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# A capacity and minimum guarantee-based service class-oriented scheduler for LTE networks

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**Abstract**

Quality-of-service (QoS) requirements have always posed a challenge from scheduling perspective and it becomes more complicated with the emergence of new standards and applications. Classical techniques like maximum throughput, proportional fair, and exponential rule have been used in common network scenarios but these techniques fail to address diverse service requirements for QoS provisioning in long-term evolution (LTE). These QoS requirements in LTE are implemented in the form of delay budgets, scheduling priorities, and packet loss rates. Scheduler design for LTE networks therefore requires handling service class attributes but preciously proposed scheduling methods ignored service class-based design and focused more on single network prospect. To address service class requirements in LTE, we propose a modified radio resource management-based scheduler with minimum guarantee in the downlink following network capacity and service class attributes defined in LTE standard. The scheduler takes advantage of best available channel conditions while maintaining data rates corresponding to minimum resources guaranteed for all major classes including the best effort class. A method is proposed to determine the scheduling resource capacity of active users in LTE networks with an admission control to limit the number of users according to available resources. In addition to closely matched theoretical and simulated active users that can be accommodated in the system, promising results are provided for system delay, throughput, and user mobility.

**Keywords:** Long-term evolution, Quality-of-service, Radio resource management, Service class, Best effort, Resource allocation, Admission control, Packet scheduler

## 1. Introduction

Long-term evolution (LTE) is a wireless cellular standard with end-to-end quality-of-service (QoS) support for IP-based traffic. It is maintained by 3GPP group and establishes itself as a 4th generation standard in the form of LTE-Advanced [1]. For smooth service flow provisioning, the standard defines delay budgets, packet loss rates, and scheduling priorities in a standard LTE service class table. The service flow IP connection established from gateway to UE is known as a 'bearer'. The bearer connection requires QoS flow treatment with proper queue management, rate shaping, and scheduling. Standard LTE service class table defines a total of nine classes, of which four are treated as GBR while the other five are treated as NGBR including the IMS signaling traffic [1]. There are some other parameters of service monitoring like ARP, MBR, and AMBR that relate to flow establishment and the throughput associated with the aggregate of flows.

Scheduling in LTE networks is implemented at the eNB station which is also responsible for the control of the time and frequency domain resources in the downlink and uplink for UE. This resource is termed as Physical Resource Block (PRB) and number of PRB's that can be scheduled every transmission time interval (TTI) depend upon the operating bandwidth. The allocation and management of PRB comes under a broader category of LTE radio resource management (RRM). The scheduling procedure is a service provider-based decision and there are no guidelines in the LTE standard. Different network and service flow criteria have been used in literature to design and test schedulers. Some of the criteria used include best multiplexing methods, fairness among flows, best channel conditions, buffer status reports, interference conditions, and flow priorities. Not all of these

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criteria can be implemented at the same time; moreover there is always some performance compromise when one technique is used against the other. Classical techniques like Max SIR, Fair Throughput, Round Robin, Opportunistic Scheduling, and Exponential Rule have been proposed to be used with LTE with modifications. These schemes combine one or two of the scheduling criteria but none takes into account the LTE service class attributes directly. If such classical techniques are implemented directly with strict priority, it would either result in the starvation of the NGBR (best effort—BE) classes, or some users is the GBR themselves would suffer from lack of resources due to less favorable channel conditions. If the schedulers only try to follow the delay budgets or the packet loss rates, then again either the classes with tightest delay requirements or the users with best scheduling conditions would take away major network resources. Hence, a balanced scheduler that follows the service class requirements while maintaining a proportion between allocatable resources among flows is required.

Following the requirements for a scheduler that takes into account the service class requirement in addition to providing a balance between the resources allocated to different service classes, we propose a balanced minimum guarantee LTE scheduler that maintains LTE service class requirements in addition to providing best channel condition use. The research methodology includes admission controller functionality with system capacity perspectives that calculates how much active users of a particular class can be admitted and then decides for user admission or rejection policy. Once the users are admitted in the system in different service class categories, we use flexible prioritization in terms of resource allocation rather than strict prioritization to limit the resource starvation for lowest priority classes. The scheduling of user packet is divided into two phases. In the first phase, PRBs are allocated to different user classes and in the second phase the data packets of users inside each class are scheduled for transmission. Hence, the first step is actually inter-class resource allocation and the second step is the intraclass packet scheduling. Major LTE resource parameters are considered and catered in theoretical formulation while performing the resource allocation and scheduling steps while corresponding LTE systems parameters are defined in the simulations section. Service parameters like delay budgets, packet loss rates, and channel conditions in the form of downlink channel signal-to-noise ration (SNR) are used in the scheduler design while simulations are carried out in a system level discrete-time event simulator 'LTE-Sim' [2].

The remainder of the article is arranged as follows. In Section 2, we formulate the problem statement and discuss relevant solution criteria. Section 3 is dedicated to the discussion of relevant literature work in the domain of scheduling, admission control, and QoS providence in LTE. In Section 4, we discuss the overall research methodology, system parameters, and system model in addition to the solution of the scheduling problem. Section 5 is dedicated to the discussion of the scheduler design results and relevant discussion. In Section 6, we finally conclude the work along with future research directions.

## 2. Problem definition

Classical schedulers proposed in literature fail to cater the requirements of LTE service class attributes because they take into account single network perspective at a time, e.g., the aggregated network throughput or proportional fairness among users. These schemes might combine one or two of the scheduling criteria but none takes into account the LTE service class attributes directly. If such classical techniques are implemented with strict priority directly, it would result in the starvation of the NGBR (BE) classes. In some cases users in the GBR themselves would experience from lack of resources due to less approving channel conditions. If the scheduling decision only tries to incorporate the delay budgets or the packet loss rates, then again either the classes with tightest delay requirements or the users with best scheduling conditions would take away major network resources.

Following the need for a balanced LTE service class-oriented scheduler, we define a minimum resource guarantee-based scheduler in the downlink that follows LTE service class attributes like delay budget and packet loss rate in addition to providing best channel condition use. The service delay parameter corresponds to the delay budget standardized for LTE service classes, e.g., 100 ms for conversational voice in GBR or 300 ms for buffered video streaming in NGBR class. The scheduler must make sure that none of the user packets in the eNB scheduling queue for a specific class exceed this delay budget or alternatively it should be transmitted within the time period. The use of channel quality index measurements is defined in LTE standard to regulate AMC scheme, therefore the scheduler must use channel quality measurements to enable channel diversity for UE. Minimum resource guarantee relates to the accessibility of PRBs of LTE networks for different service classes that need to be available in some relative percentage or ratio.

The contributions of the article include the incorporation of packet delay budget parameters from LTE service class standards specification in the scheduling of user traffic. We maintained controlled allocation of PRB for different service classes. A modified theoretical model has been used to calculate accommodated active user capacity keeping in view the data rates or type of service being run. The theoretical model has been verified with simulations that depict closeness with the theoretical limits. Finally, we also obtained minimum resource level guarantee for BE class as a contrast to typical scheduling that gets suffocated with resources when guaranteed class users are exceeded. Tabular form guidelines are presented using theoretical and simulated users with different traffic attributes that can be accommodated in LTE network.

## 3. Related work

Several research contributions exist related to scheduling and resource allocation in LTE domain that partly overlap with our research domain. Several classical schedulers have been identified and their performance studied with different LTE network characteristics [3-7]. These include the basic Proportional Fair, Round Robin, Maximal Signal-to-Interference Ratio, and Fair Throughput and complex schemes like exponential rule, intraclass, and inter-class schedulers. Major findings suggest a balance between user and network side perspectives when designing scheduler in LTE systems for proficient results. Performance analysis of Proportional Fair, Exponential Rule, and M-LWDF suggests that Exponential and M-LWDF perform better than basic Proportional Fair and can be used with LTE service class constraints for LTE downlink. Proportional Fair distributes resources to flows on the basis of channel quality measures. In Exponential method and M-LWDF, indirect delay measures are used to schedule users flow. The users having highest delay measure is selected and given access to physical channel. When analyzed in terms of capacity and throughput including Max Throughput scheme in different LTE cell sizes, it is observed that all schemes come with certain network demerits and cannot be applied for major network scenarios and for fulfillment of QoS requirements.

