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Scheduling for Proportional Differentiated Service Provision in Geostationary Bandwidth on Demand Satellite Networks

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Abstract—**The rapid emergence of multimedia applications in the Internet has highlighted the need for service differentiation in broadband satellite networks, which aim at being an integral part of the broadband network infrastructure. This paper presents a novel scheduler, called SWTP (Satellite Waiting Time Priority), to provide relative service differentiation in a DVB-RCS geostationary (GEO) satellite system where the network is structured to support a finite number of ordered service classes. We advocate the adoption of the proportional service differentiation model in the satellite domain to provide proportional delay differentiation to different traffic classes. The lightweight nature of the model makes it especially suitable for satellite systems as it minimizes computational cost by doing away with mechanisms such as admission control and resource reservation. Simulation results suggest that the SWTP scheduler can effectively and consistently provide proportional delay differentiation in satellite networks.**

I. Introduction

NEXT generation networks are expected to be largely heterogeneous and encompass multitude of networking technologies. Broadband satellite networks aim at being an integral part of this global communication infrastructure. The rapid emergence of multimedia applications and the growth of wireless data services have magnified the need for quality of service (QoS) provision mechanisms that will satisfy consistently the diverse service requirements across different network segments. Given the expectation that future data networks will provide service differentiation at the level of service class, efficient and flexible yet simple and robust mechanisms that serve the service differentiation purpose in satellite networks become mandatory.

Service differentiation and QoS provision are not new research topics and in fact, much research effort has been devoted to them over the last couple of decades. Integrated Services (*IntServ*) [1] and Differentiated Services (*DiffServ*) [2] stand at the two edges of the proposed frameworks' range; the former invokes admission control and an explicit reservation protocol (Resource Reservation Protocol – RSVP [3]) to provide hard guarantees to individual traffic flows, whereas the latter, more lightweight framework segregates traffic into classes and provides them with softer QoS guarantees. More recently and in between *IntServ* and *DiffServ*, various proposals have emerged, which try to compromise the robustness of provided QoS guarantees with scalability [4]. The proportional differentiated services (PDS) framework is one of these proposals [5], which opts to provide *relative* QoS guarantees, namely the performance spacing amongst different traffic classes is both predictable and controllable by the network manager [5].

In this paper, we essentially adopt the PDS model into the satellite network context; in particular, we introduce a scheduler that draws on the Waiting Time Priority (WTP) scheduler [6] and can serve the PDS model under the specific requirements of satellite environments. The following section gives a brief overview of the PDS model and reviews the work carried out on the WTP scheduler in the context of the specific service differentiation framework. In Section III we outline the satellite system architecture to which we apply the service differentiation model. Section IV formulates the bandwidth allocation task under the particular service differentiation requirements and presents our proposed solution, which is evaluated with simulations in the section that follows. We conclude the paper in Section VI.

II. The Proportional Differentiation Service Model and the Waiting Time Priority Scheduler

A. PDS Model

The PDS model is a lightweight framework for relative QoS provision to a finite number of service classes. Assume that the network wants to support N service classes. Each class is associated with a differentiation parameter (DP), r_i. If σ_i is the performance metric of interest for class i or a proper function of it, e.g., throughput, the inverse function of delay or packet loss, then the PDS model requires

$$\frac{\sigma_i}{\sigma_j} = \frac{r_i}{r_j}; \qquad \forall i, j \in \{1 \quad N\}. \tag{1}$$

We number classes in decreasing priority order, i.e., the lower the class index, the better the service provided to it, and normalize all DPs with reference to the highest priority class, which is assigned DP equal to 1:

$$0 < r_N < r_{N-1} < \ldots < r_2 < r_1 = 1$$

In this paper, the performance metric under consideration is the average queueing delay $\bar{d}_i$ of class i. Hence, the model requires that

$$\frac{\bar{d}_i}{\bar{d}_j} = \frac{\delta_i}{\delta_j}; \qquad \forall i, j \in \{1 \quad N\} \tag{2}$$

where δ_i is the Delay Differentiation Parameter (DDP) of class i.

