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Cross Layer Scheduling Algorithm for IEEE 802.16 Broadband Wireless Networks

Najah Abu Ali, Mohammad Hayajneh, and Hossam Hassanein*
College of IT, UAEU, Al-Ain, United Arab Emirates
School of Computing, Queen's University, Kingston, Canada*
Emails: najah, Mhayajneh@uaeu.ac.ae, hossam@cs.queensu.ca,

***Abstract*—In order to support different types of user applications, the IEEE 802.16 standard defines different service classes together with their associated Quality of Service (QoS) parameters. However, the standard lacks a MAC scheduling architecture that guarantees these defined QoS requirements. The importance of efficient scheduling is crucial to QoS provisioning for multimedia flows. In this paper we propose an opportunistic and optimized downlink scheduler that pledges fairness among admitted connections. Our approach involves separating the scheduling problem into two sub-problems. In the first problem, the proposed scheduler calculates the number of time-slots in each time frame corresponding to the service classes with the objective minimizing the blocking probability of each class. In the second problem, time-slots for each class connection are allocated using an integrated cross-layer priority functions that guarantee proportional fairness. The simulation results reveal that the proposed scheduler realizes our objectives, and provides efficient QoS scheduling without starving the connections of the best effort class.**

I. INTRODUCTION

Answering to an ever increasing demand for last mile high speed Internet access, based on IEEE 802.16 standard, Broadband Wireless Access (BWA) networks provide a large bandwidth sufficient to support multiple users' sessions of voice, video and data applications. Naturally, different applications demand different QoS requirements or levels such as delay, jitter, packet loss, and flow rate. To meet these requirements, IEEE 802.16 is designed to support different service classes over UpLink (UL) and DownLink (DL) transmission. It defines the concept of service flow, where the connections are mapped into one service flow once a Subscriber Station (SS) joined a network and a connection is established. Service flows provide a mechanism for uplink and downlink QoS management, mainly the bandwidth allocation process.

Normally, bandwidth is allocated to a SS by a Base Station (BS) as a response to a per connection request from the SS. Bandwidth allocation may be constant depending on the type of service, for example, T1 unchannalized services, or it may be adaptive such as that granted to the IP bursty services. IEEE 802.16-2004 [1] defines four service flow classes : Unsolicited Grant Service (*UGS*) supports real time services with constant bit data rate, real time Polling Service (*rtPS*) supports real-time services with variable size data on a periodic basis, non-real-time Polling Service (*nrtPS*) supports non-real-time services that require variable size data grant bursts on a regular basis, Best Effort (*BE*) supports data streams for which no minimum service level is required and therefore may be handled on space-available basis.

Even though IEEE 802.16 standard defines different service flows and their associated QoS parameters, the standard did not define a packet scheduler that enforces the required QoS parameters to various service flows associated with users' applications. Therefore, a scheduling algorithm is required to efficiently provide for the different applications' QoS requirements. We propose a downlink scheduling algorithm for IEEE 802.16 Point to Multipoint (PMP) mode that serves connections from a BS with sectorized antenna to multiple SS. We address the downlink scheduling problem in IEEE 802.16 to enforce the QoS requirements for different service flows, mainly bandwidth and delay bounds requirements. The problem is divided into two sub-tasks: the inter-class time slots allocation, where slots are optimally calculated to satisfy each service class QoS requirements. The intra-class slot allocation, where connections are selected based on a fair opportunistic priority function. The proposed scheduling scheme utilizes not only the multiuser diversity [2] through the instantaneous channel conditions of different users, but also the users QoS requirements and long term fairness among them.

Performance evaluations of IEEE 802.16 can be found in [3], [4], [5], [6], [7], [8] where authors implement well-known schedulers such as Weighted Fair Queuing (WFQ), Deficit Round Robin (DRR), and Earliest Deadline First (EDF) as an uplink and/or downlink schedulers. Normally, implementing different schedulers for the different service classes and on a per connection basis is not a trivial task. This is because: (1) IEEE 802.16 standard supports changing the connection QoS descriptors during connections life time. Thus, the schedulers are required to adapt to these changes by reassigning the slots. For instance, in case of WFQ, dynamic weights may be the solution, which considerably increases the scheduler complexity and makes its implementation challenging. (2) In IEEE 802.16, the frame size is constant. Hence and based on each service class load, some of time-slots may not be allocated, which makes IEEE 802.16 behavior closer to non-conserving schedulers. Yet, the proposed hierarchy of schedulers is work-conserving. Thus, some authors for simplicity base their work on some assumptions. For example in [8], for the sake of simplicity, the authors implement DRR as DL scheduler, irrespective of the connection scheduling service, and Weighted Round Robin (WRR) as UL scheduler with constant weights without clarifying how the weights are chosen or provide a justification for adopting constant weights. On the other hand, some authors instead of designing a hierarchical scheduler, focus on scheduling for certain applications of one service class, for example, VoIP in [9].