Several contributions in LTE scheduling have analyzed relationships between network and scheduling parameters [8-12]. These relationships include best packet scheduler features that may support variety of traffic with different priorities, channel statistics, queue sizes, and traffic loads while improving the QoE for end users. The most superior packet schedulers have been identified to be the ones incorporating delay budgets while sustaining a stable relationship between traffic loads and channel statistics. Relationships involving user priorities, queue sizes, and network conditions have been exploited to schedule user data while improving user satisfaction levels. Observations suggest that exploiting relationships can improve user satisfaction even with heavy flows while BE users get relatively more scheduling opportunities compared to basic classical methods. Hybrid schedulers in this regard are altered to cope up with frequency and as time domain scheduling suggesting the need for proper resource distribution in addition to scheduling of resources or simply splitting the scheduling process into simpler tasks.

Multi-level or hybrid scheduling that involves distributing the task of scheduling into different stages has been identified [13-19]. A two-level resource allocation and scheduling scheme allows resources in the form of PRB to be distributed among different type of traffics according to the load requirements of flow. Game theory approaches with characteristic functions like shapely value fairness metric have also been used. In the actual scheduling, schemes like exponential scheduler have been implemented with improved delay, fairness, and throughput characteristics as compared to Proportional Fair and M-LWDF algorithm. The sorting out of flows at an initial level allows reduction in the complexity of scheduler where it is required to sort various traffic mixes of users with different priorities. For a video streaming, it was observed that the scheme performs well even when simplest schedulers are used at the last scheduling step with good level of user satisfaction.

LTE schedulers that use define opportunity in the form of channel conditions or data queue have also been studied for LTE in addition to schemes adopting service attribute like priority and scheduling delay [20-26]. Opportunistic scheduling exploits channel statistics and user traffic loads to define opportunities related to resource allocation and scheduling while improving overall throughput of the network. While such an exploitation scheme for scheduling is valid for utilization of resources but having an overall impact of starvation for some user flows that never experience favorable channel or network characteristics. Head of line delay-based scheduling scheme allows delay to be measured as a function of packet head of line time instant in the scheduling queue. The user with highest utility for delay is selected for scheduling at the transmission interval. SINR is also used to perform scheduling for the resource blocks that can achieve the highest SNR. This method allows improved performance in terms of throughput, delay, and fairness. Similarly, scheduling schemes incorporating the service class priorities along with target bit error rates from LTE specifications allows increased aggregated system throughput against Maximum Throughput and Proportional Fair when channel quality statistics in addition to the user's earlier data rates and channel occupancy statistics are used.

In typical schedulers, either the resources for BE or low-priority classes go down to zero when users in high-priority class increases, or the service class attributes are ignored altogether. To cater this, in our proposal, we incorporate packet delay budget parameters from LTE service class standards specification in the scheduling of user traffic in addition to controlled allocation of PRB for different service classes. We maintain minimum resource level guarantee for BE class and use tabular form guidelines using theoretical and simulated active users with different traffic attributes that can be accommodated in LTE network.

## 4. Research methodology

The complete service class-based scheduler design is divided into three discrete parts. First, 'Admission Control' is used to admit or reject active LTE users in the network depending upon available system capacity or the accessible resources set aside for each class. An active user is defined as having data packets all the time to be scheduled. Usually, systems are provisioned for both active as well as inactive users, but we focus here on active users only to gain insight into the resource capacity of LTE networks. Next, we need to distribute PRB among different service classes or simply perform 'Resource Allocation'. After the resource allocation step, actual 'Packet Scheduling' needs to be performed. This final step involves use of delay metric from LTE service class specifications. The resource block distribution and packet scheduling phases can be distinguished as being interclass and intraclass-related sorting methods. Hence, we achieve complexity reduction by following a 'divide and conquer' strategy in which first the service classes are sorted for resource allocation and then users in a class are sorted for packet scheduling. The scheduling method after admission control is reflected in Figure 1.

### 4.1. System capacity estimation

System capacity estimation in literature uses spectral efficiency and bandwidth of operation in addition to parameters like busy hour loading and cell sectoring. System capacity is thus defined as

$$\begin{aligned}\text{Capacity\_of\_cell\_site} = {} & \text{no\_of\_sectors} \\ & \times \text{spetral\_efficiency} \\ & \times \text{bandwidth} \\ & \times \text{busy\_hour\_loading} \qquad (1)\end{aligned}$$

The simultaneous subscribers of a specific class that can be accommodated in a cell site is thus

$$\text{Simultaneous\_subscribers} = \frac{\text{capacity\_of\_cell\_site}}{\text{QoS\_data\_rate}} \qquad (2)$$

Here QoS_data_rate represents the data rate of a service type, e.g., VoIP traffic can have the requirement of 12 kbps or streaming video be run 300 kpbs. The capacity can thus be split into the percentage by which we want to accommodate each traffic flow type. At each transmission interval, UE reports their instantaneous downlink SNR to eNB station used to calculate the data rate in number of bits for the allocatable RB-pair. A user *i*'s achievable data rate for *j*th RB at time is calculated as follows:

$$R_{i,j}(t) = \frac{n\_\text{bits}}{\text{symbol}} \times \frac{n\_\text{symbols}}{\text{slot}} \times \frac{n\_\text{slots}}{\text{TTI}} \times \frac{n\_\text{subcarrier}}{\text{RB}} \qquad (3)$$

where $n$_bits, $n$_symbols, $n$_slots, and $n$_subcarrier are the number-of-bits, number-of-symbols, number-of-slots, and number-of-subcarriers, respectively [21].

### 4.2. Admission controller

We consider here the capacity of active LTE users in the downlink only. Active users always have data to send and the flows are readily available at the eNB MAC scheduler for transmission. The classical method for subscriber capacity calculation cannot be used here because we are considering only the downlink and we need to calculate only goodput for different traffic type considering their QoS requirements. In addition, the calculation of QoS data rate needs to be done corresponding to the delay budget, i.e., how many bits per second

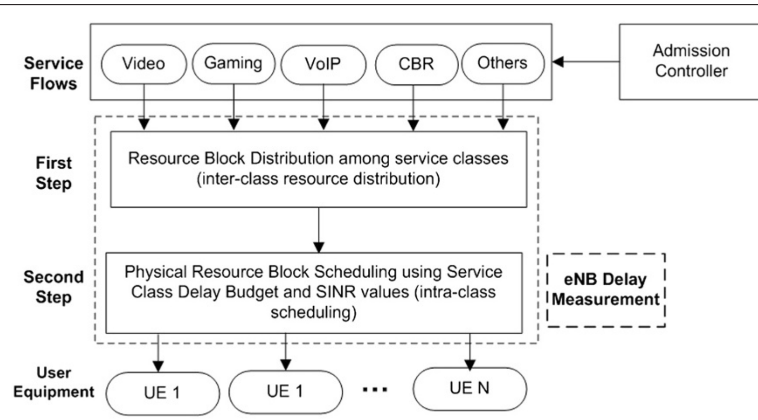


**Figure 1** Resource allocation and scheduling steps in LTE.

should be transmitted within the delay budget period. Hence, the subscriber capacity is actually

$$\text{Subscriber\_capacity} = \frac{n\frac{-\text{bits}}{\text{symbol}} \times n\frac{-\text{symbols}}{\text{TTI}} \times n\frac{-\text{subcarrier}}{\text{RB}} \times \frac{n\_\text{RB}}{\text{slot}} \times \frac{n_{DL}\_\text{slots}}{\text{frame}} \times \frac{n\_\text{frames}}{\text{TTI}}}{\text{QoS\_data\_rate(per delay budget period)}} \quad (4)$$

where $n$_DL_slots represents the number of downlink slots. The number of downlink slots may vary in LTE networks according to switch point periodicity is specified by LTE specifications to cater the traffic load and provide some balance in traffic scheduling.