The WTP scheduler, on the other hand, originates from Kleinrock's *Time Dependent Priorities* queue [6]. Packets from different classes enter first-in-first-out (FIFO) queues, each associated with a DDP. The priority of each packet in the queue is dependent on its DDP, δ_i, and its waiting time in the queue. If $w_i^p(t)$ is the waiting time of a packet p of class i at time t, then its time-dependent priority $P_i(t)$ is given by

$$P_i(t) = w_i^p(t) \cdot \delta_i$$
$$w_i^p(t) = t - \tau^p \tag{3}$$

where τ^p is the arrival time of packet p.

The WTP scheduler always estimates the time-dependent priorities of the head-of-line packets in all queues and transmits the packet with the highest priority in a non-preemptive manner.

B. *WTP as an Enabler of the PDS Model*

In [5], the WTP algorithm has been shown to approximate closely the PDS model for heavily loaded wired networks with Pareto traffic source. The WTP scheduler is then further examined in [7] where the feasibility region of the scheduler is characterised and an iterative algorithm to determine the control parameters for obtaining the desired delay ratios is proposed. In [8], three WTP variants are proposed, namely *maximum* WTP (MWTP), *variance* WTP (VWTP) and *counting* WTP (CWTP), that besides achieving the PDS model objectives, also aim at reducing the absolute packet queueing delay by considering the packet waiting times and packet transmission times. A WTP scheduler that includes an adaptive parameterisation scheme is proposed in [9] to approximate the model in moderate load conditions. The Scaled Time Priority (STP) [10] is proposed as a WTP variant with lower complexity. In [11], a controller using fuzzy rules has been introduced to reduce the effect of low priority class upon higher priority ones in a proportional relative *DiffServ* network. Based on the well-known Little's Law, the authors in [12] propose a scheduling mechanism that jointly controls the delay and throughput metrics.

The PDS model has also attracted attention in the wireless domain. By taking into account the wireless channel errors, reference [13] presented the *wireless* WTP (WWTP) scheduler. It tries to achieve PDS by providing higher bandwidth compensation for higher priority classes when the channel is in error state. In [14], a cross-layer WTP (CWTP) scheduling algorithm (also named as *distributed* WTP (DWTP) [15]) has been presented for wireless local area network (WLAN). The Neighbourhood Proportional Delay Differentiation (NPDD) [16] model is another WTP variant on achieving PDS in the wireless domain. By keeping running averages of the delays for the local and neighbouring nodes, NPDD computes an index (ratio between local and neighbouring delays), which is then used to map to the fixed level of medium access control (MAC) priorities.

However, to the best of the authors' knowledge, this is the first work on realizing the PDS model in the satellite domain.

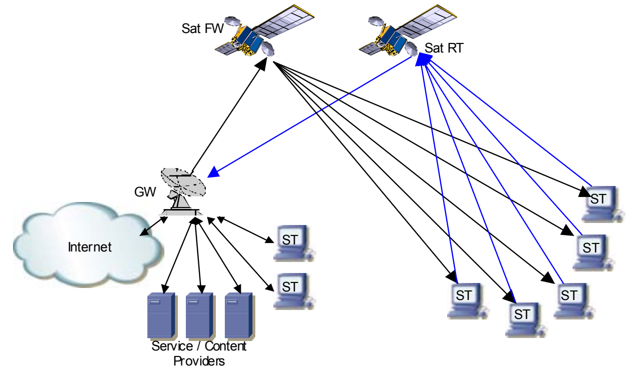

Fig. 1 Reference satellite system resembling the DVB-RCS architecture [17].

The WTP scheduler was first designed for terrestrial wireline networks. There, the scheduler only needs to schedule the departure of each contending packet *locally*. In wireless and satellite domain, the access to the transmission medium is often controlled in a distributed manner by a MAC protocol. Thereby packets from one node may contend with packets from other nodes, so that WTP scheduler variants proposed in the context of these networks cannot be applied directly to the satellite domain.

