Operator Revenue Maximizing Heuristics with QoS Guarenetees for Real Time Traffic in 4G Networks

Neeraj Poudyal[1], Ha Cheol Lee[2] and Byung Seub Lee[1]
[1] Dept of Information and Telecommunication Engineering, Korea Aerospace University
Hwajeon Dong,Goyang City, Gyeonngi Do 412719 - Korea
[e-mail: neeraj@kau.ac.kr, lbs@kau.ac.kr]
[2] Dept of Information and Telecommunication Engineering, Yuhan University
Gyeongin Ro, Goyang City, Gyeonngi Do 185-34 - Korea
[e-mail: hclee@yuhan.ac.kr]
*Corresponding author: Neeraj Poudyal

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Abstract

This paper attempts to maximize the operator's revenue while simultaneously providing a multi-constraint, multi-hop and deterministic QoS provisioning for real time traffic in IEEE 802.16m based 4G networks. The optimal solution to such a problem is NP-complete and therefore not feasible to be solved in a tolerable polynomial time. For this reason, we also provide a simple price based greedy heuristic to be used along with the admission control. Simulation results for different QoS schemes show that the heuristic produces a revenue that is very close to the optimal revenue, and is far more aggressive than the size based and other common algorithms that are computationally feasible to be implemented in IEEE 802.16m.

Keywords: Value maximization, admission control, 802.16m, QoS

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1. Introduction

Fourth Generation(4G) Networks is a set of advanced requirements that the networks of the next generation will have to meet to provide massive improvements over the current 3G based system [1][2]. IEEE 802.16m [3], which is an evolution of WiMax systems based on earlier 802.16e [4] standards, is one of the main technologies competing for the 4th generation wireless networks. The requirements are still being defined but it includes data rate of up to 1Gbps for fixed and 100 Mbps for mobile stations, seamless handover, all-IP networking, heterogeneity of devices, location based services and quality of service (QoS). The QoS requirements which might include minimum bandwidth, maximum tolerable delay, maximum tolerable packet loss etc. might be negotiated via Service Level Agreements (SLA) between the mobile operator and the mobile station user either at the time of connection or dynamically at different intervals during the operation. A large part of QoS provisioning is performed through admission control. Admission control guarantees the QoS by allowing the new traffic flow admission into the network only if the network is completely capable of fulfilling the QoS requirements demanded by the new traffic flow, while also ensuring that the QoS of already admitted traffic is not adversely affected because of the admission of this new traffic flow.

This paper provides a number of measurement based admission control criteria for supporting multiple QoS constraints to the real-time traffic class in Fourth Generation Networks based on IEEE802.16m, while at the same time maximize the revenue of the telecom operator as much as possible. In order to be effective, it is absolutely necessary for the revenue maximization to be integrated with the admission control policy. We call such a problem of integrated revenue maximization and satisfaction of QoS constraints an Operator Value Maximization Problem (OVMP). The optimal solution to OVMP is deceptively difficult to formulate as the problem comes under a class of very hard problems called Multi-Constraint 0-1 Knapsack problem [5] which has been dealt extensively in mathematics with its applications in computer science, economics, genetics and other disciplines. Multi-Constraint 0-1 Knapsack problem is a NP-complete problem [28], which implies that the computation time it requires to solve this problem is simply infeasible to be implemented in any real systems, and certainly not feasible in a IEEE 802.16m bandwidth request-grant interval where the computation must take place within a few milliseconds. This paper therefore provides an approximate algorithm that is not optimal, but works fast enough to be implemented in IEEE 802.16m networks while providing better revenue to the operator than generic schedulers based on first in first admit order (FIFO order). The admission control in this paper is different from many other works mainly in terms of support for multiple additive QoS constraints, deterministic QoS guarantee, and integrated revenue maximization scheduling. The rest of the paper is organized as follows. Section 2 deals with introduction on the related works in the area of admission control and revenue optimization, the shortcomings of those papers, and the approach taken to address the shortcomings. Section 3.1 contains implementation overview while 3.2 contains a technical introduction to the QoS feature of IEEE 802.16m network. QoS constraint formulation for IEEE 802.16m is described in Section 3.3. Section 4.1 provides a generic OVMP QoS model formulation. Section 4.2 describes the algorithm for Revenue maximization with integrated QoS admission control that is presented in section 4.3. Section 5 presents the simulation results. The paper ends with some concluding remarks in section 6.

2. Related Works

A number of approaches for controlling admission for QoS provision have been studied in the older WiMax system based on IEEE 802.16e [5] and earlier versions. In [6], the authors have proposed two queuing theoretic admission control approaches for threshold based and queue aware schemes where they have used probabilistic rather than deterministic measures, which are not able to provide 100% QoS guarantee. Also [6] only considers QoS for bandwidth guarantees and does not consider delay or other QoS measures. In the model presented in [7], an admissible region is determined to satisfy target overflow probability. Its shortcomings are the same as [6]. The delay performance for point-to-point networks has been studied in [8] and [9]. A Markov chain analysis of uplink subframe for polling is provided in [10]. The goal of [11] is to minimize average polling delay while increase the throughput; its contribution is valuable in the sense that it analyzes number of polls and the waste rate. Statistical admission control based on the frame occupancy is provided in [13] but it only provides a non-deterministic QoS bound. To analyze end-to-end delay, it is important to analyze the delays during the contention, bandwidth request and channel access periods. Bandwidth request scheme has been extensively studied in [8][11][12]. A latest and in-depth analysis of a bandwidth request with delay regulation has been done in [11]. The paper [11] introduces a novel approach for control knob to set the target delay and adjust the utilization accordingly. In [11], the author uses the use of step, linear and non linear functions to provide uplink scheduling with delay regulation in subscriber stations rather than the base station in a distributed manner. Our earlier approaches [14][15] on the other hand, provide deterministic delay guarantees by using the measurements at the base station. A comparison of performance of Region-Full and Region-Focused schemes can be found in [12]. This paper [12] also presents transmission probability, bandwidth efficiency and delay results analytically and through simulation. Packet scheduling approach has been studied in [13]. It lacks multi-constrained, multi-hop analysis. In addition this paper uses measurement based approach, which implicitly considers the effects of Adaptive Modulation and Coding Scheme (AMC) in account for more accurate admission control. The QoS provisioning provided in this paper is extended from our other works [14][15] and the QoS performance is not readdressed here. We instead address a more important issue of QoS-constrained revenue maximization problem, and provide a computationally feasible, low-complexity algorithm that produces a near-optimal solution. A number of related works in general networks so far has not addressed the multi-constrained QoS problem with revenue maximization. An interesting earlier work on revenue maximization was performed by Sridhar et al. [16]. The authors classified the traffic types as "precious" and "non-precious", and introduced two kinds of policies for CLP=0 and CLP=1 cells(see paper). The first one is called Partial Buffer Sharing (PBS) scheme (i.e., for a buffer of size K, there is a threshold K1 beyond which CLP=l cells are not accepted), and the second one is a combination of PBS with another scheme called Push-out(PBS+PO) (i.e., an arriving CLP=l is admitted only if the queue length is less than the threshold K1; in addition to this, the last CLP= 1 cell, if any, gets pushed out if a CLP=O cell arrives and sees the buffer full). The work can be extended to multiple classes of traffic – however, the paper has no provision for providing additive QoS constraints such as delay. Choi et al. [17] used semi-Markov decision process combined with linear program formulation to derive revenue maximizing admission control for multiservice networks. It too provides just the probabilistic admission control and guarantees only the bandwidth. Farrokh et al. [18] provide SLA aware revenue maximization scheduling policy by allocating the channel to users that have a chance of providing more value to the network operator. The paper describes "credit" as the reserved rate of the user minus service (bandwidth) already provided, and the user is given a priority until they have some credit left. It also provides bandwidth only QoS. Xia et al. [19] have proposed a preemptive resource management scheme to minimize SLA violations and maximize the operator's revenue. The concept of penalty when SLA is violated is used, and different priorities are provided to different flows (premium, gold, silver, bronze). The availability requirement, revenue and penalty for SLA violation are all higher for premium services than other services. A priority based resource pre-emption policy is used during two stages - the admission decision stage and periodic resource monitoring stage. This is interesting as dynamically monitoring the status of connection allows efficient utilization of network resources. This work also uses bandwidth as only the measure of admission control, and therefore cannot be burrowed to our problem unmodified. Two other works, which are not directly related to our work, must be mentioned here for the sake of completeness as well as for arousing interest in these important and not fully explored areas of revenue research. Lee et al. [20] describe a revenue maximization policy for multiple internet service providers by setting up peer contracts among each other. It provides a study on how a peer can distributively determine its optimal peering strategy. In the model presented by Hande et al.[21], an optimal combination of flat rate and usage based pricing components is provided. The authors show that the ISP can increase its revenue by setting a lower usage fee, and then dropping the packets that exceed the resources. Of course it is not applicable in our case where we must guarantee strict packet delivery. Although the technical contributions for IEEE 802.16m system have now become quite mature, very little research interest has gone towards increasing the operator's revenue in these networks. Belghith et. All [22][23][24][25] studied pricing strategies for different classes of QoS traffic. On the other hand this paper focuses exclusively on revenue optimization with integrated QoS for real-time traffic. The most relevant contributions to revenue maximization of IEEE 802.16m in this regard are presented in [26][27] which deal exclusively with the optimization issues. These contributions however are different from ours in several ways. First the Admission control criteria used in [26][27] are based on the calculation of blocking probabilities while our paper uses deterministic admission control criteria. Second, the constraints used by their revenue optimization policy are just bandwidth constraints (utility and fairness) while our paper uses a number of other additive constraints in addition to the bandwidth constraints. Adding just one more constraint such as a delay fundamentally changes the revenue maximization policy which has been addressed in this work.