Another group of schedulers are based on cross layer optimization [10], [11], [12]. The authors in [10] present a QoS architecture for IEEE 802.16 in Time Division Duplex (TDD) mode to provide for InterServ, DiffServ, and signaling under PMP and Mesh mode. The paper proposes a QoS architecture rather than focusing on scheduling. The scheduler in [11] utilizes users' diversity, however, it does not provide for fairness among users since it allocates slots for one connection in the frame after satisfying the *UGS* connections requirements. The connections are selected based on a priority function that depicts the QoS requirements of the connections and prioritizes the different service classes through using constant weights. The scheduler in [12] utilizes users diversity for bandwidth allocation, however, authors propose a heuristic algorithm for bandwidth allocation instead of an optimal bandwidth allocation algorithm since the complexity of their proposed optimal bandwidth allocation algorithm may be prohibitive from an implementation point of view.

Our work is different from the aforementioned literature by (i) supporting all service classes, (ii) optimally calculating number of slots in each frame such that the blocking probability of each class is minimized, (iii) providing isolation between classes, and (iv) integrating a proportional fairness scheme to SS channel quality information to allocate time-slots among connections of the same class.

We proceed by formulating the problem in Section II, discuss the performance evaluation and results in Section III, and conclude the paper in Section IV.

II. Scheduler Approach

The proposed scheduler is designed to solve two subproblems. The first is allocating time slots among the service classes. The second is allocating time slots within same class among the class's active connections. Thus, the scheduler isolates these service classes by allocating K_i time-slots for each class i out of K total time-slots in a given time frame.

In IEEE 802.16 time frames are divided into constant number of time slots with same time-slot duration. Given that a SS conveys its received signal to noise power ratio (SNR) from the BS through a perfect and robust feedback channel, this information is assumed not to change over same time frame. However, the slot duration in bits may change on frame-by-frame basis depending on the Adaptive Modulation Coding (AMC) defined in IEEE 802.16-2004 standard [1] mode used for transmission as a result of the channel condition.

The total K time-slots are completely partitioned among the classes such that the blocking probability of each class is minimized. Consequently, we model each class as a $M/M/1/K_i$ queue. K_i represents number of time slots required to satisfy class i connections QoS requirements. The blocking probability of a $M/M/1/K_i$ queue is given by

$$p(K_i) = \frac{(1-\rho_i)\rho_i^{K_i}}{(1-\rho_i^{K_i+1})}, \quad (1)$$

Where $\rho_i = \lambda_i/\mu_i$ is the ratio of the arrival rate (λ_i) to the departure rate (μ_i) of the connections of class i.

We define the following non linear mathematical program to optimally calculate the required time-slots for each service class such that the blocking probability of each class is minimized.

$$\min_{K_i, 1\le i\le 4} \sum_{i=1}^{4} \beta_i \, p\,(K_i) \quad (2)$$

$$\text{Subject to} \quad (3)$$

$$K = \sum_{i=1}^{4} K_i, \quad (4)$$

$$K_i^{min} \le K_i \le K_i^{max} \forall\, i \in \{1,2,3,4\}, \quad (5)$$

where the strictly convex cost function in 2 represents the total sum of the weighted blocking probabilities of all four classes; i.e. *UGS*, *rtPS*, *nrtPS*, and *BE*. The weights $\beta_i = \sum_{k=i}^{4} BW_k^{req} / \sum_{k=1}^{i} BW_k^{req}$ are introduced to reflect the priority of the different classes. BW_k^{req} is the total requested bandwidth of each class k. The first constraint in 2 is the capacity constraint; *i.e.* the total number of time-slots in a time frame is fixed and equal to K. The second constraints guarantee that connections of all classes will be assigned enough number of time-slots to achieve at least their minimum required bandwidth taking into account their priorities. K_1^{min} is a constraint to guarantee that *UGS* active admitted connections requirements are met. K_1^{max} is to guarantee that the QoS requirements of admitted active connections in addition to new *UGS* connections arrivals are met, if enough capacity is available, otherwise some or all new arrivals are rejected. Note that *UGS* maximum sustainable rate is equal to the minimum reserved rate, thus K_1^{min} is the summation of time slots of all admitted *UGS* connections, while, K_1^{max} is the summation of all admitted and new *UGS* connections. For *rtPS* and *nrtPS*, minimum reserved rate and maximum sustainable rate are denoted by K_2^{min}, K_2^{max}, K_3^{min} and K_3^{max}, respectively, given that the bandwidth requests for theses two classes are adaptive on per frame basis. The minimum value for K_2^{min}, K_3^{min} and K_4^{min} may be zero (no backlogged packets in the queue).