Moreover, there are several fundamental architectural and environmental differences that impede the adaptation of WTP variants proposed in terrestrial *wireless* networks to satellite networks supporting dynamic bandwidth allocation mechanisms. Firstly, for a bandwidth on demand (BoD)-based satellite architecture, resource has to be requested by the satellite terminals before they can make use of it, so that the scheduler ends up scheduling requests for resource rather than packets. Secondly, there is a non-negligible propagation delay between the satellite terminals and the scheduler that may, depending on the access control algorithm, inflate the waiting time of a packet in the queue of the satellite terminal. The impact of this semi-constant delay has to be taken into account by the scheduler in providing relative service differentiation.

III. System Architecture

The system architecture under consideration is an Internet Protocol (IP)-based broadband multimedia geostationary (GEO) satellite network with resource allocation mechanisms analogous to those described in the Digital Video Broadcasting – Return Channel via Satellite (DVB-RCS) system standard [17]. However, the discussion and the scheduler applicability are not limited to DVB-RCS networks. Fig. 1 illustrates the main nodes of the network architecture: -

- Satellite(s) – The satellite used is assumed to be equipped with on-board processor (OBP) and the scheduler is located on-board.
- Traffic Gateway (GW) – In line with the DVB-RCS definition, GWs are included to provide interactive services to networks (e.g., Internet) and service providers (e.g., databases, interactive games etc.).

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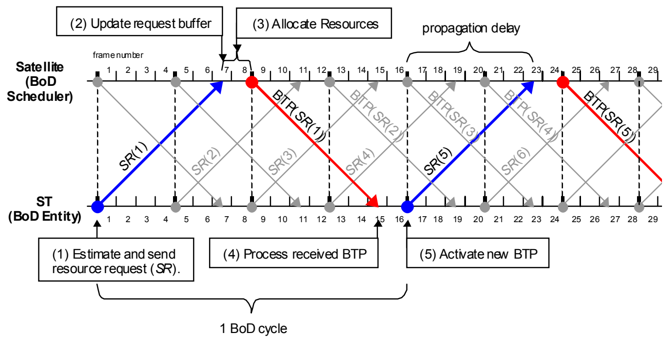

Fig. 2 BoD timing diagram

- Satellite Terminal (ST) – STs represent the users. They may serve one (residential) or more users (collective).

Time Division Multiple Access (TDMA) is used for the forward path whereas on the return path, Multi-frequency TDMA (MF-TDMA) is assumed. In a MF-TDMA frame, the basic unit of the link capacity is the TS with multiple TSs grouped in TDMA frames along several frequency carriers. In this paper, we consider fixed MF-TDMA frame whereby the bandwidth and duration of successive TSs is static.

The BoD process used in this work is derived from [18]. The procedure involves two main stages: the *resource request estimation* and *resource allocation*. The main entities involved are the BoD entity and BoD scheduler. The BoD entity is located at the ST and handles all packets of the same class, which are stored in the same queue i.e. there will be x BoD entities in a ST if this ST supports x classes. BoD entities periodically send slot requests (S*Rs*) to the BoD scheduler, when there are new packet arrivals at their queues. Upon reception of *SR*s, the BoD scheduler allocates TSs to each requesting BoD entity based on a certain scheduling discipline and policies set up by the network operator. It then constructs and broadcasts the burst time plan (BTP) that contains all the allocation information to the BoD entities. Both stages are repeated with a period equal to a multiple number of TDMA frames n_s, whilst one BoD cycle consists of k TDMA frames, where k is an integer multiple of n_s. Fig. 2 gives the BoD timing diagram, which also describes the basic tasks involved.