The working of Admission Controller algorithm is highlighted in Figure 2. Initially, the admission controller checks the GBR or NGBR service category. If the resources are available in corresponding category considering the user as active client then it is allocated resources, otherwise it is rejected. The NGBR is allowed to take up resources from GBR class if available but the opposite is not allowed. So, an additional check is required to free up GBR resources in case the NGBR occupies the GBR resource pool. For another user request, the RB allocation is again checked for underutilized resources following GBR and NGBR traffic verifications.

The partitioning of resource pool between guaranteed and non-guaranteed service flows is presented as a tuning factor for the currently adopted RRM method for LTE networks where despite having a number of subclasses falling under the BE category, the classical approach of giving the highest priority, and ability to take up all the resources by the guaranteed flows is adopted.

## 4. 3. Resource block allocation

PRB allocation to users is done following a minimum level of guarantee approach which applies for BE class as well. In typical schedulers, BE is not provided any guarantee and resource are only allocated when the guaranteed class is satisfied. This method of allowing BE to take up left over resources will result in starvation when

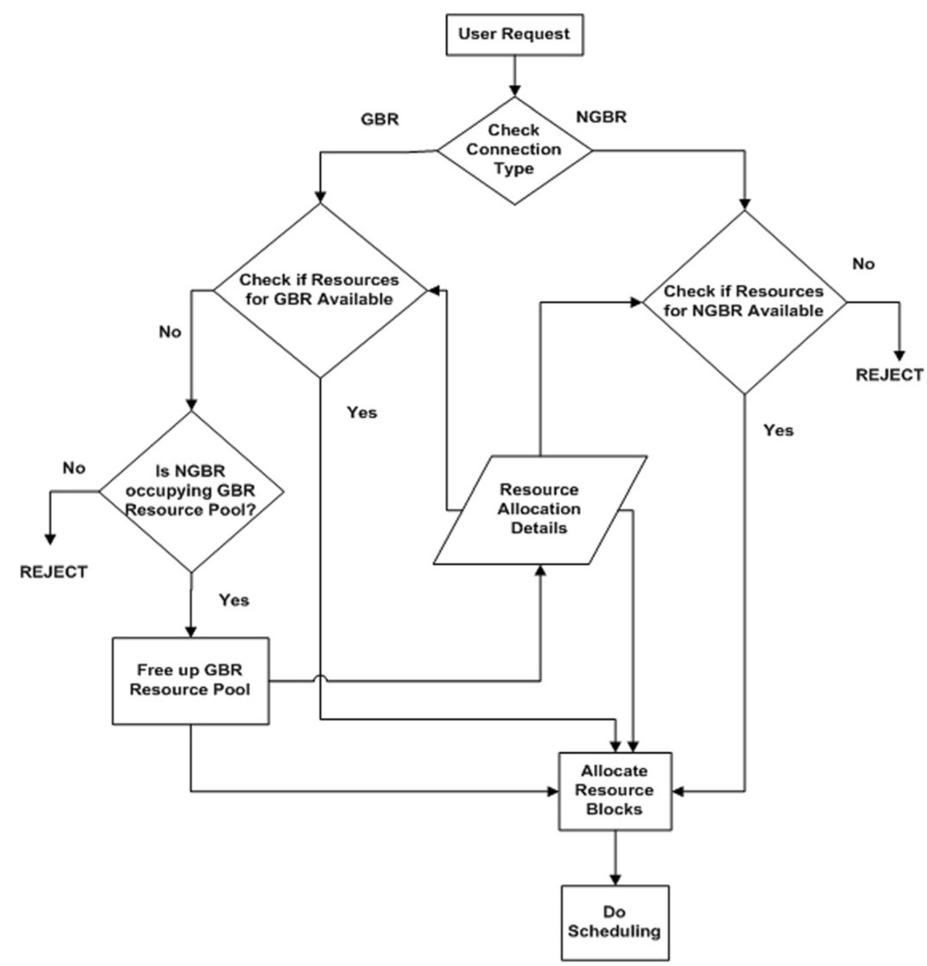


**Figure 2** Admission controller design for LTE.

the network is loaded with guaranteed traffic. BE flows are always present in a considerable amount for most of the cellular networks. In LTE with five sub-classes of BE (NGBR), it is helpful to maintain some level of resource block guarantee in the network. The resource blocks to be allocated to specific QoS class with a particular number of users are calculated as follows:

$$\mathrm{RB\_allocate} = \frac{\mathrm{QoS\_data\_rate} \times n\mathrm{\_subscribers}}{\frac{n\mathrm{\_bits}}{\mathrm{symbol}} \times \frac{n\mathrm{\_symbols}}{\mathrm{TTI}} \times \frac{n\mathrm{\_subcarrier}}{\mathrm{RB}} \times \frac{n\mathrm{\_}DL_{\mathrm{slots}}}{\mathrm{frame}} \times \frac{n\mathrm{\_frames}}{\mathrm{TTI}}} \tag{5}$$

where RB_allocate is rounded off to obtain the minimum allocatable resource blocks. The subscribers with different QoS rates are bounded by the downlink network capacity as

$$\left(\mathrm{data\_rate}_{typn} \times n\mathrm{\_subscribers}_{typn}\right) \leq \mathrm{downlink\_capacity}_{\mathrm{total}} \tag{6}$$

### 4.4. Packet scheduling

The intraclass user selection in packet scheduling is derived from delay calculations as a function of the delay budget. An HOL packet delay is measured which is defined as the time difference between the recent packet serving time and the time when the packet was stamped on its arrival in service queue. This time is directly compared with the service class delay budget the user packet belongs to. The user whose difference in the HOL delay and budget difference is the lowest is scheduled first. If the difference is exceeded the packet is dropped from the queue. Most recent SNR values in the downlink are also used in the scheduling decision. The scheduler is modeled as next.

Let the user packet delay budget parameter for a class $i$ be denoted by $\sigma_i$. Then for any user represented by $j$ in the class $i$; the HOL delay measure at a time instant $t$ is described as follows:

$$\mathrm{HOL}_j(t) = T_{\mathrm{current}}(t) - T_{\mathrm{stamp}} \tag{7}$$

where $T_{\mathrm{stamp}}$ denotes the time record of the packet since it arrived at the service scheduling queue and $T_{\mathrm{current}}$ represents the current packet processing time. The remaining scheduling time for transmission is then presented as a function of HOL as follows:

$$\mathrm{delay}_j(t) = \left|\sigma_i - \mathrm{HOL}_j(t)\right| \tag{8}$$

For final RB allocation, the user with the lowest $\mathrm{delay}_j(t)$ metric is selected.

$$u = \min\left\{\mathrm{delay}_j(t)\right\} j\forall \mathrm{user}\in \mathrm{Class}\ i \tag{9}$$

Once the user $u$ is chosen for transmission on an RB, the SNR values are also analyzed and the greatest of these is chosen. A flow chart describing various stages in the second of intra-user selection is described in Figure 3.

### 4.5. System model

The parameters used for evaluation of the scheduling method include the aggregate system throughput, system delay, packet loss ratio (PLR), and SNR. The analysis parameters are defined below.

#### 4.5.1. System throughput

The aggregate throughput of system is defined as the summation of packets transmitted in a simulation time from eNB to all UE. A certain amount of the total packets is the control portion and considered overhead. But for general throughput measurements, we consider the aggregate of all packets. In mathematical form, the aggregate throughput of the system is

$$\text{System throughput} = \frac{1}{T}\sum_{i=1}^{K}\sum_{t=1}^{T} p_{\mathrm{size}\,i}(t) \tag{10}$$

where $T$ represents the total time taken for simulation and $p_{\mathrm{size}}$ describes the packet size in bits transmitted from eNB to a particular user $i$ aggregated for the simulation time. $K$ is the total number of active users in the system.