Mapping the requested bandwidth to a maximum and minimum number of time-slots is based on the fact that IEEE 802.16 standard defines fixed size of time frames and their corresponding number of frames sent per second. Thus, given a requested bandwidth requirement per second for each connection n, the *requested bandwidth requirement per frame is equal to the requested bandwidth per second divided by the number of frames per second.* Thus, given minimum reserved bandwidth per frame, ($\tilde{B}_n^{min}$), and maximum sustainable bandwidth per frame ($\tilde{B}_n^{max}$), number of time-slots for each connection n is given by

$$\hat{K}_n^{min} = \frac{\tilde{B}_n^{min}}{r_n} \quad (6)$$

$$\hat{K}_n^{max} = \frac{\tilde{B}_n^{max}}{r_n} \quad (7)$$

where r_n is the number of bits attainable in one time slot. The value r_n can be used as the lowest AMC level mode for the new connections. For admitted connections, r_n can be used as an averaged value that reflects the channel quality over a predefined window size using a proper prediction algorithm. Then, the minimum and maximum number of time slots of service class i are: $K_i^{min} = \sum_{k=1}^{|\mathcal{C}_i(t)|} \hat{K}_k^{min}$ and $K_i^{max} = \sum_{k=1}^{|\mathcal{C}_i(t)|} \hat{K}_k^{max}$, respectively. $|\ \mathcal{C}_i(t)\ |$ is the number of connections of class i.

As such, the problem in (1) and (2) is a nonlinear convex programming problem in standard form and is equivalent to finding the minimum of the following cost function:

$$\begin{aligned} L(\{K_i\}_1^4, \alpha_1, \alpha_2) &= \sum_{i=1}^{4} \beta_i\, p(K_i) + \alpha_1^5\,(K - \sum_{i=1}^{4} K_i) \\ &+ \sum_{i=1}^{4} \alpha_1^i (K_i - K_i^{min}) \qquad (8) \\ &+ \sum_{i=1}^{4} \alpha_2^i (K_i^{max} - K_i) \end{aligned}$$

where $\alpha_1 = (\alpha_1^1, \cdots, \alpha_1^5)$ and $\alpha_2 = (\alpha_2^1, \cdots, \alpha_2^4)$ are the Lagrange multipliers. Differentiating (8) with respect to K_m and setting the derivative to zero we obtain

$$\frac{\partial L}{\partial K_1} = \beta_1 \frac{(1-\rho_1)\log(\rho_1)\,\rho_1^{K_1}}{(1-\rho_1^{K_1+1})^2} - \alpha_1^5 + \alpha_1^1 - \alpha_2^1 = 0 \quad (9)$$

and

$$\frac{\partial L}{\partial K_m} = \beta_m \frac{(1-\rho_m)\log(\rho_m)\,\rho_m^{K_m}}{(1-\rho_m^{K_m+1})^2} - \alpha_1^5 + \alpha_1^m - \alpha_2^m = 0 \quad (10)$$

where $m = 2, 3, 4$. Using both (9) and (10) and setting $X_m = \rho_m^{K_m}$ we have

$$\frac{X_m}{(1-\rho_m X_m)^2} = \frac{\beta_1(1-\rho_1)\log(\rho_1)}{\beta_m(1-\rho_m)\log(\rho_m)} \frac{X_1}{(1-\rho_1 X_1)^2} \quad (11)$$

Let

$$\chi_{1,m} = \frac{\beta_1(1-\rho_1)\log(\rho_1)}{\beta_m(1-\rho_m)\log(\rho_m)} \frac{X_1}{(1-\rho_1 X_1)^2} \quad (12)$$