3. Technical Details

3.1 Implementation Model

IEEE 802.16m standard defines Advanced Base Station (ABS) and Advanced Mobile Station (AMS) as the base station and mobile station that support IEEE 802.16m to distinguish itself from the older WiMax based naming conventions. For the purpose of analysis, the IEEE 802.16m source base station is attached to the wired network to connect it with the other destination wireless base station at the other end. Although IEEE 802.16m makes a provision of admission control and a scheduler, the details of the implementation are not defined by the standard and it is left to the vendor to decide the best solution. We fill the gap by adding our own uplink scheduler and admission control (**Fig. 1**). The standard does not mention revenue maximizing policy at all, and therefore we also provide the revenue maximization module. The three modules for Admission Control, Scheduling and Value Maximization are in fact integrated and work as a single module.

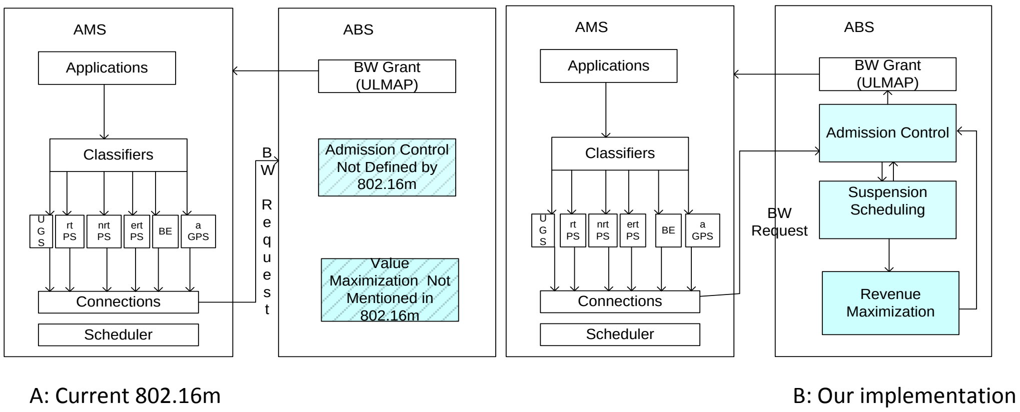


Fig. 1. Major Changes to 802.16m

In this paper the interval between bandwidth request and bandwidth grant is of particular interest to us. The bandwidth request is made by the AMSes during the BR-period of their uplink (**Fig. 2**). At the same time the calculation for admission control is done, and if the requirements are met, the ABS grants the admission during the next or successive downlinks. If the admission control is done sequentially on a FIFO basis, the QoS goal is met but the revenue enhancement goal may not be met. For this reason this paper only performs sequential FIFO admission control to the most important flows (defined by the signing of the SLA), while suspending all other requests so that they can be approximately optimized through a batch algorithmic processing. Since the amount of time available for optimization is of a few milliseconds interval, the use of elaborate algorithms is not feasible. Therefore this paper devises and compares some fast algorithms, and use the one that consistently provides the highest revenue to the operator.

3.2 Overview of IEEE802.16m Bandwidth Request Mechanism

IEEE 802.16m defines a 20ms TDD super frame divided equally into four frames of T_f (=5ms) duration each. Frames are the basic units of communication and consist of downlink and uplink durations that are configurable by the operator. For transmission, time is divided into small units called slots which are synchronized between the ABS and different AMSes. Each AMS sends and receives its data in the time slot provided by the ABS. The uplink duration T_{ul} consists of Initial Ranging (IR), Bandwidth Request (BR) and uplink data transmission periods. The uplink is used by the AMSes to send a number of control information as well as data to the ABS. The first period is known as Initial Ranging which is used for ranging information. The second period is known as Bandwidth Request period which is used by the AMSes to request bandwidth from the ABS. The rest of the uplink is used by the AMSes to send their uplink data to the ABS during the time slots specified in the ULMAP which the AMS previously received. The downlink duration T_{dl} consists of Downlink MAP (DLMAP), Uplink MAP (ULMAP) and downlink data transmission periods. After an AMS requests the bandwidth, depending on the scheduling conditions and availability of the bandwidth, the ABS grants the bandwidth in full amount or partially up to the available bandwidth, or altogether rejects the request. In the case of strict QoS provision, as described in this paper, the request is rejected completely if the QoS cannot be satisfied by the network. This bandwidth grant information is coded in the ULMAP message.

