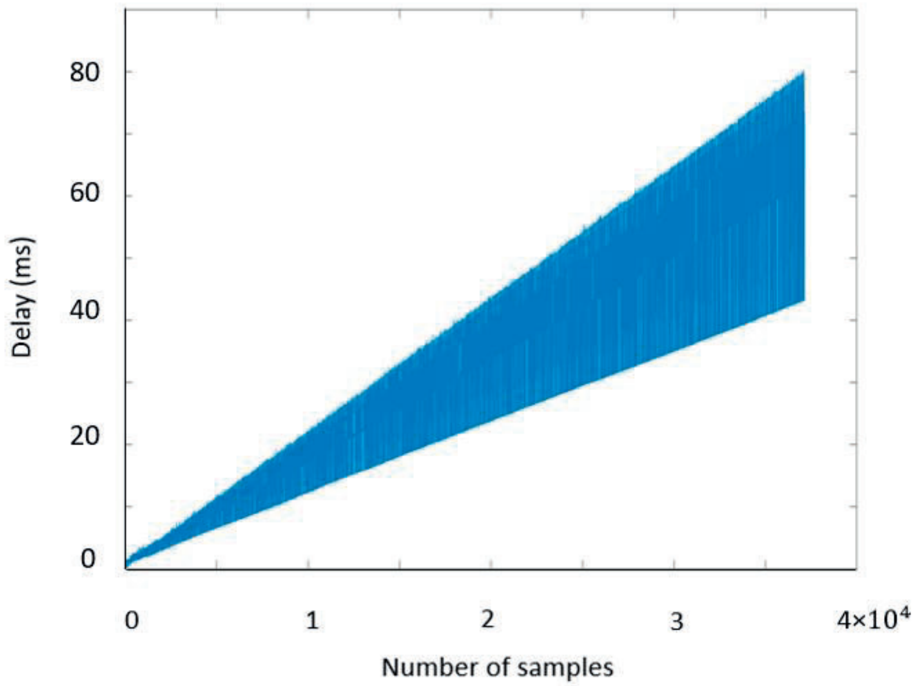

Figure 3.6: Object Delay with Window 1 Offset 3 for 882 users with 10ms periodicity

In contrast, when using a periodicity of 50ms, there is enough time for a packet to be received and possibly retransmitted if not received before the next packet of data arrives. It can be seen in the Figure 3.6 below that there is no build-up of unprocessed data packets as there is for 10ms periodicity.

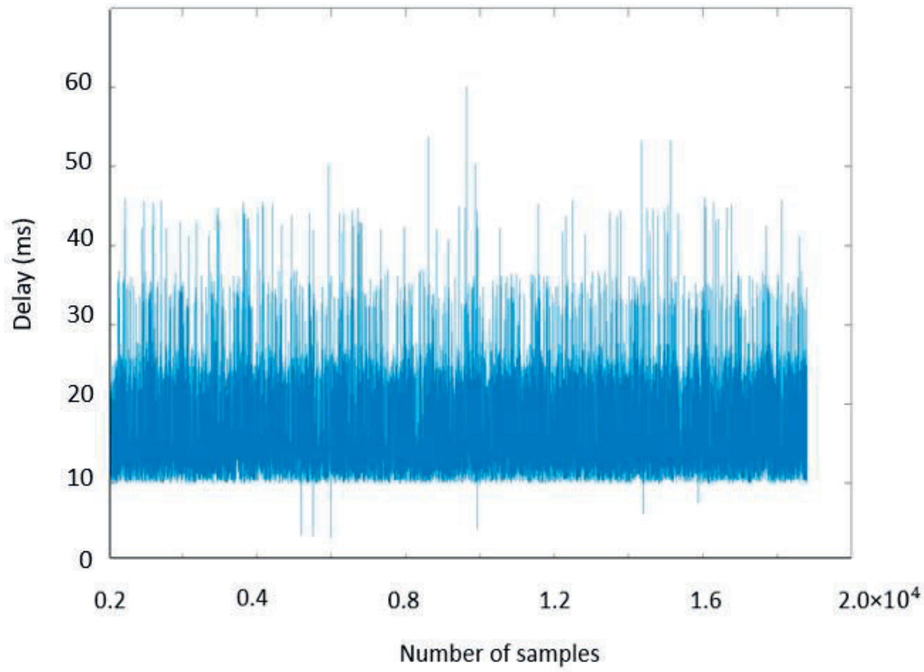

Figure 3.7: Object Delay Window 1 Offset 3 for 882 users with 50ms periodicity

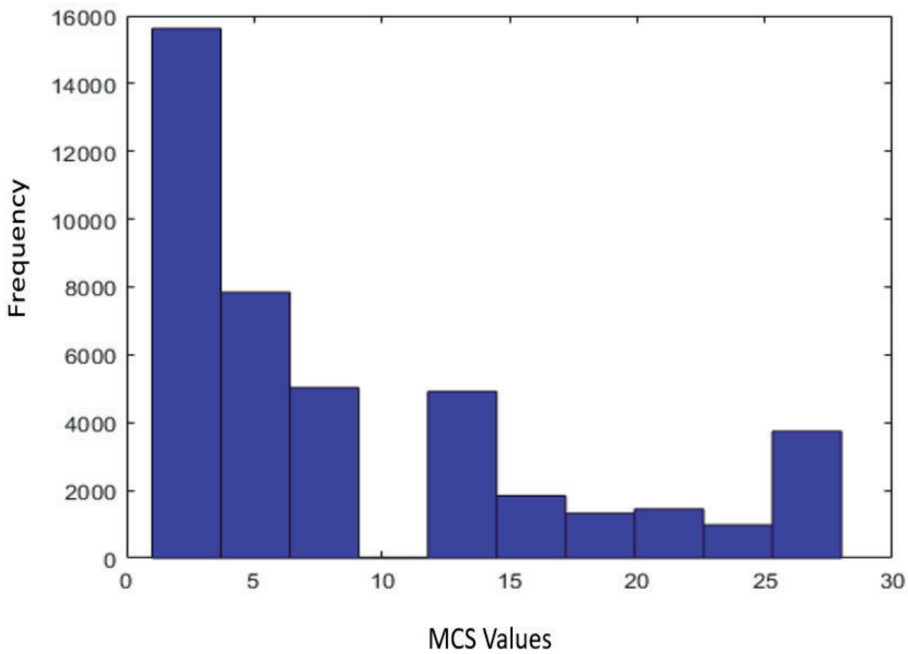

Figure 3.8: Histogram of the MCS (Window 1 offset 3)

Figure 3.8 is a histogram of the MCS values chosen for the transmissions. We are targeting very robust transmissions and using a small Window of 1 limits the SINR chosen because the Simulator has only one value to choose from i.e. it is choosing the last transmitted SINR value. As we can see from Figure 3.8, large number of high MCS values are chosen in contrast with when a bigger Window of 50 is used in Figure 3.10 where we can see from the histogram that most of the MCS values are small since there is higher likelihood of selecting a small SINR value when a bigger Window is used. In the case of Figure 3.10, lower MCS values dominate the histogram as can be observed.