Then, (11) can be written as

$$\rho_m^2 X_m^2 - X_m(2\,\rho_m + \frac{1}{\chi_{1,m}}) + 1 = 0, \quad (13)$$

which is a quadratic equation in X_m that has one feasible solution given as

$$\begin{aligned} X_m &\triangleq f(K_1, \rho_1, \rho_m, \beta_1, \beta_m) \qquad (14) \\ &= \frac{1}{2\rho_m^2}\left(2\,\rho_m + \frac{1}{\chi_{1,m}} + \sqrt{\frac{4\rho_m}{\chi_{1,m}} + (\frac{1}{\chi_{1,m}})^2}\right) \end{aligned}$$

Now, we can express $K_m, m = 2, 3, 4$ as a function of K_1 only as follows:

$$K_m = \frac{\log(f(K_1, \rho_1, \rho_m, \beta_1, \beta_m))}{\log(\rho_m)} \quad (15)$$

Using the constraints in (2), one can find K_1 as the solution of

$$K_1 + \sum_{m=2}^{4} \frac{\log(f(K_1, \rho_1, \rho_m, \beta_1, \beta_m))}{\log(\rho_m)} = K \quad (16)$$

by using an iterative technique. The above equation (16) converges to a unique solution in few iterations.

After optimally evaluating $\{K_i\}_{i=1}^4$ and isolating the four QoS classes, the connections of each class will compete for the available time-slots, given that we may have new arrivals at this time frame. Thus, the main concern is to satisfy the currently admitted connections in each class. The residual time-slots, if any, are calculated to select some or all new connections. For *UGS* class connections, we consider the following QoS metrics; Maximum Latency (ML) and Minimum Reserved Traffic Rate (MRTR), which equals to the Maximum Sustained Traffic Rate (MSTR). We propose the following priority functions of the service classes:

- *UGS*: The new connections are selected according to the following proposed priority function, $u_m^1(t), \forall\, m \in \mathcal{C}_1(t)$; $\mathcal{C}_1(t)$ is the set of all *UGS* connections at time frame t, which is given by:

$$u_m^1(t) = \begin{cases} \frac{r_m^1(t)}{\bar{r}_m^1(t)} \frac{1}{\Delta t_m^1}, & \Delta t_m^1 > 0,\, r_m^1(t) \neq 0 \\ \infty, & \Delta t_m^1 = 0, r_m^1(t) \neq 0 \\ 0, & r_m^1(t) = 0 \end{cases} \quad (17)$$

  The term $\frac{r_m^1(t)}{\bar{r}_m^1(t)}$ stands for proportional fairness among users, where $r_m^1(t)$ is the mth connection attainable bandwidth at time frame t and it reflects the channel quality between the BS and SS of connection m. $\bar{r}_m^1(t)$ is the average throughput for connection m at time t estimated over a window size $1/\alpha$ and it is updated as follows:

$$\bar{r}_m^1(t+1) = \begin{cases} \bar{r}_m^1(t)\,(1-\alpha) & m \notin \mathcal{C}_1^*(t) \\ \bar{r}_m^1(t)(1-\alpha) + \alpha\, r_m^1(t) & m \in \mathcal{C}_1^*(t) \end{cases} \quad (18)$$

  where $\mathcal{C}_1^*(t) \subseteq \mathcal{C}_1(t)$ is the subset of connections that were selected to be served at the current time frame. The latency bound of connection m is expressed as Δt_m^1. A new packet is time stamped by Δt_m^1 which is decremented as long as the packet is queued. Thus when a packet approaches its delay bound it has higher priority to be sent. When a packet meets its delay bound, its priority function becomes ∞. The remainder of K_1 time slots, if any, is used to admit new connections.
- *rtPS*: For this class, we consider MRTR, MSTR, and ML as the QoS metrics, same as *UGS* class, however, *rtPS* tolerates more delay than *UGS*. Therefore, we propose the following priority function $u_m^2(t)$, $\forall\, m \in \mathcal{C}_2(t)$ to schedule *rtPS* connections:

$$u_m^2(t) = \begin{cases} \frac{r_m^2(t)}{\bar{r}_m^2(t)} \frac{1}{\Delta t_m^2} \frac{q_m^2}{q_s^2}, & \Delta t_m^2 > 0,\, r_m^2(t) \neq 0, q_m^2 \neq 0 \\ \infty, & \Delta t_m^2 = 0, r_m^2(t) \neq 0, q_m^2 \neq 0 \\ 0, & r_m^2(t) = 0 \text{ or } q_m^2 = 0 \end{cases} \quad (19)$$