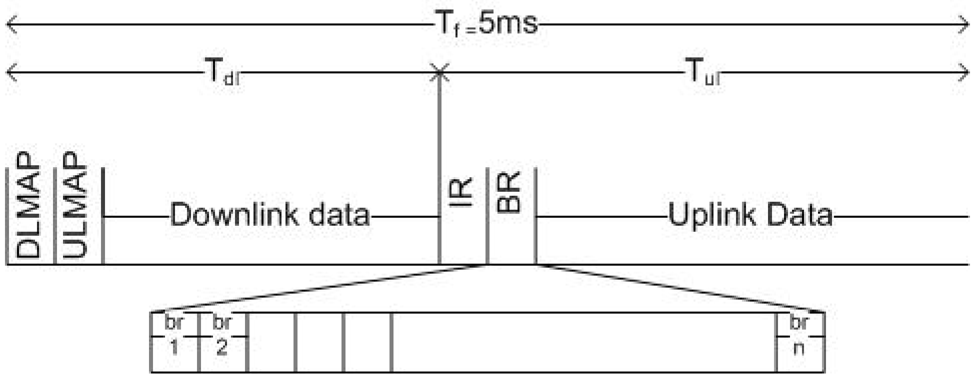


Fig. 2. Frame structure and timing of IEEE 802.16m

In addition the ABS also sends timing and synchronization information in its DLMAP and ULMAP. They are decoded by the AMSes so that all the AMSes know their timing and synchronization information which tells them the time slots in the following uplink which will be used by each AMS to send their uplink data. The rest of the downlink period is used by the ABS to send the downlink data to the ABS. Each kind of application traffic in IEEE 802.16m system have different QoS requirements as mentioned previously, and therefore treated differently. Each kind of application traffic must be associated with one of the six QoS service flow classes supported by IEEE 802.16m. They are Unsolicited Grant Service (UGS), Real Time Polling Service (rtPS), Non Real Time Polling Service (nrtPS), Extended Real Time Polling Service (ertPS) and Best Effort (BE), and Adaptive Granting and Polling Services (aGPS) [3]. The rtPS class is used for real-time variable data rates traffic such as multimedia and is the focus of this paper. IEEE 802.16m supports adaptation of service flow QoS parameters. ABS and AMS provide QoS according to the QoS parameter sets such as delay and other requirements, which are pre-defined or negotiated between the ABS and the AMS during the service flow setup/change procedure. The AMS may request the ABS to switch the service flow QoS parameter set with explicit signaling. Bandwidth is generally granted through polling mechanism for rtPS class. In this mode, each AMS is reserved a time slot during the BR period when it can send the bandwidth request. A bandwidth request can occur once per polling interval. The polling interval is the maximum amount of time before an AMS has to wait before it can make a bandwidth request again. The polling interval for rtPS class is $n*T_f$ where n=1,2… as defined by the operator. In the following downlink, if the bandwidth in the ABS is sufficient to allow access at the negotiated maximum latency, the ABS sends a bandwidth grant via ULMAP message. If not, the bandwidth request is rejected. If there are M mobile stations, the maximum number of bandwidth requests that can be made per polling interval (n frames) is M. The AMS first sends the bandwidth request indicator which may also include an optional quick access message. The ABS sends back acknowledgement, and if possible, provides the uplink grant for the data in the same duration. If the AMS receives the uplink grant for data in the ULMAP, it sends the data in the following uplink. Otherwise the AMS sends bandwidth request message (and the ABS replies by bandwidth request acknowledgement and uplink grant if possible). After that, the polling mode normally utilizes 3-step procedure (bandwidth request, bandwidth grant, and send data).

3.3 Formulating the QoS Constraints in IEEE 802.16m

Many of the QoS constraints presented in this paper are also discussed in our other works [14],

[15]. We now formally restate these constraints and extend them for revenue maximization purpose. A multi-hop IEEE 802.16m network consists of a one or more intermediate links that can be wired or wireless. For simplicity we consider a source base station of a multi-hop network attached to a full duplex wired links and has the destination base station at the other end.

Given a path P from the source 802.16m AMS to the destination 802.16m AMS in an integrated network, the system needs to ascertain that P meets the following sets of QoS constraints: 1. Minimum sustained rate constraint of the k^{th} AMS as defined by the AMS's SLA is maintained. In other words, the system must maintain a reserved rate Ψ such that $\Psi >= \sum_{k=1}^{N} \Upsilon_k$ where Υ_k the minimum sustained rate of the kth AMS, and N is is the number of active AMSes. 2. Bandwidth request is large enough to be transmitted through the network without impacting the minimum sustained rate of other flows. At the same time, each AMS is can have a configurable maximum rate Γ_i so that no single AMS can take unfair advantage of system bandwidth. 3. Deadline of the bandwidth request is large enough to be met by the multi-hop network. 4. A number of additive constraints such as hop delay, packet loss etc is supported. 5. The rtPS class of IEEE 802.16m also needs to guarantee traffic priority. Traffic priority is a trivial matter of using preemptive priority scheduling such as earliest deadline first (EDF) scheduling and will not be discussed in this paper. 6. Lastly, to fulfill the goal of this paper, the solution not only needs to ascertain all the above requirements are met in isolation but integrate them with the revenue maximization model so that the operator can reap the economic benefits while still honoring their SLA. In order to model a policy to support the above requirements, we first derive the rate, delay, packet loss and other additive constraints of IEEE 802.16m.

Rate of IEEE 802.16m: The basic unit of transmission in the physical layer is known as a symbol which can carry variable number of bits depending on various factors. The time to transmit each OFDM symbol with sampling frequency f_s , fast Fourier transform at non equispaced nodes (NFFT) and cyclic prefix ratio G can be used to derive the rate of the system.

$$Symbol\ Time = (1/[fs/NFFT]) \times (1+G) \tag{1}$$

The rate of transmission between the ABS and AMS is chosen by the Adaptive Modulation and Coding (AMC) Scheme depending on the received Signal to Noise Ratio (SNR) of the AMS. Depending on the Modulation and coding, the useful bits per symbol (*ubps*) is calculated as shown in example **Table 1**.

$$\begin{gathered} Rate = Number\ of\ symbols \times ubps \\ Rate = \frac{1}{(1/[fs/NFFT]) \times (1+G)} \times ubps \end{gathered} \tag{2}$$

(2) provides a theoretical system rate. In our implementation, we use measured rate rather than theoretical rate for accuracy. As can be seen in (2), the rate of the IEEE system is variable depending on the signal to noise ratio of the received signals from the AMSes. A fraction of this rate is reserved by the system for real-time traffic. Since this is the total rate available for

the rtPS traffic, it is denoted by *Btol*.

Table 1. Adaptive Modulation and Coding Scheme example

SNR	Modulation	Coding	Useful Bits Per Symbol (ubps)
6.0	QPSK	½	192*2*1/2=192
8.5	QPSK	¾	192*2*3/4=288
11.5	16 QAM	½	192*4*1/2=384
15.0	16 QAM	¾	192*4*3/4=576
19.0	64 QAM	2/3	192*6*2/3=768
21.0	64 QAM	¾	192*6*3/4=864

Terminology

For a single base station analysis the following terms are used.
Br= Bandwidth request. *Br* is removed after it is served
B_{tol}=Total IEEE 802.16m system bandwidth (measured) without considering network links
B_{used}= Bandwidth occupied (measured), which is the sum of all Br_k, *where* $k=1...i-1$
$B_{avail}= B_{tol} - B_{used}$
Di= Maximum Delay requested by the request *i*
C= Total number of pending requests, each request is removed from C when it is served
N=Number of connections
aik(u) and aik(d) $=k^{th}$ additive constraint for uplink and downlink
R_k = the rate of the total 802.16m system measured with the modulation rate of the station *k*. For example if the measured rate(capacity) of the IEEE 802.16m system is 10 Mbps at 64 QAM(3/4) and 8 Mbps at 64 QAM(1/2), and the modulation rate of station k is 64 QAM(1/2) as dictated by its SNR, then R_k = 8Mbps.
Γi = Maximum user rate for connection i
Υj = minimum sustained rate of connection j
ζi = Price per Mb of *Bri*
In addition, for multi-hop analysis the following terms are used.
Bp=Bandwidth of a link p in P
P=Network path having *H* hops,
p=Links in P including network links as well as the IEEE 802.16m wireless uplink and downlink
aik(p) and Aik(P)= $=k^{th}$ additive constraint for link p , and for path P
Min(Bp) = Lowest bandwidth among all the *p* in *P*