#### 4.5.2. System delay

The delay of the system is computed as an average of the total time delay difference between the packet arrival time in queue and the time instant it is transmitted to UE from the service queue. This calculation accounts for the HOL packet delay and is averaged over all transmitted packets. In mathematical terms we write

$$\mathrm{Systemdelay} = \frac{1}{T}\sum_{t=1}^{T}\frac{1}{K}\sum_{i=1}^{K}\mathrm{HOL}_i(t) \tag{11}$$

where $K$ represents the total number of users in a particular service flow and $T$ is the total simulation time.

#### 4.5.3. PLR

The PLR is calculated as the ratio of $t$ packets discarded for not meeting the delay budget to the sum of packets arriving at eNB station buffer over the simulation time $T$.

$$\mathrm{PLR} = \frac{\sum_{i=1}^{K}\sum_{t=1}^{T} p_{\mathrm{discard}\,i}(t)}{\sum_{i=1}^{K}\sum_{t=1}^{T} p_i(t)} \tag{12}$$

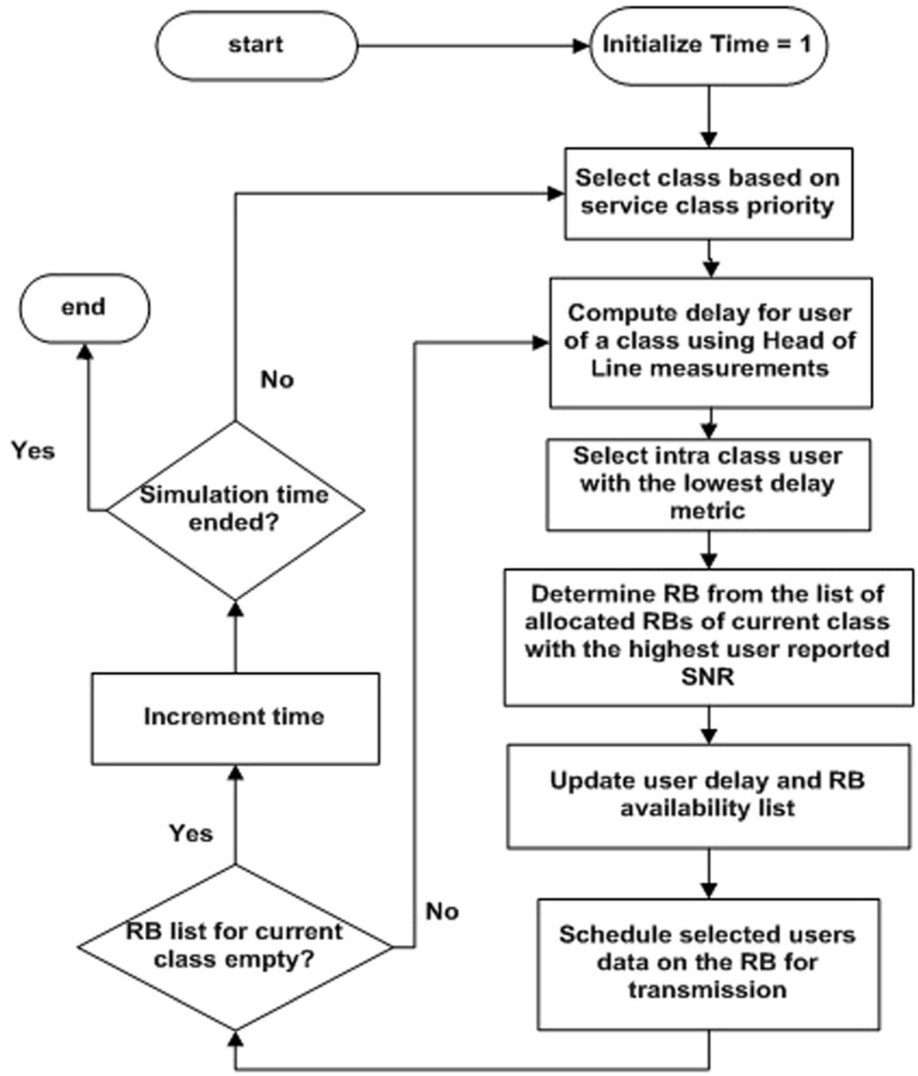


**Figure 3** LTE delay-based scheduling algorithm.

### *4.5.4. SNR*

The path loss experienced by users is measured for each allocated RB. The gain of channel at time $t$ for a user $i$ on $j$th RB is then calculated as follows:

$$C_{\mathrm{Gain}\,i,j}(t) = 10^{\left(\frac{\mathrm{pathloss}}{10}\right)} \quad (13)$$

where path loss is measured in dB scale. From the channel gain measures, UE calculates instantaneous downlink SNR and report it to eNB. The final SNR value is

$$\mathrm{SNR}_{i,j}(t) = \frac{P_{\mathrm{total}} \times C_{\mathrm{Gain}\,i,j}(t)}{N(N_o + I)} \quad (14)$$

$P_{\mathrm{total}}$ is the aggregate power with which eNB station carries out the transmission in the downlink direction, $N$ represents total available RBs, $I$ determines the neighboring cell interference, and $N_o$ is a measure of thermal

**Table 1 Downlink SNR values and modulation scheme mapping for LTE**

| Minimum instantaneous downlink SNR value (dB) | Modulation scheme |
|---|---|
| 1.7 | QPSK |
| 3.7 | QPSK |
| 4.5 | QPSK |
| 7.2 | 16QAM |
| 9.5 | 16QAM |
| 10.7 | 16QAM |
| 14.8 | 64QAM |
| 16.1 | 64QAM |

noise. Since we consider only one un-sectored cell, therefore $I$ is set to zero. The SNR derives the modulation scheme according to Table 1 [27,28].

### 4.6. Fairness index

Fairness in resource allocation level in the system is defined as the ratio between difference of total packet sizes for the most and least served users to the total accumulated packet size of all the flows that arrive at the eNB scheduler over a time $T$. Considering $p_{\text{size}}$ as the size of the packet, the fairness index is given as follows:

$$\text{fairness\_index} = 1 - \frac{p_{\text{size}\max} - p_{\text{size}\min}}{\sum_{i=1}^{K}\sum_{t=1}^{T} p_{\text{size}i}} \tag{15}$$

### 4.7. System parameters

System bandwidths used for our simulation purpose are 5, 10, and 20 MHz which includes 100, 50, and 25 PRBs in the downlink (Table 2). The propagation loss model incorporates shadowing with 0 dB mean and 8 dB standard deviation. The loss model also takes into account the penetration loss with 12 dB setting, multipath used as Jakes model and simple path loss determined as a function of distance form eNB terminal. The delay budget used for test purpose is 100, 200, and 300 ms corresponding to the delay budget in the LTE service table. The UEs are placed with uniform distribution throughout the area and move around with Random Walk Mobility Model at an average speed of 3 km/h. The cell radius is fixed to 1 km and the switch point periodicity is set to 1 (4 DL subframes in each 10 ms frame). Users vary from unity to the level where PLR is not met. The simulation system parameters are listed in Table 3.

## 5. Results and discussion

We have proposed a scheduler with minimum resource level guarantee for service classes following the delay budget and packet loss rates in addition to providing best channel usage. The simulation setup for scheduling consists of a single cell network with interference noise. The simulator used is a discrete event simulator 'LTE-Sim' with LTE specifications. There are four types of service flows in the network with requirements of 242 kbps for trace-based video data, 3 kbps for BE, 12 kbps for VoIP service, and constant bit rate (CBR) traffic at 100 kbps. The PLRs for the four types of traffic are fixed to 0.01 except the trace-based video which is fixed to 0.001.