  Here, $\mathcal{C}_2(t)$ is the set of all *rtPS* connections at time frame t, and $\mathcal{C}_2^*(t) \subseteq \mathcal{C}_2(t)$ is the set of the served connections at time frame t based on the priority function $u_m^2(t)$, *i.e.,* $|\ \mathcal{C}_2^*\ | = K_2$. The size of the queue of connection m is denoted as q_m^2 and $q_s^2 = \max_{m \in \mathcal{C}_2(t)} q_m^2$. This is to take the amount of backlogged packets waiting for transmission

TABLE I
TRAFFIC MODEL

Service	Traffic Type	MRTR	MSTR	ML	Packet (bytes)
UGS	Voice	12.5kbps	12.5kbps	80ms	60
rtPS	Stream video	3 Mbps	5 Mbps	180 ms	170-320
nrtPS	FTP	0.5 Mbps	2 Mbps	–	250
BE	Background	–	4 Mbps	–	250

into consideration. The remainder of K_1 time slots, if any, is used to admit new connections.

- *nrtPS*: The priority metric for this class is the minimum reserved bandwidth, hence we propose the following priority function, $u_m^3(t)$, $\forall m \in \mathcal{C}_3(t)$ such that:

$$u_m^3(t) = \frac{r_m^3(t)}{\overline{r}_m^3(t)} \frac{q_m^3}{q_s^3}, \forall m \in \mathcal{C}_3(t) \quad (20)$$

where q_m^3 is introduced to guarantee that no connection will be scheduled if it has no packets to transmit even if it has a good channel quality.

- *BE*: In this class, there are no QoS requirements, therefor we propose a proportional fair priority function $u_m^4(t)$, $\forall m \in \mathcal{C}_4(t)$, expressed as:

$$u_m^4(t) = \frac{r_m^4(t)}{\overline{r}_m^4(t)}, \forall m \in \mathcal{C}_4(t) \quad (21)$$

where $r_m^4(t)$, the attainable bandwidth of connection m, captures the channel quality. The connection with better channel quality will have higher priority to increase the system throughput, while the average bandwidth is to provide for fairness among all connections.

III. SIMULATION RESULTS

Our simulation model consists of one BS and several SSs randomly distributed over a simulation grid size of 5000m×5000m. The channel is of 20 MHz bandwidth and it is shared between the uplink and the downlink implementing TDD multiplexing. All nodes operate in PMP MAC layer mode and WirelessMAN-OFDM PHY mode. Nakagami-m Channel model was adopted to describe the statistical variation of channel gains between the BS and the SSs using all AMC modes described in IEEE 802.16-2004 standard. The frame size is fixed at 10 ms equally divided between UL and DL subframes, the OFDM symbol duration is 12.5 μs, the rate of frames is 100 frames/second and the simulation time is five minutes.

We consider four services classes, *UGS*, *BE*, *rtPS*, and *nrtPS*. Connections from each service class arrive following exponential distribution process with an exponential holding time as well. The packets arrival within each connection is designed as a poisson process. The schedular is initiated at the beginning of each frame. Thus, time slots are allocated for active connections at the beginning of each frame. For the connections' traffic model, we implemented some models presented in [13], since they were tested for WiMAX simulation. Table I shows the traffic model used in simulation.

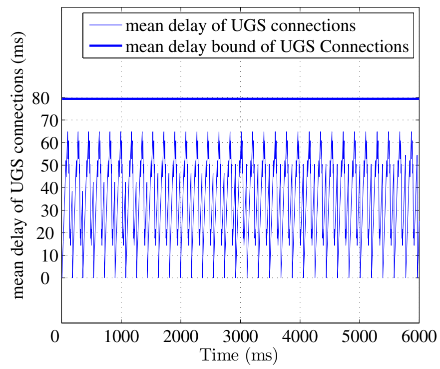

Fig. 1. Simulation time versus the average delay bound of all *UGS* class connections in ms

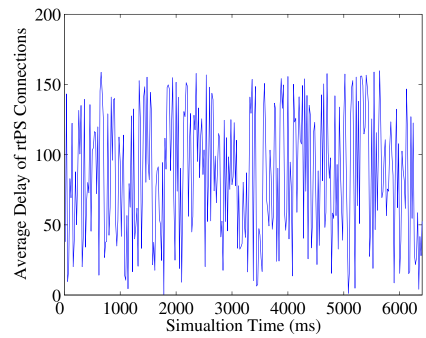

Fig. 2. Simulation time versus the average delay bound of all *rtPS* class connections in ms

We evaluated the performance of the schedule under heavy loaded network, where the queues at the BS are always backlogged.