IV. SWTP Scheduling Discipline

A. Problem Statement

Consider a satellite network with M geographically distributed BoD entities serving N different service classes, each one associated with a DDP, δ_i. BoD entity m, responsible for service class i, periodically sends slot requests SR_i^m. Let $\bar{d}_i$ denote the average queueing delay for packets of class i. In this network, the bandwidth allocation task is formulated into an online resource management problem as follows:

"*Given a finite capacity C and the set of slot requests* $\{SR_i^m\}, 1 \le i \le N\ 1 \le m \le M$, *how does the BoD scheduler allocate resources to BoD entity m so that for a given set of DDPs,* $\{\delta_i\}$, *the PDS model objective of Eq. (2) is achieved.*"

B. SWTP Algorithm

We consider an adaptation of the WTP algorithm, called Satellite Waiting Time Priority (SWTP), as the BoD scheduler that will serve Eq. (2). The basic idea of SWTP is that instead of scheduling individual packets as in terrestrial networks, the SWTP schedules the resource requests *SR*s from BoD entities.

B.1. SWTP Resource Request Rules

Since the scheduler and the queues are not physically co-located, information regarding the waiting time of packets has to be communicated to the BoD scheduler. The BoD entity adds a timestamp to each request, which is used by the BoD scheduler to estimate the request priorities and schedule them according to (3) and (4). Here lies the second difference of our scheduler from other WTP variants. Since each *SR* is submitted for a batch of packets, i.e., the new arrivals within the latest resource allocation period (RAP), BoD entities have several alternatives for computing the *SR* timestamps. Unlike terrestrial networks, *SR* timestamps do not necessarily correspond to the arrival times of head-of-line packets as the SWTP determines the aggregate priority of the *whole* request.

Formally, if Q_i^m is the set of newly arrived packets, i.e. packets that came within the last RAP at the queue i of BoD entity m, $\mathbf{q}$ its cardinality, and τ_j the arrival time of packet j, $1 \le j \le q$, indexed in increasing order of arrival times, then the BoD entity m may compute at time $\boldsymbol{t}$ the *SR* timestamp ts_i^m using the subsequent rules:

1. According to the arrival time of the last packet that arrived in the queue during the last RAP: $ts_i = t - \tau_q$
2. According to the arrival time of the first packet that arrived in the queue during the last RAP: $ts_i = t - \tau_1$
3. According to the sample mean of the arrival times of all packets that arrived in the queue during the last RAP:
$$ts_i = t - \frac{1}{q} \cdot \sum_{j=1}^{q} \tau_j$$

The first rule corresponds to the "worst" case, since the request priority will be defined by the packet with the least waiting time in the queue. Conversely, the second rule maximizes the request priority by considering the packet with maximum waiting time in the queue (best case). The third rule is effectively a compromise between the former rules by considering the waiting times of all newly arrived packets.

B.2. SWTP Resource Allocation

The allocation process is centralized. The BoD scheduler computes the priority of each *SR* stored in the request buffer. The priority $P_i^m(k)$ allocated to SR_i^m at k^{th} RAP is given by

$$P_i^m(k) = \delta_i \cdot \left(w_i^{SR}(k) + \alpha\right) \tag{4}$$

whereby α is a constant added to the waiting time of packets to account for the propagation delay of BTP and the processing delay of BoD entities, while $w_i^{SR}(k) = t - ts_i^m$ and ts_i^m is the timestamp information encoded in each *SR* based on one of the resource request rules presented in section B.1. Compared to other WTP schedulers, there are two significant differences in the computation of the priority. Firstly, there is an addition of α to account for the exact packet transmission time due to the fact that there is non-negligible delay between the allocation time and the actual packet transmission time. Secondly, although the equation for $w_i^{SR}(k)$ remains unchanged, it must be noted that *t* here refers to the time when the BoD scheduler is actually computing the priority i.e., *t* no longer correspond to the packet service instance as in terrestrial network. Note that in the considered BoD system, the functions can be in terms of *k* instead of *t* due to the periodical nature of the system.

At each allocation period, the SWTP scheduler allocates TSs by considering requests in decreasing priority order: requests can be fully satisfied as long as they do not exceed the available capacity. Therefore, at k^{th} period, the SWTP will first allocate TSs to the *SR* with the highest priority among all *SR*s buffered at the BoD scheduler.