Capacity Constraints: In a *complete share* scheme the mobile users don't have the maximum usage rate threshold, whereas in *threshold based* scheme their maximum user rate Γi is limited by the IEEE 802.16m operator. The new i^{th} bandwidth request Br_i has to be less than or equal to the minimum of the IEEE 802.16m system bandwidth B_{tol}, and the minimum of the path bandwidth *Min(Bp)* where *p* is a link in path *P (p=1,2..| p belongs to P)* after making reservations for minimum sustained rate of each AMS *Yi* .

$$Bri \le MIN\left(Btol - \sum_{k=1}^{i-1}(Brk - \Upsilon k) - \sum_{\substack{j=1,\\ j \ne k}}^{N} \Upsilon j\ ,\ MIN(Bp\ \forall\ p\varepsilon P) - \sum_{k=1}^{i-1} Brk - \sum_{\substack{j=1,\\ j \ne k}}^{N} \Upsilon j\right) \tag{3}$$

or complete share scheme and

$$Bri \le MIN\left(\Gamma i, Btol - \sum_{k=1}^{i-1}(Brk - \Upsilon k) - \sum_{\substack{j=1,\\ j \ne k}}^{N} \Upsilon j\ ,\ MIN(Bp\ \forall\ p\varepsilon P) - \sum_{k=1}^{i-1} Brk - \sum_{\substack{j=1,\\ j \ne k}}^{N} \Upsilon j\right) \tag{4}$$

for threshold based scheme with a limited maximum user rate threshold.

Delay constraint: Packet delay is an important deterministic measure of QoS for the real-time applications that require stringent bounds. Delay is dependent on the rate of the system (in complete share), and the also on the rate of the AMS (threshold based). There is an overhead of two other kinds of delays - called channel acquisition delay of one time frame which is used for signaling before the bandwidth request is sent, and polling delay of $n*T_f$ where n is the polling duration as defined by the telecom operator. A delay of a new packet depends on the time it takes to transfer this packet and all the pending packets that were admitted but not served till now.

$$Di \ge (n+1)Tf + \sum_{p=1}^{P} \frac{Bri + \sum_{k=1}^{i-1} Br_k}{Bp} + CEIL\left(\frac{1}{Tf} \left(\sum_{k=1}^{i-1} \frac{Br_k}{R_k} + \frac{Bri}{Ri} \right) \right) Tf \tag{5}$$

for complete share scheme and

$$Di \ge (n+1)Tf + \sum_{p=1}^{P} \frac{Br_i + \sum_{k=1}^{i-1} Br_k}{Bp} + CEIL\left(\frac{1}{Tf} \left(\sum_{k=1}^{i-1} \frac{Br_k}{R_k} + \frac{Bri}{\Gamma i} \right) \right) Tf \tag{6}$$

for threshold based scheme.

The first term in (5) and (6) is the combination of channel access ($1T_f$) and polling delay (n*$T_{f,}$ where n is selected by the operator). The second term is the total delay that occurs on the network path. The third delay is the delay occurring in the IEEE 802.16m uplink and downlink system, including transmission and queuing delay, which should always be in the multiple of frames which is why the time is divided and again 'ceil'ed with T_f. (The system needs to reserve at least one frame to send data of smallest size -T_{ul} to transmit and T_{dl} to receive). If n is 1, then the minimum delay for a byte size packet in a single-hop network is 3 $T_{f.}$ (for channel access, polling and transmission).

Packet loss constraint: Packet loss is not a strict requirement of rtPS traffic class, thus a probabilistic measure can be used for packet loss.

$$Li \le \prod_{p=1}^{P} (1 - \Pr(li_p)) \times Bri \ldots \left\{ i.e,\ Li \le\ -\left(\sum_{p=1}^{P} \log(1 - \Pr(li_p)) \times Bri \right) \right\} \tag{7}$$

The probability of packet loss at hop k multiplied by the bandwidth gives the number of packets lost. It is a multiplicative measure. Multiplicative constraints such as probability of packet loss can be converted to additive constraints by using logarithmic manipulation (as shown within the curly braces) which is much easier for calculation. This paper does not explore packet loss further and just considers them to be one of the other additive constraints.

Other additive constraints: Since 802.16m requires guaranteeing bandwidth and delay only, this paper doesn't concern with other individual constraints. But they are still acknowledged and denoted as *Aij(P)*where connection *i* is requesting j^{th} additive constraint in path *P* (*aij(p)* refers to j^{th} constraint in link *p* for connection *i*).

$$Aik(P)^{+} \geq \sum_{p=1}^{P} aik(p) \ , k = 1..MAXCONSTRAINTS \tag{8}$$

It should be noted that delay is also a kind of additive constraint. Other examples of additive constraints are hop-count or packet loss. However, it is important to deal with delay as a separate additive constraint because unlike the other additive constraints, delay of a new request depends directly on the previously admitted bandwidth requests. In other words delay is not memory-less constraint like hop delay and packet loss probability. Since IEEE 802.16m requires guaranteeing bandwidth and delay only, other constraints are not dealt with individually.

4. Admission Control & Revenue Optimizing in IEEE802.16m

4.1 Problem Formulation

Theorem 1: OVMP is NP-complete.

Proof: It can easily be proven that OVMP is a NP-complete problem by showing that it is a special case of a well-known multi-constraint 0-1 knapsack problem which is already a proven NP-complete problem. The proof is shown through equivalency of the reduced form of OVMP problem with the MC01 problem. The structure of MC01 is:

$$Maximize(\sum_{i=0}^{n} c_i * X_i)$$

$$Subject\ to\ constraints$$

$$bj \geq \sum_{i=0}^{n} aji * Xi, \ j = 1..MAXCONSTRAINTS \tag{9}$$

$$X_i \in \{0,1\}\ and\ \{a,b,c\} \geq 0$$

$$for\ any\ a,b,c$$

A multi-hop, multi-constraint, heterogeneous IEEE 802.16m network can be seen as a Graph G{V,E} where V is the set of vertices and E{*p1,p2...pn*}is the set of edges or links . Any connected subset of G from a source vertex to a destination vertex is a QoS path *P* if it meets both the capacity and additive constraints. Assuming delay to be a kind of additive QoS constraint, a reduced problem statement (without operator thresholds like minimum sustained rate or maximum user rate) for OVMP is:

$$Maximize(\sum_{i=0}^{n} Xi * \Pr i) \quad , Xi = \{0,1\} \; and \; \Pr i = Bri * \zeta i$$

$$Subject\ to\ QoS\ constra\text{int}\ s$$

$$1.\ B_{tol} \geq \sum_{i=1}^{n} Bri * Xi$$

$$2.\ A_j^{+} >= \sum_{i=1}^{n} a_j^{+} i * Xi,\ j = 1...MAXCONSTRAINTS \tag{10}$$

where Pr_i is the total price of i^{th} bandwidth request *Bri* and *Xi* is the binary variable which is set to 1 if *Bri* is admitted by the admission control procedure, 0 otherwise; ζi is the price per Mb of *Bri*, $a_j i$ are the j^{th} additive constraints for the individual network link *p* of the network path *P*, and A_j is the user-requested maximum QoS threshold for the j^{th} QoS constraint of the total path *P*.

Since the reduced OVMP is structurally similar to MC01 from the above definitions, the full OVMP is at least as hard as the MC01 problem. Since MC01 is NP-complete, OVMP is NP-complete and therefore not feasible to be solved optimally. This does not mean MC01 is exactly the same as the full OVMP, as the full OVMP requires satisfaction of additional constraints. Our problem is, therefore, to simply find the best revenue among the tested solutions in cases where the applications have different prices while ensuring 1. The applications still maintain their QoS requirements 2. The system meets its computation timing constraints. This is accomplished by the heuristic mentioned in the next section.