We expected to have a generally flat trend in the delay shown in Figure 3.9, but we note an increase towards the end of the simulation for the last 500 samples. It could be due to the large window used which gives each user a more robust modulation and coding scheme. This gives each of the users more resources that starves out the total resources available to allocate to new retransmissions that the system is wholly dependent on at that time in the simulation.

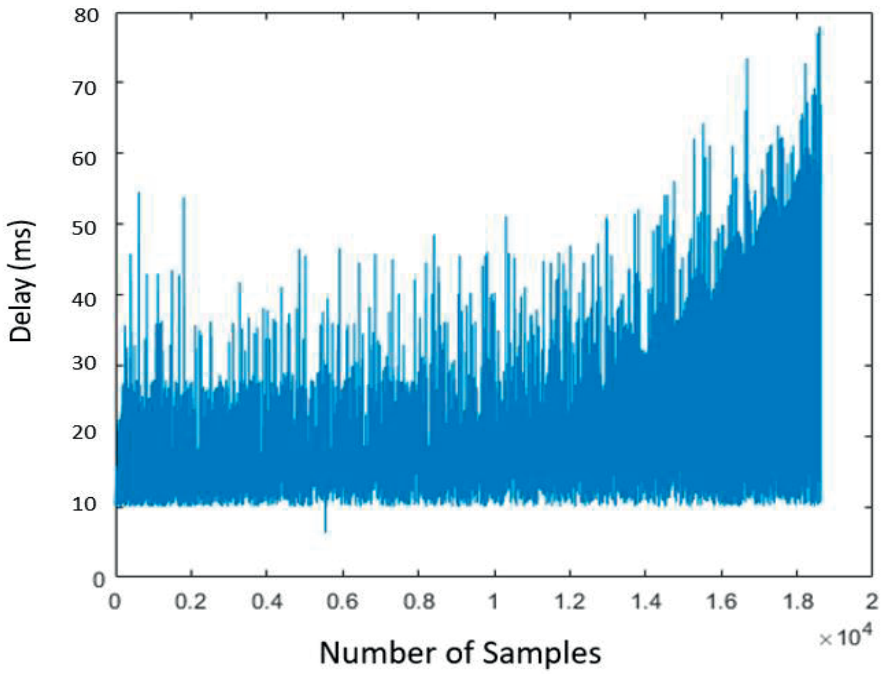

Figure 3.9: Object Delay Window 50 Offset 3 for 882 users

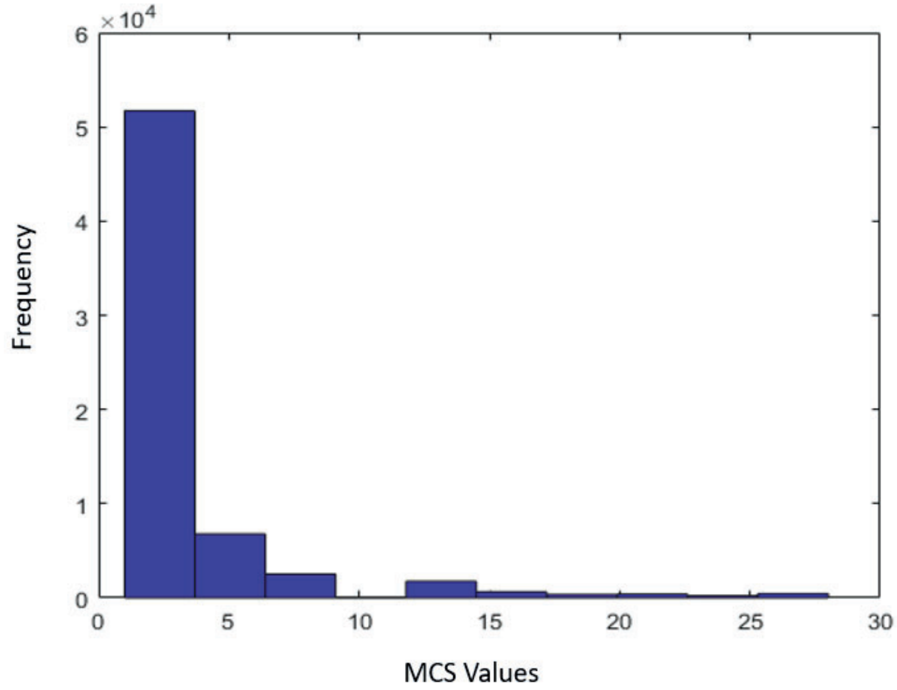

Figure 3.10: Histogram of the MCS (Filter 50 offset 3)

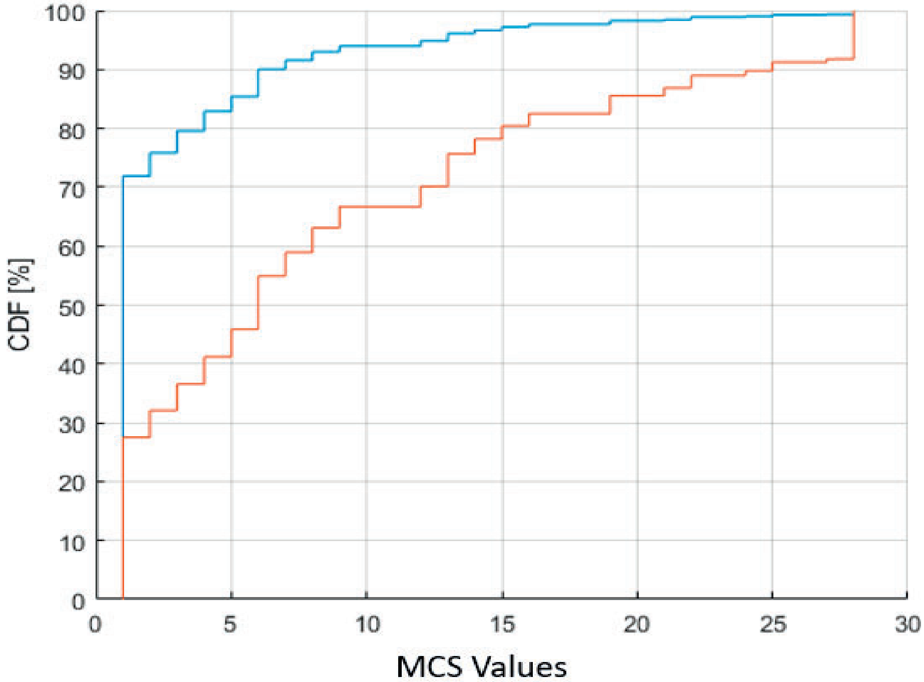

Figure 3.11: Comparison of the CDF MCS of the two window lengths of 50(blue) and 1(orange).