**Table 2 LTE resource blocks corresponding to different operating bandwidths**

| System bandwidth (MHz) | 1.4 | 3.0 | 5 | 10 | 15 | 20 |
|---|---|---|---|---|---|---|
| PRBs | 6 | 15 | 25 | 50 | 75 | 100 |

**Table 3 System parameters used for simulation**

| System parameters | Values |
|---|---|
| System bandwidth | 20, 10, and 5 MHz |
| Number of resource blocks | 100, 50, and 25 |
| Sub-carriers per resource block | 12 |
| Sub-carrier spacing | 15 kHz |
| Sub-channel bandwidth | 180 kHz |
| Slot duration | 0.5 ms |
| Scheduling time (TTI) | 1 ms |
| OFDM symbols per RB | 6 |

Each TTI in the simulator is of 1 ms length composed of two time slots of 0.5 ms duration. An LTE frame is formed by 10 consecutive TTIs and within each 1 ms subframe, 12 OFDM symbols are used. First, we determine un-compared results in the form of accommodated active users and match it against theoretically computed users for varying switch point periodicity and variable channel conditions. Next comparison results for system delay and system throughput are presented.

### 5.1. Theoretical versus simulated users

For evaluation purpose, theoretical users that can be accommodated in different resource distributions and bandwidths are calculated first and then verified with simulations using proposed scheduler. Simulations are conducted with 20, 10, and 5 MHz corresponding to 100, 50, and 25 PRB. The four service flows of VoIP, Video, CBR, and BE are taken at 12, 242, 100, and 3 kbps, respectively. The delay budget is set to tightest 100 ms time for all classes except the BE class. The BE class is scheduled with FIFO method and no packet is dropped for even if 100 ms delay budget is passed. The guaranteed classes are scheduled with time delay measurements and the SNR values are maintained corresponding to 16QAM modulation scheme. The switch point periodicity of 5 ms is used with configuration 0. Resource ratio of 7:3 is used for guaranteed and BE service in individual. Individual and mixed simulations have been performed for both types of classes (Tables 4, 5, and 6). User extrapolation is used where the users become too large for simulation. The gap between the simulated and theoretical users is more for larger number of users while the approximations are close for vice versa. Mixed traffic with resource ratios of 3:2:2:3 for Video VoIP, CBR, and BE is used. The results are listed in Tables 4, 5, and 6.

### 5.2. Switch point periodicity

Different switch point periodicity configurations can also be used for LTE frames. These switch point periodicities are used to handle traffic load in the uplink and downlink directions. If the load in the downlink direction

**Table 4 Theoretical and simulated user capacity for mixed and individual service users with 20 MHz bandwidth setting and varying resource ratios**

| Flow setting | Traffic type | Data rate (kbps) | Resource ratio GBR: NGBR | Resource blocks allocated | Resource percent | Simulation users | Theoretical users |
|---|---|---|---|---|---|---|---|
| Individual Flows | Video | 242 | 7:3 | 70 | 70 | 24 | 27.76 |
| | VoIP | 12 | 7:3 | 70 | 70 | ~400 | 560 |
| | CBR | 100 | 7:3 | 70 | 70 | 55–58 | 67.2 |
| | BE | 3 | 7:3 | 30 | 30 | ~550–600 | 960 |
| Mixed Flows | Video | 242 | 3:3 | 30 | 30 | 9 | 11.9 |
| | VoIP | 12 | 2:3 | 20 | 20 | ~130 | 160 |
| | CBR | 100 | 2:3 | 20 | 20 | 17-18 | 19.2 |
| | BE | 3 | 7:3 | 30 | 30 | ~550–600 | 960 |

increases, a switch point periodicity with more downlink slots can be used. A switch point periodicity with higher downlink slots will increase the downlink data rate and more users can be accommodated. The number of accommodated users in 5-MHz bandwidth and switch point periodicity configuration of 5 with eight downlink slots per frame is described in Table 7 for different GBR to NGBR resource ratios.

### 5.3. Downlink SNR

Downlink SNR plays a key role in deriving the AMC method. With higher SNR, more data rate can be achieved in the downlink direction via higher-order modulation schemes. The minimum SNR values with corresponding modulation schemes for LTE is described in Table 1. Users near eNB station tend to achieve higher SNR values while users at the end of the cell usually suffer from lower SNR. With constant placement of UEs in LTE cell against target SNR values, the maximum number of accommodated active users is described in Table 8 for modulation schemes of 16QAM (4 bits/symbol) and 64QAM (6 bits/symbol).

### 5.4. System delay

The delay characteristics in terms of HOL and aggregated system delay have been compared with Proportional Fair, Exponential Rule, and M-LWDF. The HOL delay measures are provided for a simulation setup with guaranteed video at 242 kbps (Figure 4) and BE at 3 kbps (Figure 5) in a 10-MHz bandwidth setup and a delay budget of 200 ms for the guaranteed case with 7:3 resource ratio, respectively. The overall system delay measure for the same flow setup is provided in Figure 6. The HOL delay measures the maximum delay experienced by any packet in the scheduling line while the system delay measures the aggregated HOL over all the packets. The Proportional Fair algorithm performs the worst for the delay comparison since it does not take into account any form of delay measures. It assigns radio resources taking into account both the experienced channel quality and the past user throughput. The goal is to maximize total network throughput and to guarantee fairness among flows. Only MLWDF and Exp Rule take into account the delay characteristics indirectly. The exponential rule is designed to increase the priority of real-time flows with respect to non-real-time ones. The M-LWDF is used to improve QoS of different flows by defining a probability function that represents the urgency for data transmission corresponding to the time spent in the buffer queue.

Our proposed scheme incorporates the delay parameter from LTE service class table and is used to drop

**Table 5 Theoretical and simulated user capacity for mixed and individual service users with 10 MHz bandwidth setting and varying resource ratios**

| Flow setting | Traffic type | Data rate (kbps) | Resource ratio GBR: NGBR | Resource blocks allocated | Resource percent | Simulation users | Theoretical users |
|---|---|---|---|---|---|---|---|
| Individual Flows | Video | 242 | 7:3 | 35 | 70 | 12 | 13.88 |
| | VoIP | 12 | 7:3 | 35 | 70 | 244 | 280 |
| | CBR | 100 | 7:3 | 35 | 70 | 27 | 33.6 |
| | BE | 3 | 7:3 | 15 | 30 | ~400 | 480 |
| Mixed Flows | Video | 242 | 3:3 | 15 | 30 | 6 | 5.9 |
| | VoIP | 12 | 2:3 | 10 | 20 | 70–73 | 80 |
| | CBR | 100 | 2:3 | 10 | 20 | 10 | 9.6 |
| | BE | 3 | 7:3 | 15 | 30 | ~400 | 480 |

**Table 6 Theoretical and simulated user capacity for mixed and individual service users with 5 MHz bandwidth setting and varying resource ratios**

| Flow setting | Traffic type | Data rate (kbps) | Resource ratio GBR: NGBR | Resource blocks allocated | Resource percent | Simulation users | Theoretical users |
|---|---|---|---|---|---|---|---|
| Individual flows | Video | 242 | 7:3 | 17 | 70 | 6 | 6.77 |
| | VoIP | 12 | 7:3 | 17 | 70 | 98-104 | 136 |
| | CBR | 100 | 7:3 | 17 | 70 | 13 | 16.32 |
| | BE | 3 | 7:3 | 8 | 30 | ~220 | 256 |
| Mixed flows | Video | 242 | 3:3 | 9 | 30 | 3 | 3.57 |
| | VoIP | 12 | 2:3 | 4 | 20 | 25 | 32 |
| | CBR | 100 | 2:3 | 4 | 20 | 4 | 3.84 |
| | BE | 3 | 7:3 | 8 | 30 | ~220 | 256 |

packets for guaranteed class when the delay budget is exceeded. In BE case, HOL is exceeded from the delay budget of 200 ms since packets exceeding the delay budget are not dropped. Hence, it can be manipulated that less resources and higher load results in packets reaching the delay budgets earlier. From delay comparison, it is visible that PF performs the worst while MLWDF performs the closest. The Exponential rule performs in between the two schemes. The delay is maintained below 200 ms or 0.2 s for less than 60 users on average but reaches 200 ms level after that. This shows that some of the flows have now started to cross delay budget and the average is close to the delay budget itself. Hence, there is a compromise of packet loss as compared to other schemes. This can be catered for by limiting traffic by an admission controller function to the level where delay thresholds can be satisfied for majority of the users.