4.2 Heuristic for OVMP

IEEE 802.16m system has around 1-2 ms of computation time available between receiving of bandwidth request and granting of bandwidth, and therefore, the solution needs to find an optimal solution that is fast enough to compute, and consistently provides much better revenue to the operator than a FIFO scheduling algorithm.

Let

$S_R = \{Br1, Br2.....Brn\}$ *'Ordered set of all requests*

$S_S = \{\}$ *'Ordered set of suspended Br*

$S_A = \{\}$ *'Ordered set of accepted Br*

The commonly used FIFO algorithm simply checks the QoS as soon as the request arrives. FIFO algorithm can be stated as:

From $i = 1$ *to Sizeof* (S_R) *Do*

    If QoS AC Criteria is TRUE then

        $S_A \leftarrow S_A \cup Bri$

        $Bavail \leftarrow Bavail - Bri - \Upsilon i$

    End If

End From

We note that there is a small time frame available for using the approximate revenue optimizing algorithm between the arrivals of bandwidth request, till the bandwidth is granted.

Since an exact optimal solution is infeasible, we provide a greedy heuristic called Price based Greedy Approximation Scheduling Algorithm (PAGASA) to solve the problem with full QoS guarantee and approximate revenue maximization in linear time. The heuristic is described as follows:

```
Stage I
From i = 1 to Sizeof(S_R) Do
    If Bri ≤ ϒi then  ' SLA requires this request to be admitted if it meets QoS
        If QoS AC Criteria is TRUE then
            S_A ← S_A ∪ Bri      ' add request to admit set
            Bavail ← Bavail − Bri − ϒi
        Else
        ......' nothing (reject)
        End If
    Else  ' Bri > ϒi, so suspend
        S_S ← S_S ∪ Bri    ' add request to suspend set for later optimization
    End If
End From
Wait Until BR_period is over

Stage II, Processing in Batch,
' don't apply optimization algorithms if not full utilization
If Sum(S_S) ≤ Bavail Then ' just admit if they fulfill QoS
    From i = 1 to Sizeof(S_S) − 1 Do
        If QoS AC Criteria is TRUE for Bri then
            S_A ← S_A ∪ Bri
            Bavail ← Bavail − Bri − ϒi
        Else
        ......' nothing (reject)
        End If
    End From
End If
  ' faster sorting methods can be used instead
  From i = 1 to Sizeof(S_S) − 1 Do
      From j = i + 1 to Sizeof(S_S) Do
          If Price(Bri) > Price(Brj) then     ' SAGASA use Size(Bri)
          SWAP positions of Br(i) and Br(j)
          End If
      End From
  End From
```

$From\ \ i = 1\ to\ Sizeof\,(S_S) - 1\ Do$
$\quad If\ \ Bri \le Bavail\ then$
$\quad\quad If\ QoS\ \ AC\ Criteria\ \ is\ TRUE\ \ for\ Bri\ then$
$\quad\quad\quad S_A \leftarrow S_A \cup Bri\ \ 'add\ to\ admit\ set$
$\quad\quad\quad Bavail \leftarrow Bavail - Bri - \Upsilon i$
$\quad\quad\quad S_S \leftarrow S_S - Bri\ \ 'remove\ \ from\ suspend\ \ set$
$\quad\quad Else$
$\quad\quad S_S \leftarrow S_S - Bri\ \ 'remove\ \ from\ suspend\ \ set$
$\quad\quad End\ If$
$\quad End\ If$
$End\ From$

Although simple, this heuristic seems to consistently provide revenue well within 1% of the optimal revenue in a practical system, as demonstrated in the simulation results of section 5. The next section provides the full sets of QoS admission control criteria.

4.3 QoS Admission Control Criteria for IEEE 802.16m System

This section provides QoS admission control criteria for single hop and multi hop IEEE 802.16m networks operating under complete share and threshold based schemes. The algorithms presented here are extensions of [14], [15] and can be used with any criteria.

Admission Control for Single-hop Complete Share Scheme. A new rtPS connection with a new bandwidth request Br_i, delay request D_i and other additive constraints $A_i x^+$ (x^{th} additive constraints such as hop-count, packet loss etc.), is schedulable with minimum sustained rate guarantees in a complete share scheme of IEEE 802.16m system with C already admitted bandwidth requests if

$$1.\ Bri \le Btol - \left(\sum_{k=1}^{C} Brk - \Upsilon k \right) - \sum_{\substack{j=1,\\ j \ne k}}^{N} \Upsilon j$$

$$2.\ Di \ge (n+1)Tf \ \ + Ceil\left(1/Tf \ \Big(\sum_{k=1}^{C} BRk/Rk + Bri/Ri \Big) \right) \times Tf$$

$$3.\ Aik(P)^+ \ge aik(u) + aik(d),\ k = 1..MAXCONSTRAINTS$$

$$Di \in N \times Tf, N = 3, 4, ... \tag{11}$$

Admission Control for Multi-hop Complete Share Scheme. A new rtPS connection with a new bandwidth request Br_i, delay request D_i and other additive constraints Aij^+ , is schedulable with minimum sustained rate guarantees in a complete share multi-hop scheme of IEEE 802.16m network with C already admitted bandwidth requests if

$$
\begin{aligned}
&1.\ Bri \le MIN\left(Btol - \left(\sum_{k=1}^{C} Brk - \Upsilon k\right) - \sum_{\substack{j=1,\\ j\ne k}}^{N} \Upsilon j\ ,\ MIN(Bp\ \forall\ p\varepsilon P) - \sum_{k=1}^{C} Brk - \sum_{\substack{j=1,\\ j\ne k}}^{N} \Upsilon j \right)\\
&2.\ Di \ge (n+1)Tf + \sum_{p=1}^{P} \frac{Bri + \sum_{k=1}^{C} Brk}{Bp} + Ceil\left(\frac{1}{Tf}\left(\sum_{k=1}^{C} \frac{Brk}{Rk} + \frac{Bri}{Ri}\right)\right) Tf\\
&3.\ Aik(P)^{+} \ge \sum_{p=1}^{P} aik(p)\ ,\ k = 1..MAXCONSTRAINTS\\
&Di \in N \times Tf\ ,\ N = 3, 4, \ldots
\end{aligned} \tag{12}
$$

Admission Control for Single-hop Maximum Rate Limited Scheme. A new rtPS connection with a new bandwidth request Br_i, delay request D_i and other additive constraints Aij^{+} , is schedulable with minimum sustained rate and maximum user rate guarantees, in a threshold based scheme of IEEE 802.16m system with *C* already admitted bandwidth requests if

$$
\begin{aligned}
&1.\ Bri \le MIN\left(\Gamma i,\ Btol - \left(\sum_{k=1}^{C} Brk - \Upsilon k\right) - \sum_{\substack{j=1,\\ j\ne k}}^{N} \Upsilon j \right)\\
&2.\ Di \ge (n+1)Tf\ + Ceil\left(\frac{1}{Tf}\left(\sum_{k=1}^{C} \frac{Brk}{Rk} + \frac{Bri}{\Gamma i}\right)\right) \times Tf\\
&3.\ Aik(P)^{+} \ge aik(u) + aik(d),\ k = 1..MAXCONSTRAINTS\\
&Di \in N \times Tf\ ,\ N = 3, 4, \ldots
\end{aligned} \tag{13}
$$