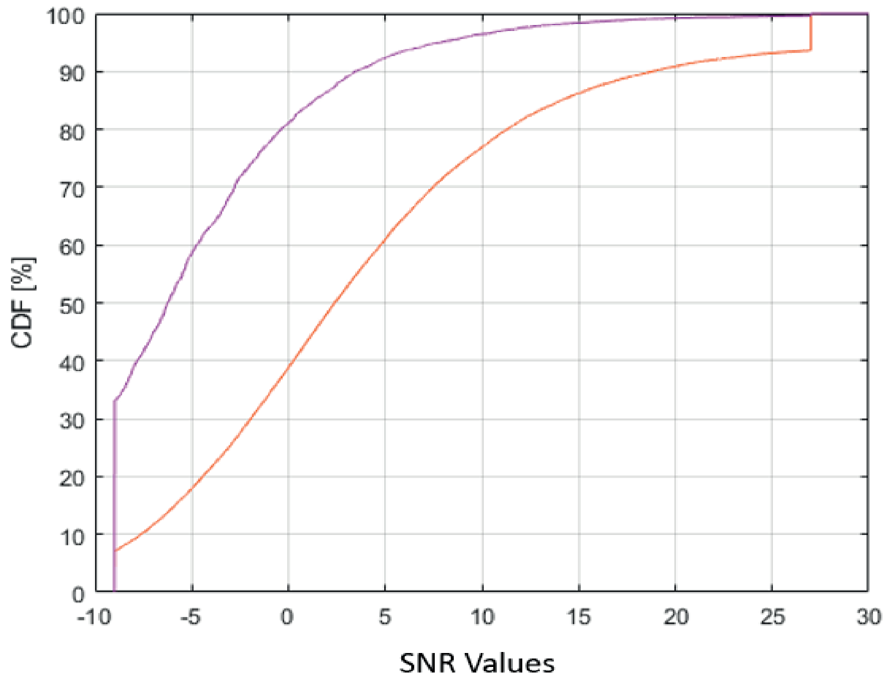

Figure 3.12: Comparison of the CDF SNR of the two window lengths of 50(purple) and 1(orange) for 882 users.

From the figure 3.11 we see that when a bigger window of 50 is used, half of the SNR values lie below -7dB. This may be because when it is easier to get a different minimum SNR when the window is smaller because there will be a much higher probability of getting to a different minimum since the simulator will be choosing the smallest of the last value. In contrast, there is a high probability that we will have the same minimum when we use a big window of 50. The sudden peak in the CDF is because most of the values have a maximum at 27dB but a few of the transmissions get to 30dBs.

3.5 Simulations

Task 1: Link Adaptation

We made simulations using four different Window and Offset settings (Window 5 offset 3) (Window 20 offset 0) (Window 20 offset 3) (Window 30 offset 3) and obtained the outage probability statistics for the six number of users (98, 200, 300, 392, 648, 882). The periodicity was set to (10, 20, 30, 40, 50).

Task 2: Power Control

All nodes in the model have been transmitting data with a full output power of 0.1 Watts. We implemented power control using a link budget by adjusting the transmit power of the nodes such that at each base station, the received power will be the same for all the nodes transmitting to it. The existing fixed scheduling was maintained for this task.

We expected to see improvements in the outage probability because after applying power control, nodes which are near the base stations transmit with less power than those that are further, and this reduces the interference between the transmitted signals from the nodes. The SIR will thus improve for all the uplink transmissions.

Task 3: Scheduling Modification

The Simulator had been using fixed scheduling where equal amount of resources (6PRBs) were being allocated to each scheduled user. We changed this to the Buffer-based scheduling in which resources were allocated depending on the amount of data that was available in the transmit Buffer for each scheduled transmission. We expected to see a further reduction in latency because less resources were being wasted in this buffer aware scheme. Time is also a parameter that is part of the resource block and efficient allocation of PRBs translates to improved latency statistics.