Figure 1 and Figure 2 show the performance evaluation of the scheduler to meet the delay bounds of the *UGS* and *rtPS* service classes during simulation time. The Figures show the delay over a truncated interval of the simulation time to allow Figures to be readable. Figure 1 shows the average delay practiced by all connections of *UGS* class with a delay bound, ML, of 80 ms. The Figure shows that the maximum delay practiced by the *UGS* flow packets does not exceed 65 ms and the minimum is around zero, we also notice that this variation is almost constant since the *UGS* traffic has a constant number of slots to meet its bandwidth requirement. Figure 2 shows the performance of the scheduler in meeting the delay bound of all *rtPS* connections. The maximum delay practiced by *rtPS* connections is 155ms, while the ML requirement is 180ms. The delay variation is not constant as the *UGS* case, since the requested bandwidth is adaptive and the number of slots allocated for each flow within the class is varying over the different frames.

Figure 3 shows the mean of the moving average throughput of all connections of *rtPS* class. The mean throughput is calculated over a predefined window size that is a multiple number of a frame duration. The Figure shows that the schedular is capable of meeting the QoS parameters of *rtPS*

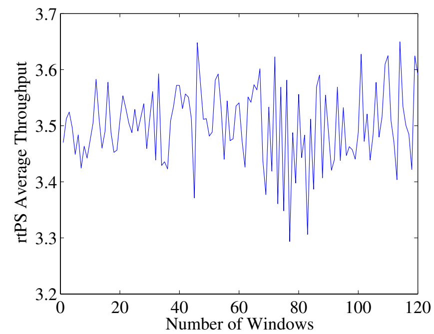

Fig. 3. The mean of the Exponential Average Throughput of all *rtPS* connection in Mbps

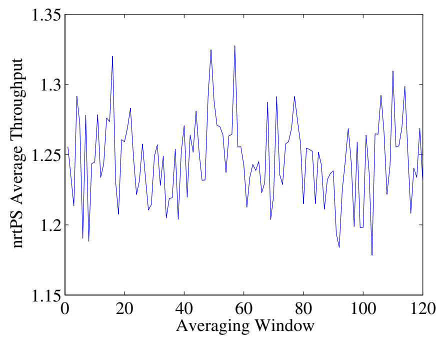

Fig. 4. The mean of the Exponential Average Throughput of all *nrtPS* connection in Mbps

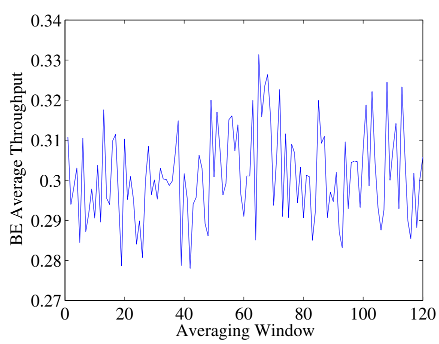

Fig. 5. The mean of the Exponential Average Throughput of all *BE* connection in Mbps

connections given in table I. We notice that during the window interval 78 and 82 some of the SS suffer bad channel quality which results in decreasing the average throughput, while the opposite is noticeable during window interval 45. Figure 4 shows the average throughput of all *nrtPS* connections, again the proposed scheduler was able to honor the QoS requirements of *nrtPS* connections aforementioned in Table I.

Figure 5 shows the throughput of best effort traffic. We noted over the simulation time that the *BE* connections were not starved. This is because we considered it as part of our mathematical formulation to minimize the blocking probability. The throughput of the *BE* traffic is the smallest because in the mathematical formulation we assumed that the minimum number of slots assigned for the best effort is one slot and the maximum number of slots is the number of slots necessary to meet the maximum sustainable rate, thus, the number of slots assigned for the best effort traffic is the least.

IV. Conclusions

We presented an opportunistic cross layer based scheduler to support all QoS classes in IEEE 802.16 standard. Our main contribution is that the scheduler is optimal, fair and capable of isolating the flow classes. It optimally calculates the number of time-slots required to meet the QoS requirements of the connections within each class such that the blocking probabilities of connections are minimized. The proposed scheduler selects connections within each class that have the highest value of a priority function, which facilitates the long term fairness among connections. The priority function is based on the connections average throughput, current attainable transmission rate and the connection QoS requirements. Performance evaluation of the scheduler shows that the scheduler is capable of meeting all connections QoS requirements without starving the best effort class connections.

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