### 5.5. System throughput

The proposed service class-based scheduler allows for a minimum resource block guarantee hence a minimum level of data rate can be maintained even for BE class. A compromise however exists for the data rate of other classes since resources are borrowed for BE from guaranteed class. Since we initially allocate resources to different flows rather than having a flexible approach of allowing higher classes to take up resources from lower priority flows; therefore, we have tried to maintain a minimum level of data rate for low-priority traffic. The throughput results for CBR and BE classes are given in Figures 7 and 8 where both flows are simulated individually and allowed to take up all resources. The simulation setup runs at 10 MHz for CBR and at 5 MHz for BE. The data rate of CBR is taken as 150 kbps while the BE runs at 50 kbps. In the guaranteed traffic CBR case (Figure 7), the proposed scheme suggests results similar or near to M-LWDF scheme while the EXP-Rule achieves the highest throughput. The PF scheme results in lowest comparative throughput for CBR. For BE (Figure 8), the minimum resource guarantee approach results in higher throughput for the proposed scheme while other methods show lower throughput with loaded users because they treat BE at lowest priority for resource allocation (Figure 8).

For mixed traffic case with GBR as well as NGBR running services, BE is allowed to take resources from the guaranteed pool when there are free resources available but the opposite is not allowed. This is so because if some guaranteed user is admitted in the network then the BE has to be limited to its resource pool without much compromise but if

**Table 7 Theoretical and simulated user capacity for 5 MHz and switch point periodicity configuration 5 (eight DL slots per frame)**

| Flow setting | Traffic type | Data rate (kbps) | Resource ratio GBR: NGBR | Resource blocks allocated | Resource percent | Simulation users | Theoretical users |
|---|---|---|---|---|---|---|---|
| Individual flows | Video | 440 | 7:3 | 70 | 70 | 55 | 61.09 |
| | VoIP | 64 | 7:3 | 70 | 70 | ~400 | 420 |
| | CBR | 500 | 7:3 | 70 | 70 | 50 | 53.75 |
| | BE | 200 | 7:3 | 30 | 30 | 52 | 57.6 |
| Mixed flows | Video | 440 | 3:3 | 30 | 30 | 24 | 26.18 |
| | VoIP | 64 | 2:3 | 20 | 20 | 120 | 108 |
| | CBR | 500 | 2:3 | 20 | 20 | 15 | 15.36 |
| | BE | 200 | 7:3 | 30 | 30 | 52 | 57.6 |

**Table 8 Theoretical and simulated user capacity for 5 MHz and switch point periodicity configuration 3 (six DL slots per frame) with variable downlink SNR**

| Traffic type | Data rate (kbps) | Resource blocks | Average DL SNR (dB) | Bits per symbol | Simulation users | Theoretical users |
|---|---|---|---|---|---|---|
| CBR | 100 | 25 | >7.2 & <10.7 | 4 | 64 | 72 |
| CBR | 200 | 25 | >7.2 & <10.7 | 4 | 31 | 36 |
| CBR | 500 | 25 | >7.2 & <10.7 | 4 | 13 | 14.4 |
| CBR | 100 | 25 | >14.8 | 6 | 90 | 108 |
| CBR | 200 | 25 | >14.8 | 6 | 45 | 54 |
| CBR | 500 | 25 | >14.8 | 6 | 18 | 21.6 |

guaranteed traffic is allowed to take resources from the BE pool and needs to limit to its own resource ratio then the guaranteed class would suffer. For a 100-ms delay budget comparison for CBR and BE at 150 and 200 kbps, respectively, the results are depicted in Figures 9 and 10.

The mixed GBR and NGBR traffic results show that when the number of users in the network increases, resources are taken away from the BE class to fulfill the requirements of guaranteed traffic. But this is not the case with proposed scheme since we have maintained a minimum level of guarantee for the two traffic types by defining different resource pool ratio at both ends. For CBR (Figure 9), the EXP-Rule algorithm performs the best because it takes into account buffer queue with an exponentially growing delay priority for user packets. The proposed method performs in between the EXP-Rule and other approach. PF performs worst for high user load in the network corresponding to more than 40 users on average.

For the BE case (Figure 10), the proposed scheme performs much better than other three methods since they deprive BE class from resources when the users in the guaranteed class increase. PF perform worst in this case, the MLWDF and Exp Rule in between but the proposed scheme maintains a considerable gap with some consistency in the throughput. This consistency in throughput is also visible in the CBR case (Figure 9) validating the claim of minimum resource level guarantee.

### 5.6. User mobility

User terminal device mobility plays a critical role in shaping the throughput and end-to-end delay for the service flows. User mobility hinders coverage and incurs limitations on the capacity of the network as well. End-to-end combined delay measures for GBR and NGBR case are provided for user terminals moving at a velocity of 30 km/h in Figure 11 and with a velocity of 120 km/h in Figure 12. The simulation settings are at 150 kbps data rate for GBR and 50 kbps for NGBR. In both scenarios, the proposed scheme performs better than the other scheduling methods. In 120 km/h case, the delay for the proposed scheme is less than the MLWDF method for users greater than 65 on average. The reason for this is the earlier delay approaching deadlines for packet transmission at higher velocities and large service flows in the system which can