4 Results

4.1 Task 1: Link Adaptation

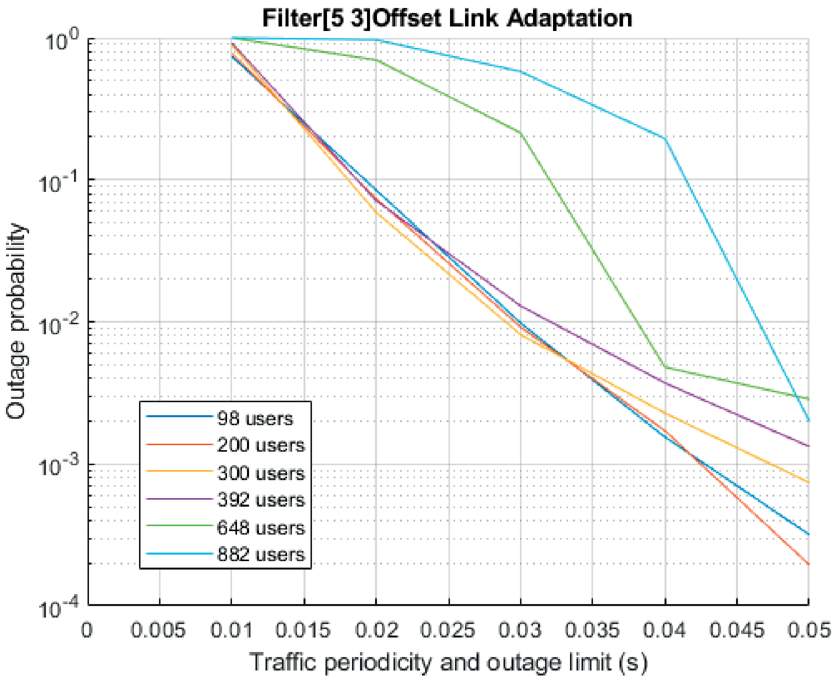

Figure 4.1: Outage Probability for Filter Setting 5 and offset 3

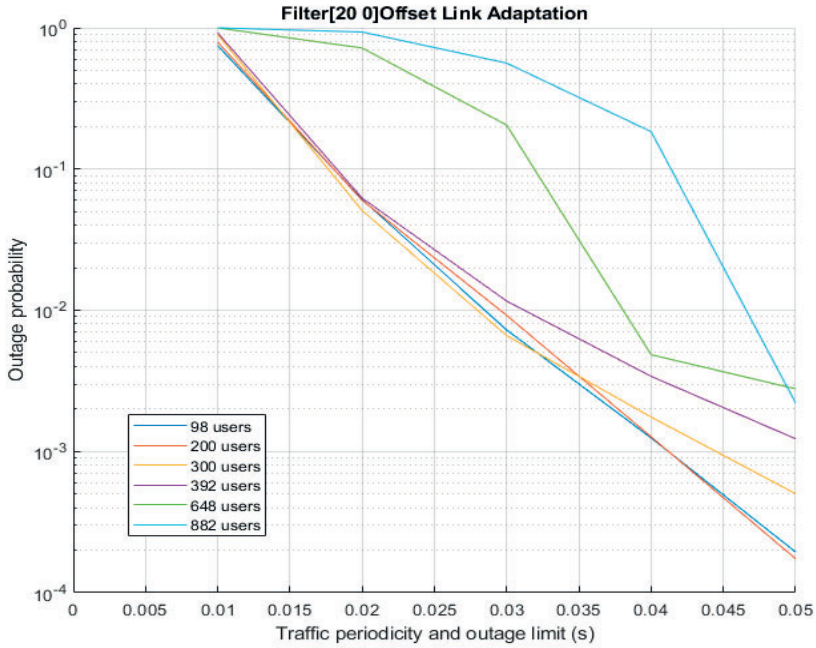

Figure 4.2: Outage Probability for Filter Setting 20 and offset 0

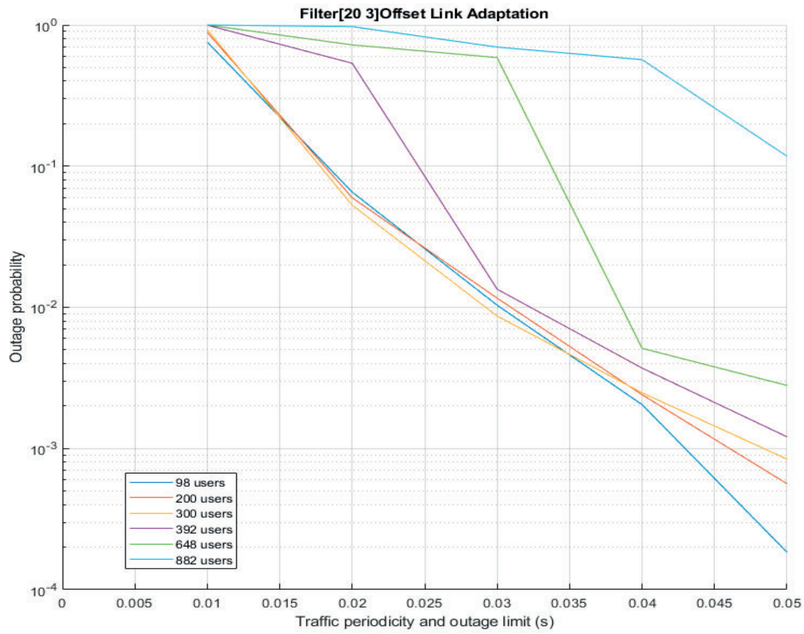

Figure 4.3: Outage Probability for Filter Setting 20 and offset 3

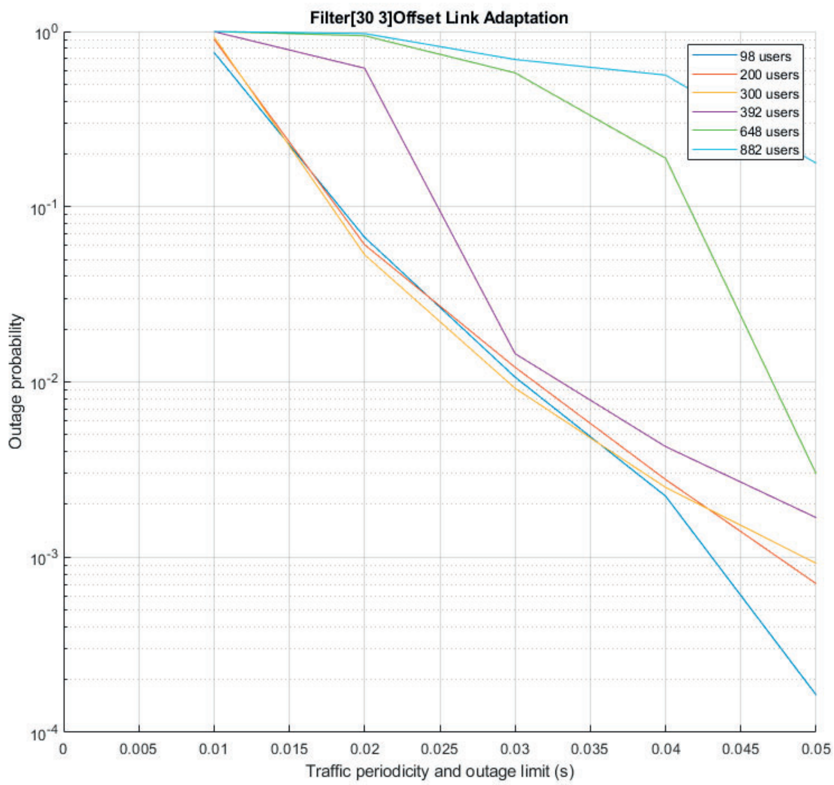

Figure 4.4: Outage Probability for Filter Setting 30 and offset 3

From the simulation results above, the Filter setting of 20 combined with an offset of 0 gave the best results which are analyzed in Table 4.1 and 4.2 below. We used 0.001 as a threshold for the outage probability and in Figure 4.1 the values marked in red are those for which the threshold was met. In Figure 4.2 the value of the outage probability when the threshold is met is indicated and the Window 20 and offset 0 has the smallest average of the four settings. This is why we selected it as our best setting.

	Periodicity				
Number of Users	**10ms**	**20ms**	**30ms**	**40ms**	**50ms**
98	0.75	0.06	0.007	0.0013	0.0002
200	0.8	0.06	0.0065	0.0013	0.00018
300	0.9	0.05	0.009	0.0018	0.0005
392	0.9	0.06	0.013	0.0034	0.0013
648	1.0	0.7	0.2	0.0049	0.0028
882	1.0	0.9	0.6	0.19	0.0022

Table 4.1: The outage probability of all the Number of users with their corresponding Periodicities for Window 20 offset 0

	Periodicity				
(Window-Offset)	**10ms**	**20ms**	**30ms**	**40ms**	**50ms**
(5 - 3)	None	None	None	None	(98users 0.0425) (200users 0.042) (300users 0.0475)
(20 - 0)	None	None	None	None	(98users 0.0415) (200users 0.0415) (300users 0.044)
(20 - 3)	None	None	None	None	(98users 0.043) (200users 0.046) (300users0.048)
(30 - 3)	None	None	None	None	(98users 0.043) (200users 0.0475) (300users 0.049)

Table 4.2: Number of users that meets the threshold for each Window-offset setting and the outage probability value at the point when threshold is met for each Window-offset setting.

4.2 Task 2: Power Control

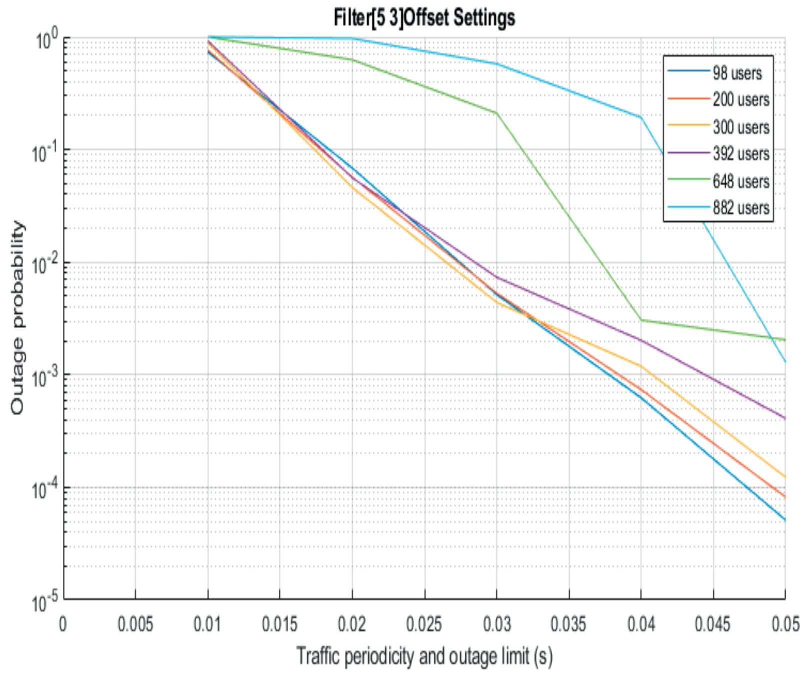

Figure 4.5: Outage Probability with Power Control for Filter Setting 5 and offset 3