Admission Control for Multi-hop Maximum Rate Limited Scheme. A new rtPS connection with a new bandwidth request Br_i, delay request D_i and other additive constraints Aij^{+}, is schedulable with minimum sustained rate and maximum user rate guarantees, in a threshold based multi-hop scheme of 802.16m network with *C* already admitted bandwidth requests if

$$1.\ Bri \le MIN\left(\Gamma i,\ Btol - \sum_{k=1}^{C} Brk - \sum_{\substack{j=1,\\ j\neq k}}^{N} \Upsilon j \quad , MIN(Bp\ \forall\ p \varepsilon P) - \sum_{k=1}^{C} Brk - \sum_{\substack{j=1,\\ j\neq k}}^{N} \Upsilon j \right)$$

$$2.\ Di \ge (n+1)Tf + \sum_{p=1}^{P} \frac{Bri + \sum_{k=1}^{C} Brk}{Bp} + Ceil\left(\frac{1}{Tf} \left(\sum_{k=1}^{C} Brk/Rk + Bri/\Gamma i \right) \right) Tf$$

$$3.\ Aik(P)^{+} \ge \sum_{p=1}^{P} aik(p)\ ,\ k = 1..MAXCONSTRAINTS$$

$$Di \in N \times Tf\ ,\ N = 3, 4, \ldots \tag{14}$$

In high speed network links, the term $\sum_{p=1}^{P} \frac{Bri + \sum_{k=1}^{C} Brk}{Bp}$ tends to be very small and in high speed IEEE 802.16m system, the term $\sum_{k=1}^{C} Brk/Rk$ tends to be very small compared to the term $Bri/\Gamma i$ in case there is a complete partitioning (which means the maximum user rate is set to be the system rate equally divided by the number of users). In most threshold based scheme the maximum user rate is the determinant factor for limiting the throughput and increasing the delay of that user. However maximum user rate also maximizes the chance of QoS provisioning to a large number of users. When there is no maximum user rate threshold, the bandwidth requests arriving earlier (FIFO) might take an unfair advantage of the system resources.

5. Results

The simulation environment comprises of a large number of user stations making up to 100 bandwidth requests in the bandwidth request period of a polling interval. The base station receives the requests, and controls admission using different algorithms (12) or (14) for revenue comparison purposes. All algorithms guarantee 100% QoS to the admitted traffic. We test our hypothesis that either the Price based Greedy Approximation Scheduling Algorithm (PAGASA) or Size based Greedy Approximation Scheduling Algorithm (SAGASA) integrated with admission control criteria in (12) or (14) provides a better revenue maximization to the operator than the FIFO (First in First Out) based conventional Scheduling algorithm (FIFOSA). The price is in a very small unit per Mb. We have also tested dynamic programming based algorithms but the computation time was far too large to integrate into the IEEE 802.16m system frame time. For this reason, we have not shown any dynamic programming based heuristics in our results. In addition we have used the brute force algorithm to derive optimal solution. The brute force optimal algorithm is a solution for NP-complete problem and therefore not feasible to be implemented in IEEE 802.16m because of the timing constraints; however, it provides a useful benchmark to compare the deviations of our approximate solutions from the optimal price set.

Table 2. Growth of computation times with increasing number of bandwidth requests

Requests per second(per frame)	FIFOSA	PAGASA	SAGASA	Optimal (Brute force)
10000 (20)	~0	0.0017	0.0017	0.009
15000 (30)	~0	0.0033	0.0033	0.0257
20000 (40)	~0	0.0052	0.0052	0.074
25000 (50)	~0	0.006	0.006	0.124
50000 (100)	~0	0.024	0.024	0.418

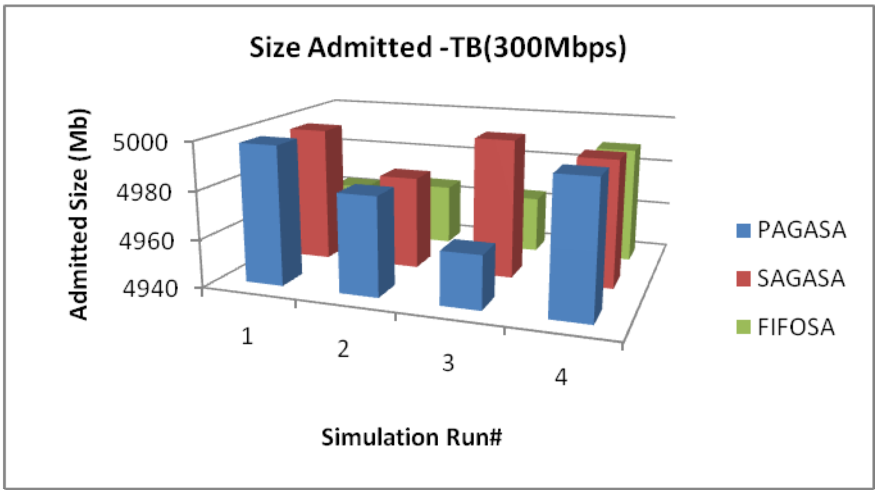
The growth of algorithmic computation times(in seconds) are plotted in Table.2. In contrast to the optimal algorithm, the heuristic works quite fast under fairly high loads. Greedy heuristic requires an average of O(nlogn) sorting time where n is the number of requests, when sorting methods such as quick-sort is used (with worst case of n^2). Brute force optimal algorithm is NP complete.

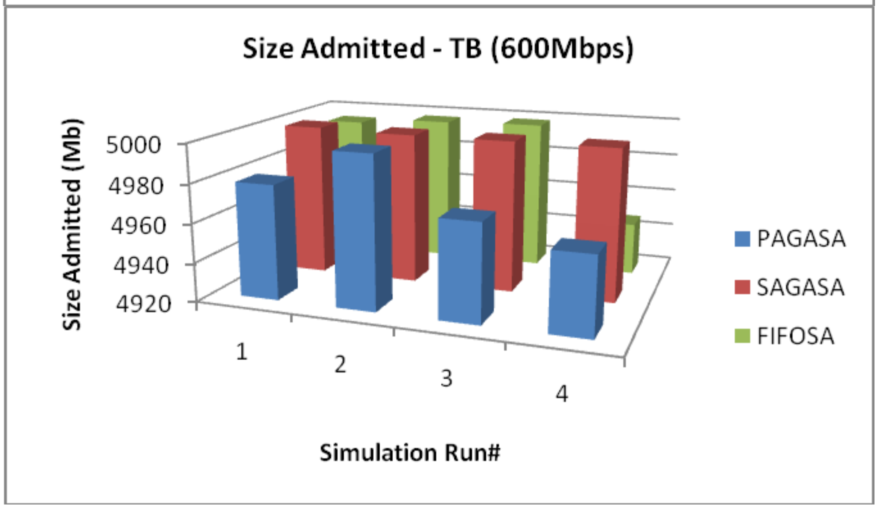
While not optimal, PAGASA resulted in better revenue for the telecom operator by prioritizing premium applications over lower-premium ones, while ensuring the lower-premium applications still maintain their service level agreements. This kind of premium-priority greedy solution is intuitive, but the analysis in mathematical and computer sciences has shown time and again that such greedy schemes achieve solutions that are far from optimal. We first demonstrate that our greedy heuristic has been able to achieve a close to optimal result, and then discuss the reason behind such a result. The parameters used in the simulation to evaluate the generated revenue by various algorithms are as follows. The number of bandwidth requests is set to 100 per polling interval. The bandwidth request is randomly priced between 20 and 30 units(small) per Mb. System bandwidth is 500Mb but it is multiplied 10 times to see more precise view of the results. Minimum sustained rate is random between 100 and 500 Mb (scaled 10 times). Similarly the maximum user rate is 300 and 600 Mb (scaled 10 times) for threshold based scheme, and up to the maximum system bandwidth for complete share scheme.