The process proceeds until all TSs for the MF-TDMA frame have been allocated. Those requests that are not considered or partially satisfied will be buffered for the next allocation period. When the next RAP arrives, the priorities of these buffered requests are recalculated to account for the additional waiting time of the request at the scheduler queue.

The algorithms executed by the BoD entities and scheduler are given in Table I and II respectively. At the BoD scheduler, the allocation process is divided into two steps. Firstly, for each request, a priority metric has to be computed. Then based on these priorities, TS allocations are determined. Finally, the allocation information is broadcast to BoD entities in the form of the BTP.

TABLE I: SWTP ALGORITHM FOR BOD ENTITIES

BEGIN (k = request time)
get the number of newly arrived packets in the current RAP, $q_i^m(k)$
compute resource request, $SR_i^m(k)$
read δ_i
compute $ts_i^m(k)$
send request packet [ST id, $SR_i^m(k)$, $ts_i^m(k)$, δ_i]
END

TABLE II: SWTP ALGORITHM FOR BOD CONTROLLER

BEGIN (k = allocation time)
for each request
{compute $P_i^m(k)$ based on $w_i^{SR}(k)$ and δ_i}
while (TS available)
{allocate $SR_i^m(k)$ TS to the request with the highest $P_i^m(k)$ unconsidered request}
buffer all unconsidered requests
broadcast new BTP
END

V. SIMULATION RESULTS

The capacities for all links in this paper are configured to be 2048kbps. Unless explicitly stated otherwise, the network is set to have DDPs: 1, 1/2, 1/4, 1/8. The IP packet size used in all simulation is 500 bytes, while MAC frames are of size 48 bytes with additional 5 bytes header. Unless explicitly stated otherwise, all simulations use Poisson traffic sources.

A. *Evaluation of Slot Request Rules*

Simulation runs of 100s with four service classes under all three *SR* estimation rules described in section IV (B.1) have been carried out. Fig. 3 plots the achieved differentiation ratio, normalized with respect to the target ratio δ_i/δ_j. Intuitively, the more complex rule 3 would perform most accurately. However, simulation shows that all three rules give similar performance in terms of achieving the accurate proportionality in delay. All of them yield ratios close to the ideal value (=1.0). Rule 1 actually achieves better performance though only very marginally.

The performance of each slot request rule has also been assessed in short-term. Fig. 4 shows the individual packet delay upon departure for all three rules i.e. the delay suffered by each packet when departing from the ST is logged down and plotted. Three observations can be made: -

1. Delay – All three achieve similar delay performances.
2. Consistency – only rule 1 satisfies the requirement "*higher class always performs better than lower class*". The requirement is violated by the other two rules.
3. Fluctuation – Comparatively, less fluctuation is seen for rule 1. Smaller packet delay deviations are generally desirable for real-time streaming video applications.

It is found that rule 1 performs the best. Firstly, it emulates most closely the PDS model; hence satisfying the "*controllability*" property of the model. Secondly, it performs consistently adhering to the order of different service class. Hence, it satisfies the "*predictability*" property of the model. Thirdly, it gives smaller packet delay variation. Therefore, it is the best option for real-time multimedia applications. From here onwards, all simulations use *SR* estimation rule 1.

B. *SWTP in Achieving PDS Model*

Fig. 5(a) shows the queueing delay for each service class, while Fig. 5(b) presents the corresponding delay ratios under constant bit rate traffic. The ideal value for the ratios is 0.5 for all cases. From the plotted results, it is clear that the SWTP scheduler can indeed emulate closely the PDS model.

Since the PDS model requires that the spacing between any two service classes adhere strictly to the ratio of the DDPs for specified service classes, the scheduler should not be dependent on the traffic distribution between service classes. Fig. 5(c) shows the result of this test at utilization, U=95%.

The ideal value is 0.5 and in all simulations, the achieved ratios are very near to this value.

C. Controllability of SWTP

This section illustrates the capability of SWTP in accurately controlling the spacing between different service classes. Three sets of DDPs have been defined below.