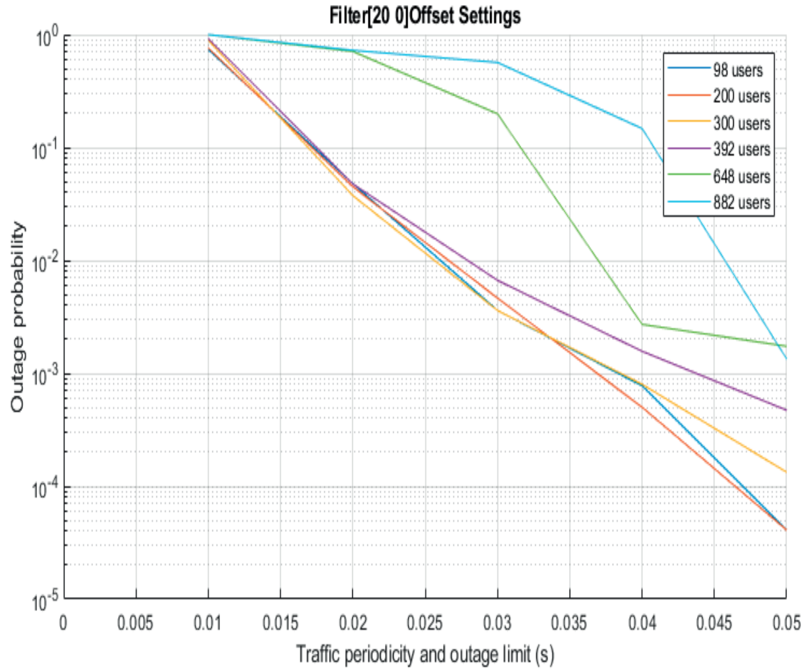

Figure 4.6: Outage Probability with Power Control for Filter Setting 20 and offset 0

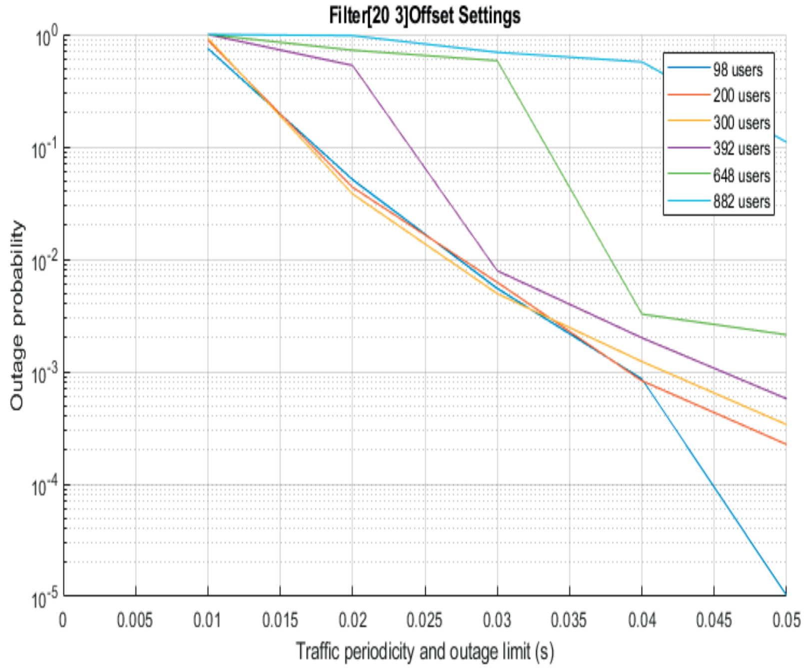

Figure 4.7: Outage Probability with Power Control for Filter Setting 20 and offset 3

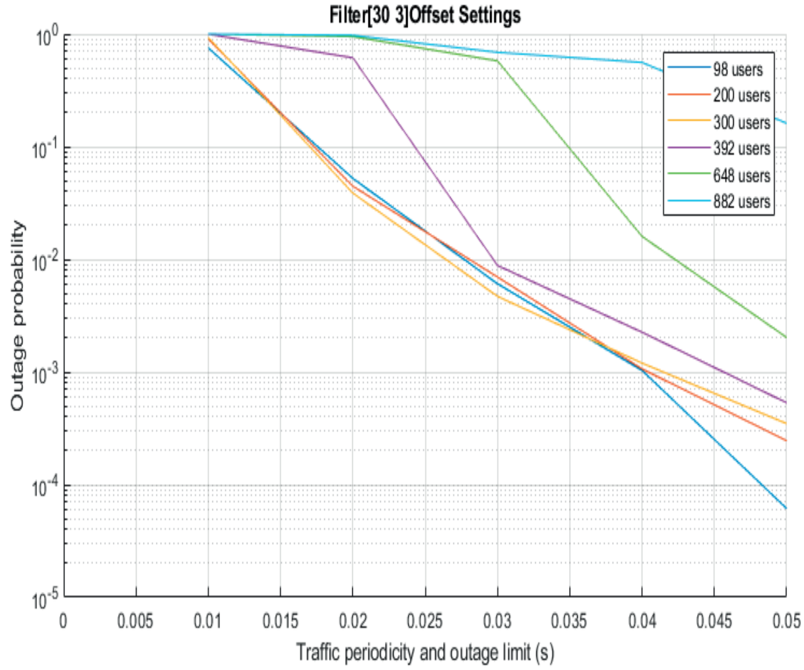

Figure 4.8: Outage Probability with Power Control for Filter Setting 30 and offset 3

The Filter setting of 20 with an offset of 0 was found to give the best results which are analyzed in the table below. As done in the first task, we used 0.001 as a threshold for the outage probability to compare the output with and without power control and the values marked in red are those for which the threshold was met.

	Periodicity				
Number of Users	**10ms**	**20ms**	**30ms**	**40ms**	**50ms**
98	0.7	0.05	0.0035	0.0008	0.00004
200	0.7	0.05	0.005	0.0005	0.00004
300	0.9	0.04	0.0035	0.0008	0.00015
392	0.9	0.05	0.007	0.0015	0.0005
648	1.0	0.7	0.2	0.0027	0.0017
882	1.0	0.7	0.6	0.15	0.0015

Table 4.3: The outage probability of all the Number of users with their corresponding Periodicities

	Periodicity				
(Window – offset)	**10ms**	**20ms**	**30ms**	**40ms**	**50ms**
(5 – 3)	None	None	None	(98) (200) users	(98) (200) (300) (392) users
(20 – 0)	None	None	None	(98) (200) (300) users	(98) (200) (300) (392) users
(20 – 3)	None	None	None	(98) (200) users	(98) (200) (300) (392) users
(30 – 3)	None	None	None	None	(98) (200) (300) (392) users

Table 4.4: Number of users that meets the threshold for each filter setting and Periodicity with power control

Applying power control, Window setting 20 and offset 0 yielded the best results. Below are the results for this setting with and without power control. As can be seen from the two diagrams, power control made a slight improvement to the system. Without power control, at the 50ms periodicity, none of the users was getting to an outage probability of 0.0001 but after power control some users in the 98 and 200 user settings achieve this. Without power control, only three settings of users (98, 200, and 300) were meeting the threshold of 0.001 at 50ms but after power control, four settings (98, 200, 300, and 392) achieve the threshold when the periodicity is 50ms. At a periodicity of 40ms, 98 users and 200 users are able to meet the threshold for the Window settings (5 – 3), (20 – 0), and (20 – 3) with an additional 300 users also meeting the requirements for Window setting (20 – 0) unlike what was observed without power control where none of the users achieved the threshold at a periodicity 0f 40ms for any of the filter settings.