Simulation results show that the sizes of total bandwidth requests admitted by various algorithms are quite random (**Fig. 3**). With the older networks that had a single price for all the traffic, it used to be a norm to increase the utilization as much as possible because higher utilization meant higher revenue. With a differentiated pricing scheme, this is no longer the case. This can be seen by comparing the size admitted (**Fig. 3**) with revenue generated (**Fig. 4**) where revenue generated has little to do with the difference in sizes.

After running dozens of simulations on random data on multi-hop threshold based scheme where maximum user rate was defined, PAGASA which generated the revenue that was closest to the optimal revenue, outperformed SAGASA and FIFOSA 100% of the time (**Fig. 4** and **Fig. 5**). The results were similar in complete share scheme (**Fig. 4** and **Fig. 5**) where PAGASA outperformed other algorithms all the time. It is not possible to promise such a result in complete share scheme if the size of all the requests is very large. However, complete share scheme has to be removed for fairness reasons especially during high utilization (which is the only time the revenue optimization is applicable).

It has been mathematically shown that such an impressive result is not normally achieved in 0-1 knapsack problems by using greedy algorithms. In fact greedy algorithm almost always fails to achieve optimal solution. We argue however that unlike ideal mathematical problems, the knapsack items in IEEE 802.16m networks namely the bandwidth requests have a particular distribution in some cases. Where the maximum user rate threshold is defined and small, most bandwidth requests items are also small compared to the capacity of the IEEE 802.16m system. In such cases, the price based greedy algorithm does outperform other common algorithms because having a large item does not interfere with the ability to add another item until we reach the end of the capacity (as large item is still small compared to the capacity). Most of our simulation shows that the size admitted is between 4924 – 4999 Mb which means the biggest hurdle of greedy algorithms, that the formerly admitted item #X won't allow the next two or more smaller items having their combined price greater than #X * Price(X) , is very unlikely until most of the items are already admitted. Finally we address the question as whether it is possible to have a heuristic that provides a revenue that is better than the revenue generated by the priced based greedy heuristic. Simulation results of our threshold based schemes show that the price based greedy heuristic has been able to consistently produce a revenue that is 99.24 – 99.77% of the optimal solution. This means any additional gain in revenue through the use of to a better heuristic may not be significant to the operator.





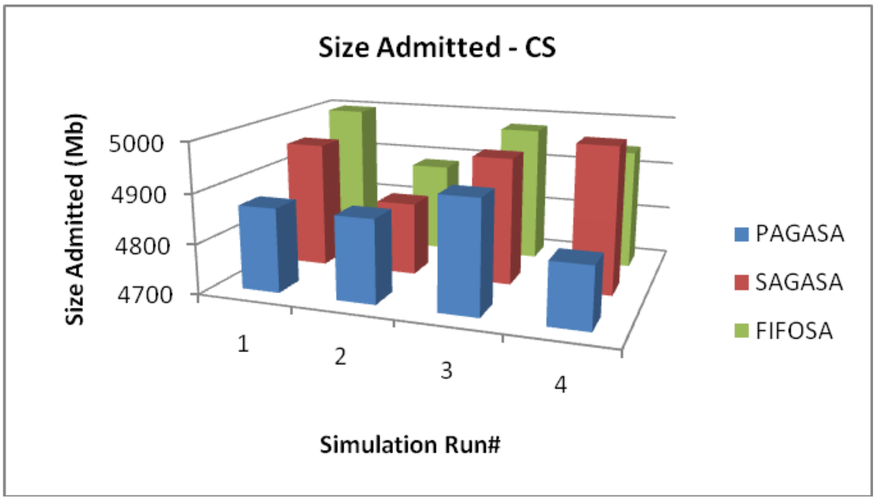
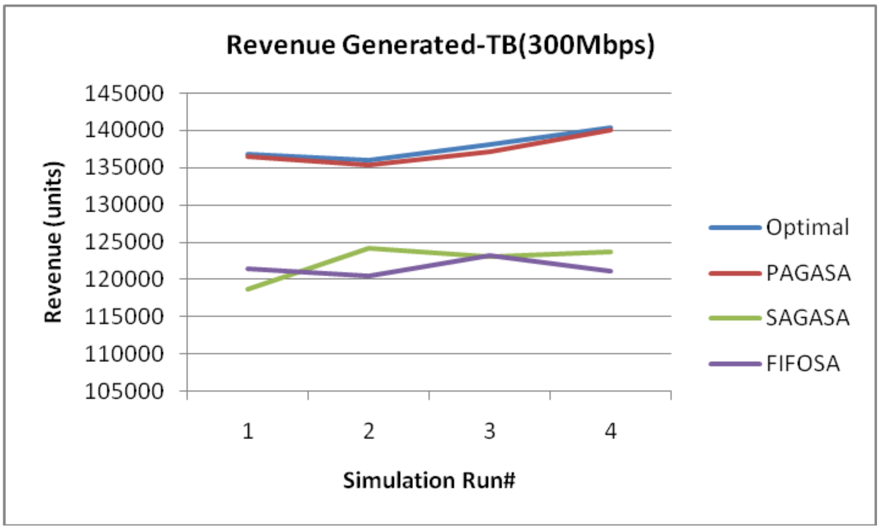


Fig. 3. Maximum size admitted in IEEE 802.16m system using various algorithms in threshold based (TB) and complete share (CS) schemes



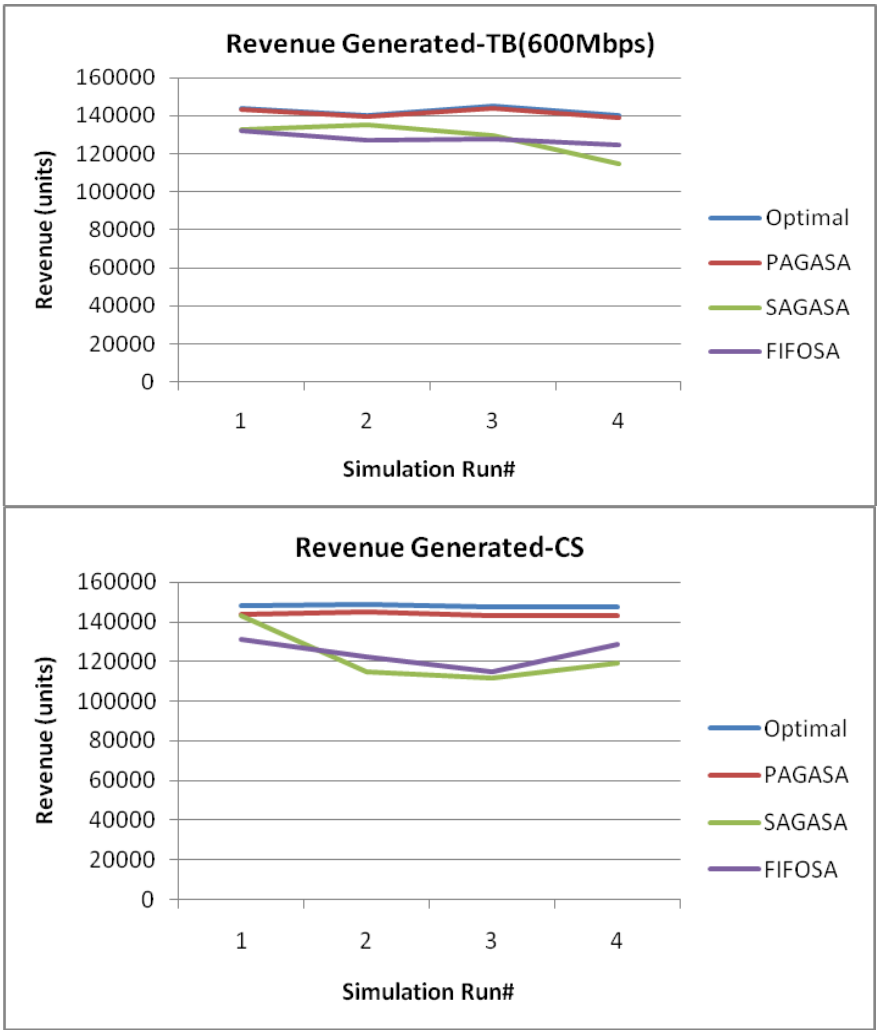
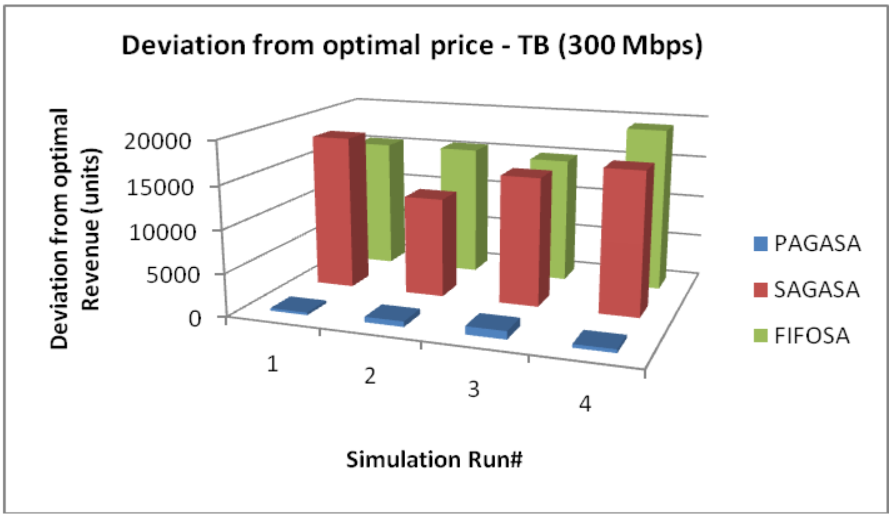