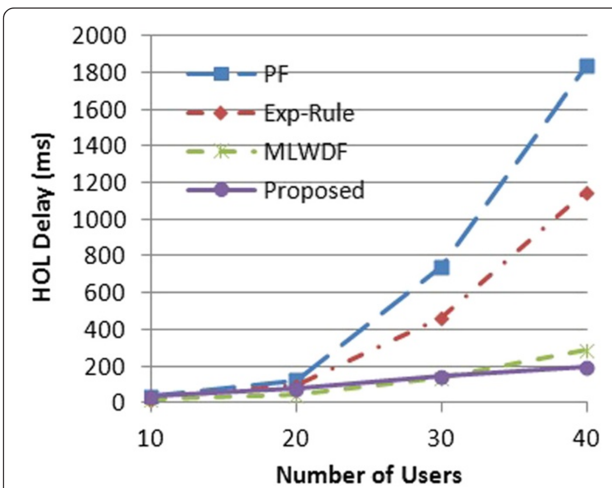


**Figure 4** HOL delay comparison for guaranteed service flow.

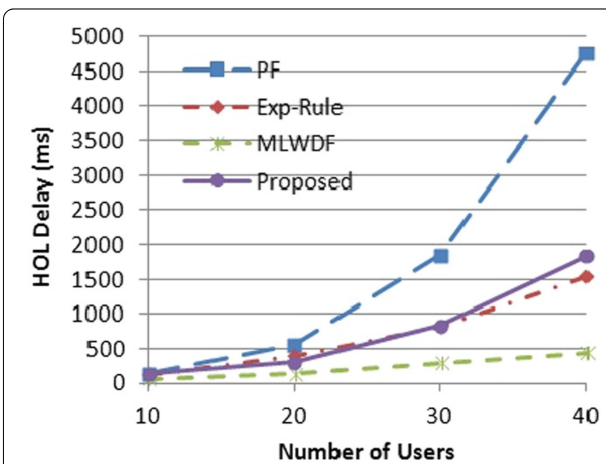


**Figure 5** HOL delay comparison for BE service flow.

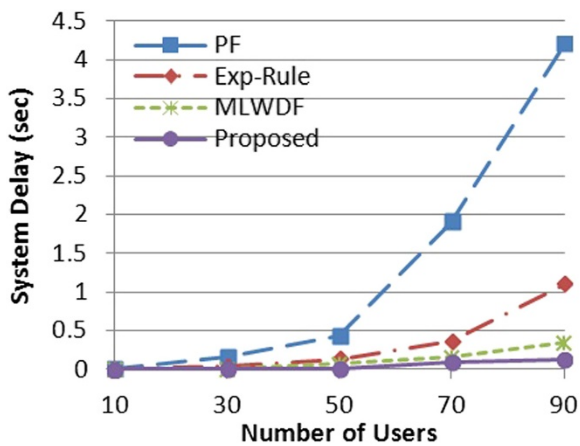


**Figure 6** System delay comparison for proposed scheduler.

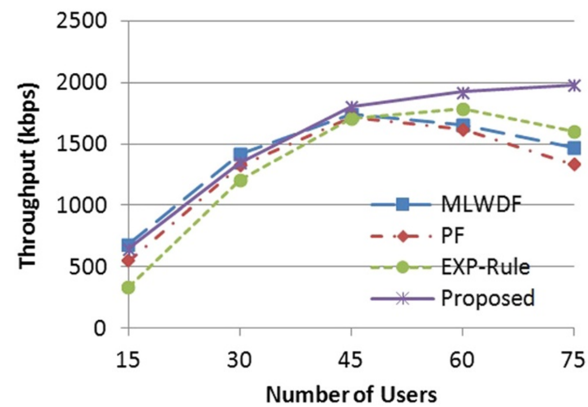


**Figure 8** Throughput comparison for proposed scheme with BE traffic at 50 kbps and resource allocation of 100% in 5-MHz bandwidth.

be better satisfied by the strict priority mechanism used by MLWDF rather than a linear method.

Average throughput is measured for GBR users and NGBR users moving with speeds from 10 to 80 km/h (Figures 13 and 14). The data rate requirements for both cases are kept at 500 and 350 kbps, respectively. The average throughput of the users decrease with decent drops as speeds increase with a follow up trend of slightly less observed throughput for GBR flows and the highest observed average throughput for GBR flows. The reason for slightly lower and higher throughput in both cases can be contributed to the resource pool partitioning.

### 5.7. Fairness

The combined fairness results for GBR and NGBR flows in the proposed scheduling setup are compared with other methods in Figure 15. The GBR is kept at 150 kbps while the BE data rate requirement is kept at 50 kbps. From the results it can be concluded that the system fairness for the proposed scheduling scheme performs similar to the other methods for a low loaded nominal user settings of 20 to 25 on average. The variance after that is observed due to the ability of other schedulers being able to filter out the most suitable user data with channel conditions in the scheduling queue as contrast to having to choose from two different pools of user data for GBR and NGBR in our case. The low fairness at higher service flows can be contributed to the compromise between providing minimum resource level guarantee to low-priority flows and not providing at all in the classical scheduling approach. The data rate of NGBR is therefore sustained corresponding to the guaranteed physical resources even when the system is loaded with GBR users which in contrast to normal scheduler usage goes down to zero after the resources get mostly occupied by guaranteed service.

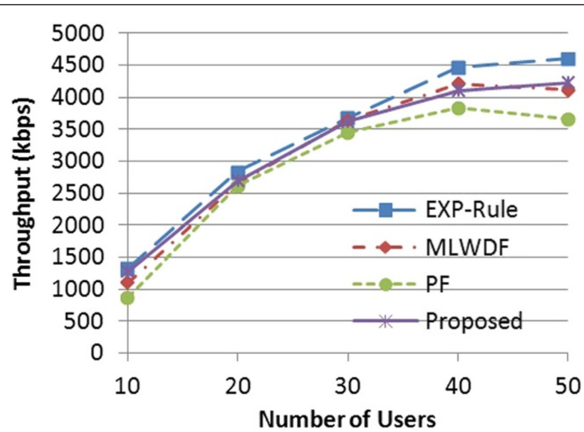


**Figure 7** Throughput comparison for proposed scheme with CBR traffic at 150 kbps and resource allocation of 100% in 10-MHz bandwidth.

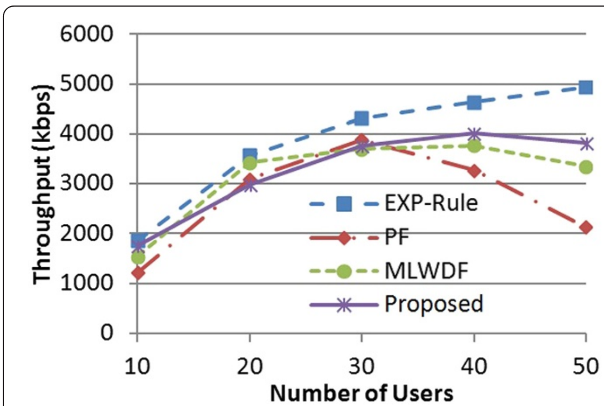


**Figure 9** Throughput comparison for proposed scheme with CBR traffic at 150 kbps and resource allocation of 70% in 10-MHz bandwidth.

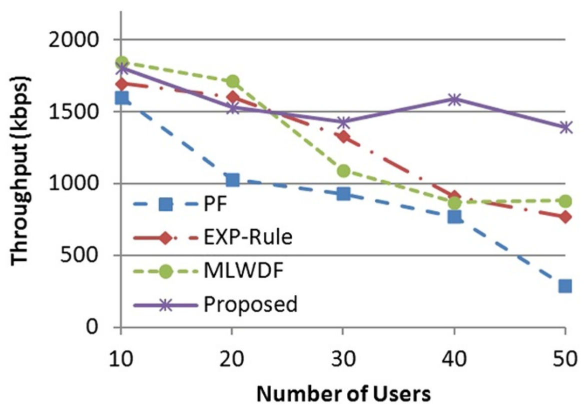


**Figure 10** Throughput comparison for proposed scheme with BE traffic at 200 kbps and resource allocation of 30% in 10-MHz bandwidth.

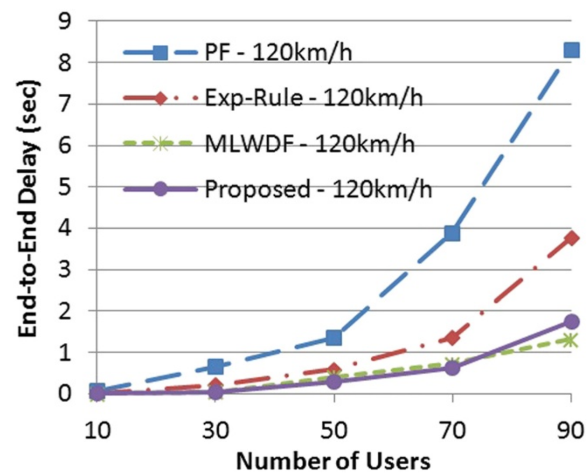


**Figure 12** End-to-end delay comparison for 120 km/h user speed with BE traffic at 50 kbps and resource allocation of 30% in 10-MHz bandwidth.

## 6. Conclusions

Meeting up the service flow requirements have always posed a challenge from scheduling perspective. As new standards and applications are being developed, the QoS requirements are becoming more stringent. LTE defines delay budget, packet loss rates, and flow priority for a set of nine service classes to be followed by service provider. Classical techniques like Maximum Throughput, Proportional Fair, and Exponential Rule fail to cater the needs of QoS requirements for service provisioning in LTE because scheduler function in LTE requires handling service in addition to network perspective like throughput or fairness as followed by previous methods. Moreover, previously proposed methods have treated BE class with lowest priority and if the same priority is given to BE classes in LTE, then half of the provisioned services will suffer from resource scarcity. Hence, there is a need to intelligently control the resource allocation and only allow a certain number of users in each class through admission control while taking advantage of best available channel conditions.