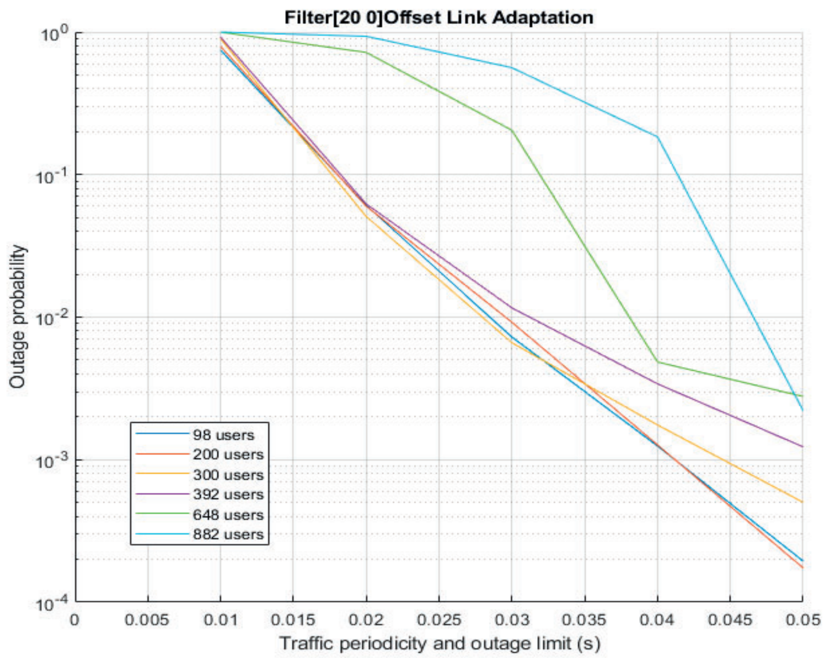

Figure 4.9: Outage probability Without Power Control

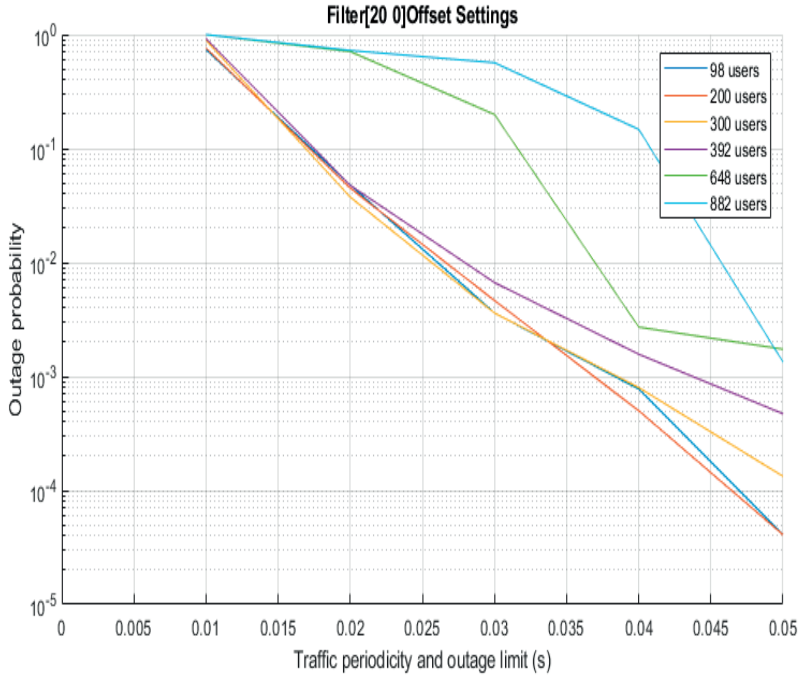

Figure 4.10: Outage probability with power control

Using Different SINR values

After applying power control, window value of 20 and offset of 0 yielded the best performance so we used this setting to test the system using different target SINR values of 10dB 20dB and 30dB.