Fig. 4. Generated revenue for different schemes in threshold based and complete share schemes



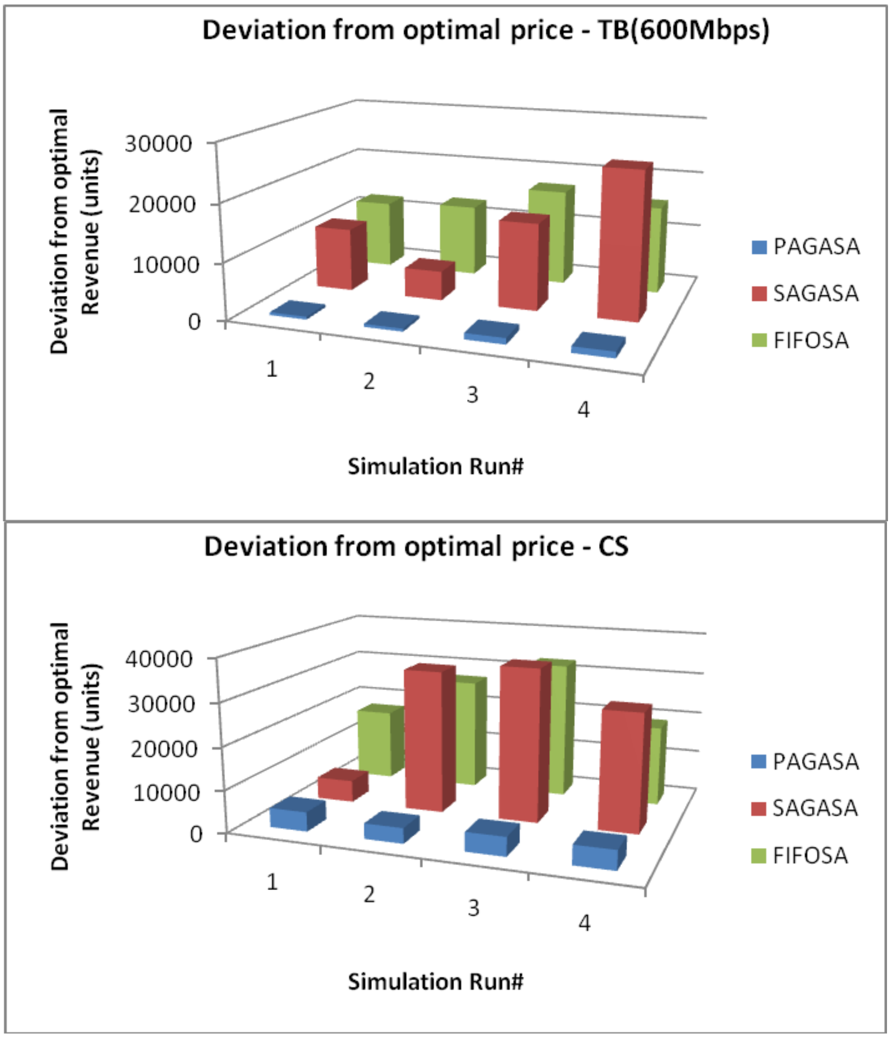


Fig. 5. Deviation from optimal price in threshold based and complete share schemes

6. Conclusion

This paper has addressed the problem of revenue maximation in networks that need to support multiple deterministic QoS constraints. We first show that such a problem is NP complete by proving that it is a special case of a well known multi-constrained 0-1 knapsack problem. This means that the optimal solution to the problem is not feasible to be implemented in real 4G networks because of their short computational timing constraints. An approximate heuristic therefore has been proposed using greedy algorithm which seems to produce a computationally feasible solution generating a revenue that is well within 1% of the optimal revenue in certain cases. Simulation results have shown that this heuristic consistently produced a revenue that is 99.2-99.7% of the optimal revenue. The operator is suggested to use PAGASA along with the threshold based admission control criteria (14) during the peak hours in order to guarantee the multi-constraint QoS, increase the revenue of the operation, and maintain the fairness to the flows.

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Neeraj Poudyal is a PhD candidate in Information and Communication Engineering at Korea Aerospace University. His research interest includes deterministic quality of service in the next generation wireless networks. He holds a Masters degree in Computer Applications from Sikkim Manipal University of Health, Medical and Technological Sciences, and a Bachelor degree in Computer Applications from MCRP University. Prior to his PhD, Neeraj worked in the software industry for several years developing wide range software applications for the international client-base. He is also involved in designing software controllers for communication equipments, simulators and emulators.

Ha Cheol Lee received his B. S., M. S. and Ph. D. degrees in Communication Engineering from Korea Aerospace University, Korea, in 1983, 1990 and 1999, respectively. Since 1995, he has been with the Department of Information and Communication Engineering of Yuhan University in Korea and is currently a professor. He also holds a certificate of professional engineer since 1993. He has alro remained a research engineer in ETRI(Electronics & Telecommunications Research Institute) and KT(Korea Telecom) for twelve years. His current interests include MIMO/OFDM and space-time coding in broadband wireless communications.

Byung Seub Lee completed his PhD from New Jersey Institute of Technology in 1992 and is currently a professor at the Department of Information and Communication Engineering, Korea Aerospace University. He holds his M.S. degree in Electronic Engineering from Seoul National University and B.S. degree in Electronic Engineering from Korea Aerospace University. His research interest include Satellite Communication, Digital Signal Processing and Adaptive Arrays. He also worked as a senior research engineer for several years at ETRI (Electronics & Telecommunications Research Institute).