- Set A – [1, 1/2, 1/4, 1/8]
- Set B – [1, 1/2, 1/3, 1/4]
- Set C – [1, 1/4, 1/5, 1/6]

Simulations with U= 95% have been conducted based on these DDP sets and the results given in Fig. 6 shows the normalized ratios of all three cases. With the ideal value as 1.0, it can be concluded that SWTP indeed is able to control the class spacing. However, due to the long propagation delay, the spacing between the highest and lowest DDP should not be too large to ensure reasonable delay for the lowest class.

D. Predictability of SWTP

The behaviour of SWTP in short timescale is investigated to ensure that the predictability requirement of the PDS model is satisfied. Fig. 7 shows the individual packet delays upon departure of four-class scenario for a period of 100ms. The graph shows that SWTP can consistently provide the appropriate spacing for the service classes.

E. Feasibility Region of SWTP

Up to this point, the results given are all obtained from simulation runs under high network load. However, it is found that, similar to other WTP schedulers, SWTP suffers from the same problem of not being able to provide service differentiation when running under low load. Fig. 8 shows the delay ratios for a four-class network against different levels of network utilization. Similar to [5], SWTP cannot maintain the service class spacing defined by the DDPs when the network load is lower than 80%. Although the performance of each service class still maintains the pre-defined order, the spacing between the classes deviates from the settings provided. However, service differentiation is only needed when the network load is high. Forcing service differentiation by depriving customers of lower priority available bandwidth is unnecessary. Maximizing the utilization of satellite bandwidth is of greater importance here.

VI. Conclusions

This paper studies the problem of providing proportional service differentiation in GEO BoD satellite networks. It advocates the adoption of the proportional differentiation model within the satellite domain and proposes as well as evaluates a novel scheduler in this model context.

Simulation results show that the SWTP scheduler can serve the desired service differentiation model in different settings. Three slot request estimation rules have been devised and evaluated. It is found that rule 1 exhibits the best performance. Regarding resource allocation, the SWTP scheduler is shown to be capable of providing proportional service differentiation. It is also able to operate in conformance with two important properties of the PDS model; namely the *controllability* and *predictability* properties. The spacing between classes can be controlled via the DDP of each service class, while higher classes always performs consistently better than lower classes. The feasibility region of the scheduler has also been presented.

Acknowledgment

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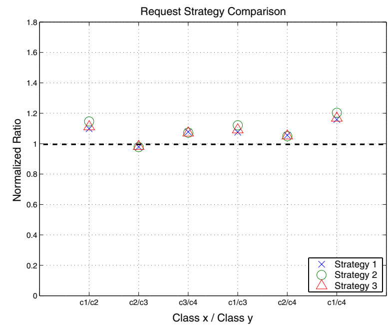
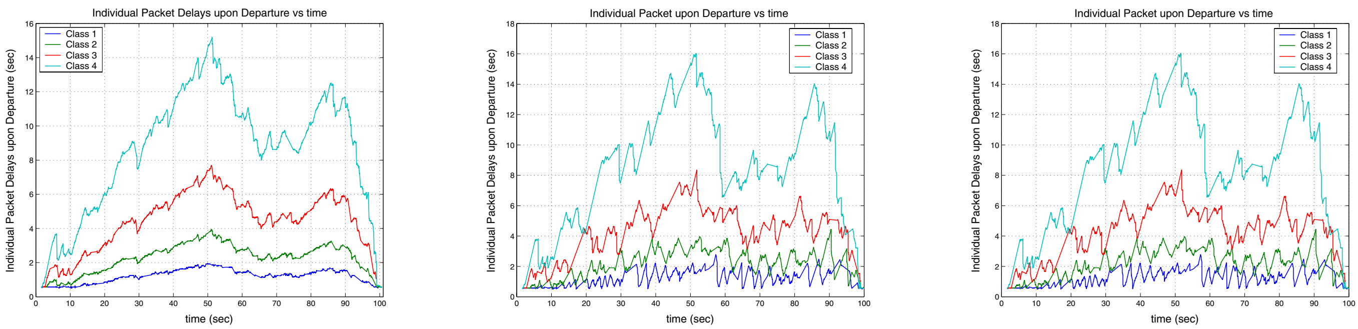
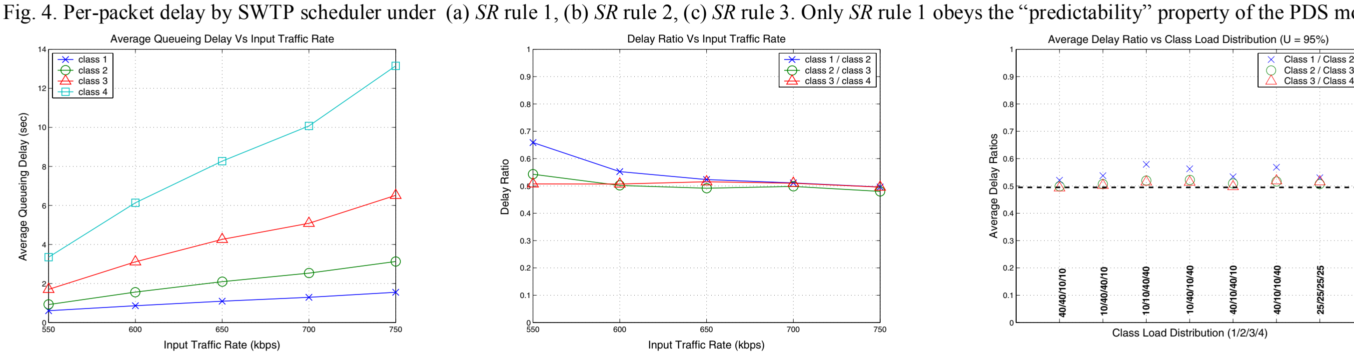