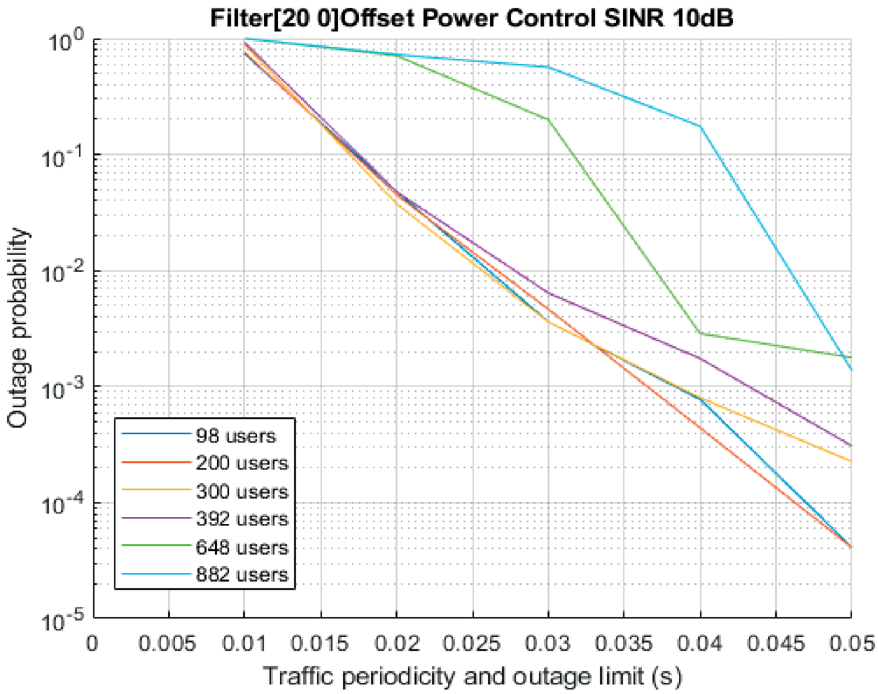

Figure 4.11: Outage probability with Target SINR of 10dB

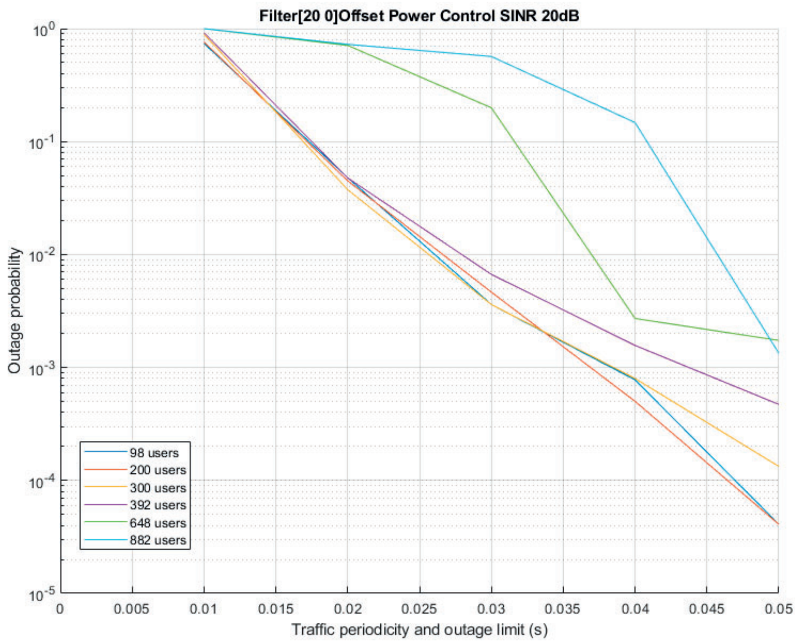

Figure 4.12: Outage probability with Target SINR of 20dB

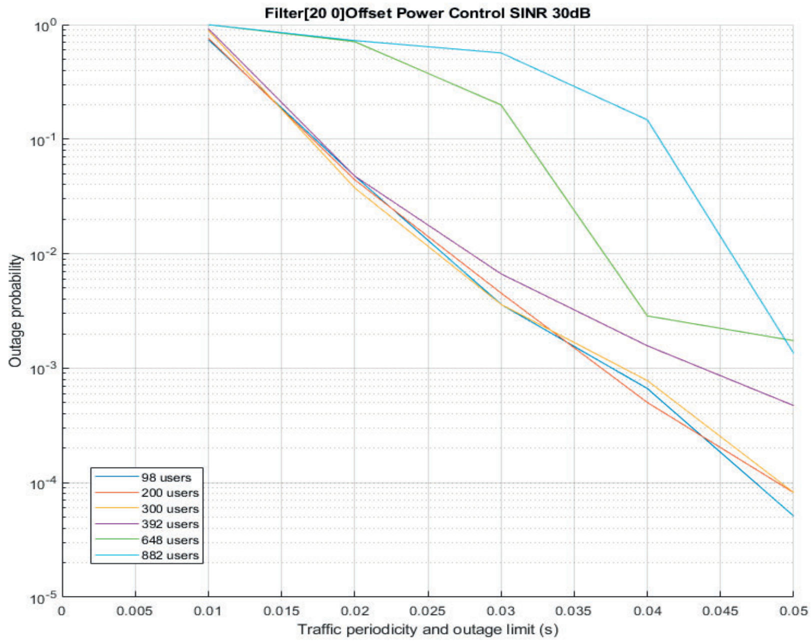

Figure 4.13: Outage probability with Target SINR of 30dB

Increasing the target SINR would help the users that are far from the eNodeBs and thus transmitted packets by these users would have a lower outage probability compared to when a lower target SINR is used. For the users that are close to the eNodeBs, an increase in the target SINR would also decrease the outage probability experienced but this will also increase the interference between the received packets. This is reflected in the results when we compare the SINR 10dB in Figure 4.11 and SINR 30dB in Figure 4.13 which show an improvement for 98 users and 300 users at 40ms and 50ms periodicity respectively.

4.3 Task 3: Scheduling Modification

Below are the outage probability results for four Window settings of (Window 1 offset 3), (Window 20 offset 0), (Window 20 offset 3) and (Window 50 offset 3) obtained after the scheduling was changed from fixed scheduling to buffer-based where resources were allocated to scheduled users depending on the amount of data that was available in the uplink buffer.

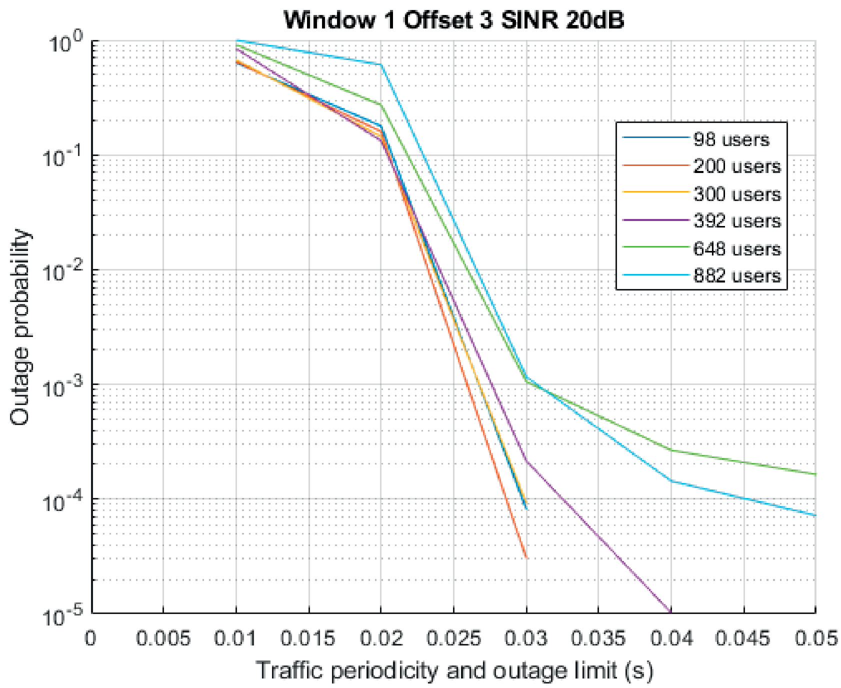

Figure 4.14: Outage probability with Target SINR of 20dB with Buffer-based scheduling for Window 1 offset 3

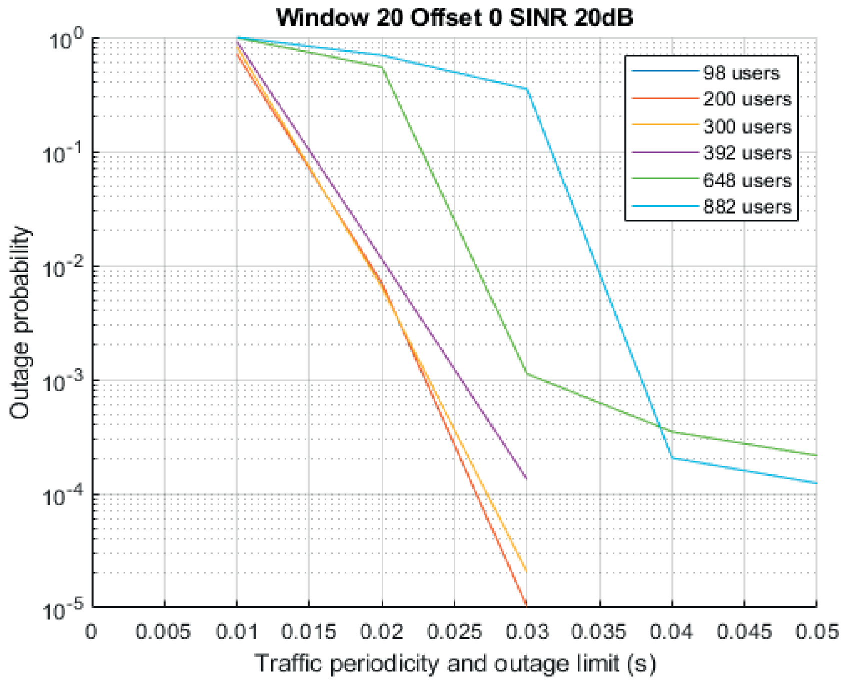

Figure 4.15: Outage probability with Target SINR of 20dB with Buffer-based scheduling for Window 20 offset 0