To cope up with the LTE scheduler design challenge, we propose a modification in the resource management strategy for LTE with a minimum resource guaranteed scheduler design in the downlink that follows the LTE network capacity and service class attributes like delay budget and packet loss rates. Minimum guarantee is achieved by bounds on the number of resources that can be assigned to each class. The scheduler is designed to take advantage of the best channel conditions while maintaining data rates corresponding to minimum resources guaranteed for all major classes including the BE

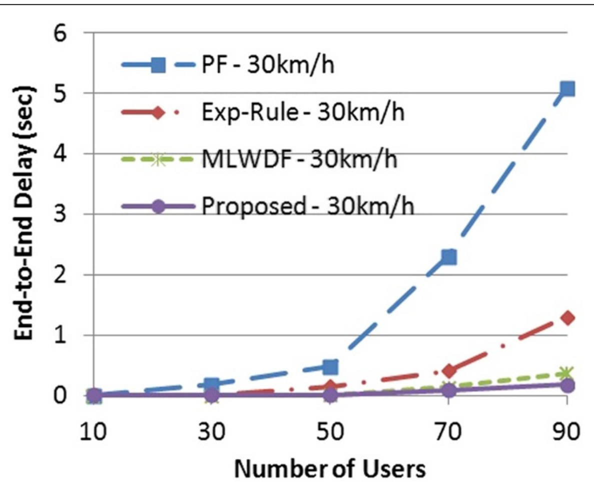


**Figure 11** End-to-end delay comparison for 30 km/h user speed with CBR traffic at 150 kbps and resource allocation of 70% in 10-MHz bandwidth.

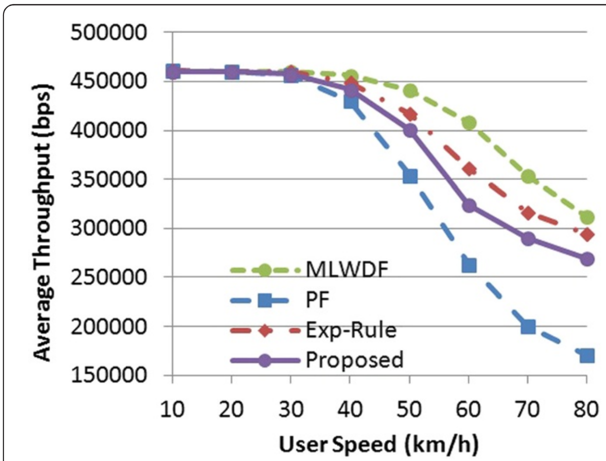


**Figure 13** Average throughput comparison for CBR traffic at 500 kbps with varying user speeds.

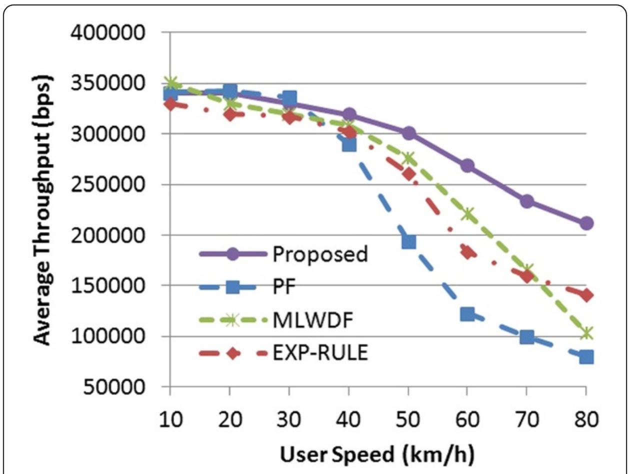


**Figure 14 Average throughput comparison for BE at 350 kbps traffic with varying user speeds.**

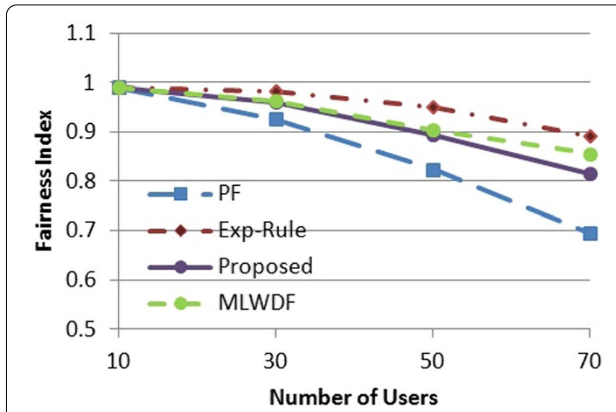


**Figure 15 Fairness comparison of mixed GBR at NGBR traffic scheduling for proposed scheme.**

class. A method is proposed to determine the scheduling resource capacity of active users in LTE networks. By simulations we showed that the theoretical limits of allowable number of active users can be achieved closely in good channel conditions. The design of the service class-based scheduler finds applications in LTE admission control design, the foundations of which are also discussed in the article.

Findings suggest that the data rate of NGBR is sustained corresponding to the guaranteed physical resources even when the system is loaded with GBR users which in contrast to normal scheduler usage goes down to zero after the resources get mostly occupied by guaranteed service. Even with user mobility, the same pattern is observed for throughputs of service flows. When compared with MLWDF, Exponential Rule and Proportional Fair, the system delay of the proposed scheduler is maintained corresponding to the delay specified for LTE services while other methods exceed the delay boundaries. The HOL measures also provide promising results where much of the packets are scheduled before the delay budget period. The fairness of the proposed resource management scheme is similar in behavior to Exp-Rule and MLWDF for slightly loaded system. This however deviates with large number of service flows because other schedulers can filter out the most suitable user data packets with channel conditions in the scheduling queue as contrast to having to choose from two different pools of user data for GBR and NGBR as in our method. The summarized contributions of the article include controlled allocation of PRB for service classes as a modification in the resource management strategy for LTE. We also use packet delay budget parameter from LTE service class standards specification in the scheduling of flows and the development of theoretical model to calculate accommodated active user capacity keeping in view the service data rates. Minimum resource level guarantee for BE class is maintained by use of admission control function and compared with theoretical findings with close results.

In future, we intend to take into account the LTE QCI parameters for prioritization of LTE traffic. Attributes like fairness will be tested for different traffic types to achieve some hybrid method of allocation and scheduling. Moreover, interference from other cell sites and throughput for different sectored cells will be explored in different frequency setups.

### Abbreviations

AMBR: Aggregate maximum bit rate; ARP: Allocation and retention priority; AMC: Adaptive modulation and coding; QoE: Quality of experience; RB: Resource block; RRM: Radio resource management; BE: Best effort; CBR: Constant bit rate; DL: Downlink; eNB: Evolved node B; EPC: Evolved packet core; FDD: Frequency division duplex; GBR: Guaranteed bit rate; HOL: Head of line; IMS: IP multimedia system; LTE: Long-term evolution; LTE-A: LTE-advanced; M-LWDF: Modified largest weighted delay first; MME: Mobility management utility; NGBR: Non-guaranteed bit rate; OFDMA: Orthogonal frequency division multiple access; PCRF: Policy control and charging function; PDCP: Packet data convergence protocol; PLR: Packet loss rate; PRB: Physical resource block; QoS: Quality-of-service; RAT: Radio access technology; RNC: Radio network control; ROHC: Radio header compression; TDD: Time division duplex; TTI: Transmission time interval; UE: User equipment; UL: Uplink; UTRA: Universal terrestrial radio access; UTRAN: Universal terrestrial radio access network.

### Competing interests

The authors declare that they have no competing interests.

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