Fig. 3. The behaviour of the scheduler under the three *SR* rules is similar.



(a) (b) (c)

Fig. 4. Per-packet delay by SWTP scheduler under (a) *SR* rule 1, (b) *SR* rule 2, (c) *SR* rule 3. Only *SR* rule 1 obeys the "predictability" property of the PDS model.



(a) (b) (c)

Fig. 5. (a) Queueing delay of different service class following the specified spacing of the model; (b) the corresponding delay ratios achieved whereby they are closed to the ideal delay ratios; (c) SWTP emulating the PDS in different load distributions with all values achieved close to the ideal value.

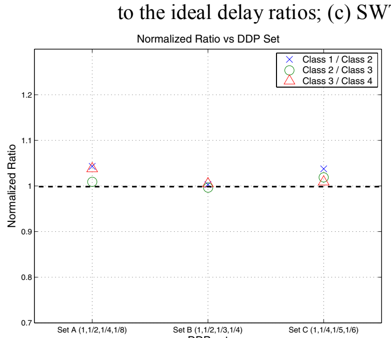


Fig. 6. SWTP with 3 sets of DDPs: all normalized delay ratios achieved are close to the ideal value

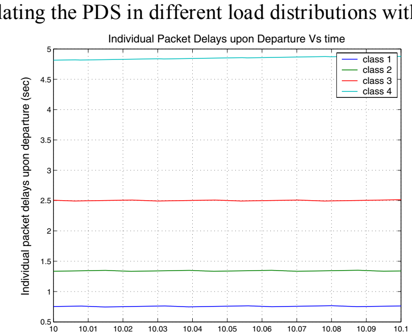


Fig. 7. Short time scale behaviour of SWTP showing its predictability property

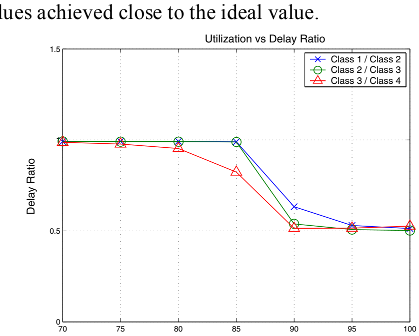


Fig. 8. Feasibility region of SWTP similar to other WTP schedulers