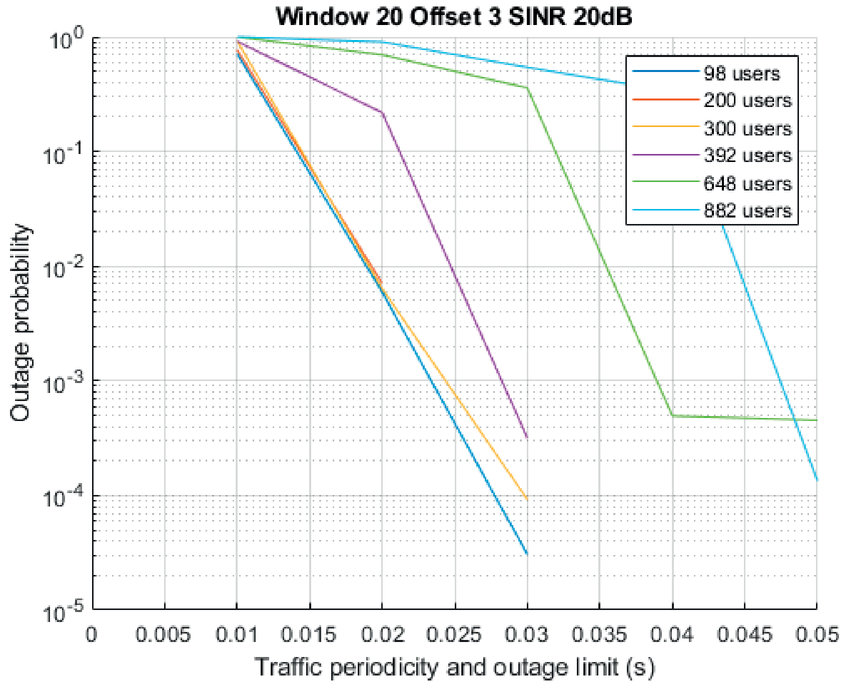

Figure 4.16: Outage probability with Target SINR of 20dB with Buffer-based scheduling for Window 20 offset 3

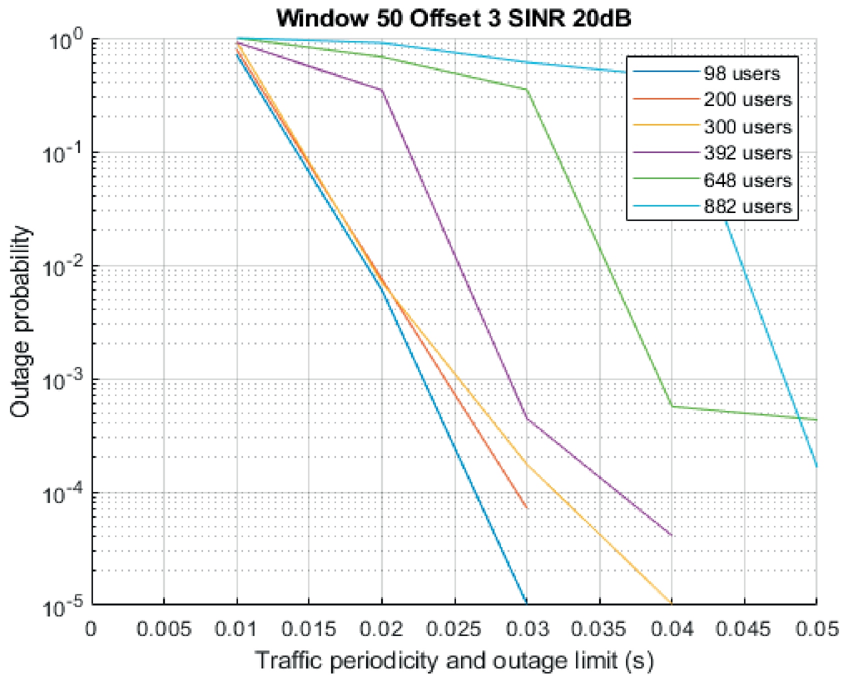

Figure 4.17: Outage probability with Target SINR of 20dB with Buffer-based scheduling for Window 50 offset 3

As can be seen from Figures 4.14 – 4.17 using the buffer – based scheduling enabled all the users to meet the threshold of 0.001 outage probability as we had expected since it made resource allocation efficient and minimized wastage of resource in allocation of PRBs to users that did not need the resources. Since the eNodeB has access to buffer status reports, that are specified in 3GPP for LTE, the efficiency with which resources are allocated and utilized is optimal. In comparison, the previously used fixed allocation that allocated 6PRBs recorded worse statistics because:

- To nodes that required less than 6PRBs, the fixed scheme wasted resources that would otherwise have been given to nodes that required them.
- For the nodes that that required more than 6PRBs, the fixed allocation scheme starved these nodes of needed resources.

5 Conclusion

An implementation of LTE in Industry was analyzed in this project. The main objective was to determine if the currently used settings used in the Simulator set-up could be improved. Based on the obtained results, the overall conclusion is that the LTE model can be improved to accommodate more users with these users experiencing lower latency than previously recorded.

Link adaptation settings were modified, and the outage probability was reduced. The window of 20 and an offset of 0 gave better outage probability as compared to the previous window of 20 and offset of 3. The results show improved performance when there is no offset in the SINR estimation. We thus recommend the use of this Window and offset setting for further Simulator tests.

Applying Power control greatly improved the outage probability recorded. Without power control, only three users (all within 50ms) met the threshold for 0.001 outage probability but with power control, seven user settings met the threshold with three settings of the users achieving this in 40ms periodicity and four settings of users achieving this with 50ms periodicity. We recommend the implementation of power control using a link budget as we did for better latency results. We also recommend the use of fractional power control as has been shown in [12] to decrease latency in LTE networks.

For all the Window and offset settings that we simulated, we observed a significant improvement in the latency as all the users met the threshold at some point in the simulation runs. These results confirmed that the buffer-aware scheduling scheme enhances the performance of the LTE implementation as compared to the fixed allocation scheme. There is a fixed TTI duration in 3GPP LTE specifications but in 5G this TTI duration can be smaller. If this Industrial wireless network will be modified to use 5G specifications, we recommend scaling down of the TTI to enhance the latency statistics and therefore increase the number of users that can be served by the network.

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