Providing Proportional TCP Performance by Fixed-point Approximations over Bandwidth on Demand Satellite Networks

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***Abstract*—In this paper we focus on the provision of proportional class-based service differentiation to transmission control protocol (TCP) flows in the context of bandwidth on demand (BoD) split-TCP geostationary (GEO) satellite networks. Our approach involves the joint configuration of TCP-Performance Enhancing Proxy (TCP-PEP) agents at the transport layer and the scheduling algorithm controlling the resource allocation at the Medium Access Control (MAC) layer. We show that the two differentiation mechanisms exhibit complementary behavior in achieving the desired differentiation throughout the traffic load space: the TCP-PEPs control differentiation at low and medium system utilization, whereas the MAC scheduler becomes the dominant differentiation factor under high traffic load. The main challenge for the satellite operator is to appropriately configure those two mechanisms to achieve a specific differentiation target for the different classes of TCP flows. To this end, we propose a fixed-point framework to analytically approximate the achieved differentiated TCP performance. We validate the predictive capacity of our analytical method via simulations and show that our approximations closely match the performance of different classes of TCP flows under various scenarios for the network traffic load and configuration of the MAC scheduler and TCP-PEP agent. Satellite network operators could use our approximations as an analytical tool to tune their networks.**

***Index Terms*—BoD GEO satellite networks, proportional differentiated services, TCP, fixed-point, proxy agents.**

I. Introduction

SATELLITE networks have long been integral parts of the Internet. Thanks to their inherent broadcasting capabilities that do not require large-scale infrastructure, they are particularly suitable for providing low-cost ubiquitous coverage even to the most remote rural areas. Traditionally, satellites have been deployed for television and radio broadcasting. Nowadays, satellite networks also present attractive alternatives for diverse applications such as emergency/crisis support, high speed vehicle communications (*e.g.*, trains) and content broadcasting to mobile users. Irrespective of the application in question, the seamless integration of satellite networks with the terrestrial Internet Protocol (IP)-based infrastructure bears important benefits: reuse of technologies, easier network deployment, and lower cost. Significant standardization effort in this direction has been carried out by the ETSI Broadband Satellite Multimedia (BSM) working group [1]. One of the requirements identified for future satellite systems is the ability to provide service differentiation to users.

Service differentiation has been mainly approached in two directions, *i.e.*, *absolute* and *relative*. Whereas Integrated Services (*IntServ*) [2] and Differentiated Services (*DiffServ*) [3] have been the most well studied frameworks, they have not seen large-scale deployment in terrestrial networks. Nevertheless there is stronger motivation for service differentiation in wireless access networks. The capability to charge the end-user in response to the offered level of service has long been sought after by satellite network operators. Such traffic class based charging requires consistent control of the performance difference amongst traffic classes. In particular, the tariff policies could be simplified considerably if the service differentiation has quantitative features; as a simple example, if traffic class i is configured to outperform traffic class $i+1$ by two times, class i users could be charged twice the price of class $i+1$ users. Related work in the area of satellite networks has investigated an IP-based satellite-terrestrial platform under the *IntServ* framework in [4] and a *DiffServ* gateway architecture featuring a joint resource management and marking mechanism in [5]. Focusing on the Medium Access Control (MAC) layer in IP-based broadband satellite access networks, Iuoras and Le-Ngoc describe in [6] a dynamic capacity allocation scheme for *DiffServ* support based on combined free/demand assignment multiple access.

In this paper, we investigate a specific *relative* service differentiation model, called proportional differentiated services (PDS) [7]; PDS effectively comes under a broader set of service differentiation frameworks that trade-off the service guarantees of *IntServ* with the scalability of *DiffServ* [8]. The model has been considered in a broad variety of networking contexts, including optical and multihop, wireless networks (*e.g.*, [9] and [10]); to the best of our knowledge, however, our work is the first one that addresses proportional service differentiation in Bandwidth on Demand (BoD) satellite networks. We apply the PDS model to transmission control protocol (TCP) flows traversing BoD split-TCP geostationary (GEO) satellite networks. What mechanisms should be in place in such networks to achieve the PDS model commitments? We answer this question focusing on the transport and MAC layers and proposing separate tuning knobs at both layers that can

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achieve the differentiation objective. The work in this paper adds to a broader study of service differentiation provision in GEO satellite networks [11].

The contributions of this paper are in the area of differentiated service provisioning. The addressed question is how to realize a specific quality of service (QoS) framework in the satellite domain. To this end, we first propose differentiation mechanisms at the satellite transport and MAC layers. We then derive *fixed-point* approximations to analytically predict the achievable performance differentiation. A common feature of fixed-point methods, when used in the context of TCP/IP networks, is the distinct analytical modelling of the TCP end sources and network resources (storage, link capacity), and the capture of their interaction into a non-linear system of equations. We expand here the vector-oriented formulation in [12] in three directions: (a) we incorporate asymmetric network paths, (b) we add broadcast and MAC-shared links to the network resource models, and (c) allow for multiple traffic classes. Our extensions result in a framework for analytical network performance investigation applicable to satellite networks. The aim is to provide the satellite operator with the means to tune the network so that the performance obtained by different traffic classes does obey the PDS model and supports class-based charging schemes.

In order to evaluate both our engineering approach and the predictive capacity of the fixed-point framework, we carry out a systematic simulation study that explores thoroughly the model parameter space. Inputs to our analytical method are existing models in the literature for both MAC and transport layer protocols. We use various kinds of plots to discuss the strengths and weaknesses of our work and support statements for its applicability. Our simulation results show that our differentiation framework is capable of achieving closely the PDS model. The analytical approximations also show good agreement with the simulation results throughout the space of traffic load values. The hard constraints on the predictive capacity of our analytical methods are rather set by the accuracy of the existing analytical models for TCP and MAC protocols.

The contributions of this work are also methodological. We illustrate the advantages that modest use of cross-layer approaches can have in satellite network engineering. In addition, we provide arguments in favor of the utility of TCP - Performance Enhancing Proxies (TCP-PEPs).

The reference system architecture considered in this paper is given in section II. We detail the differentiation mechanisms in section III. A generic framework for analytical performance investigation is detailed in section IV. In section V we outline the analytical models used at the transport and MAC layers and derive the fixed-point approximations. We evaluate and validate our analytical framework via extensive simulations in section VI. Finally, we conclude our paper in section VII by discussing the applicability spectrum of our approach and its limitations.

II. Reference Satellite Network Architecture

We consider a broadband GEO satellite network with resource allocation mechanisms similar to the DVB-RCS standards [13]. The network includes a network control center (NCC), which provides control and monitoring functions, satellite terminals (STs) and the satellite with an onboard BoD scheduler enabling mesh connectivity amongst STs. The multiple access scheme is multi-frequency time division multiple access (MF-TDMA); the transponder spectrum is divided into different frequency carriers shared in TDMA mode. The basic unit of link capacity is the timeslot, with multiple timeslots grouped in TDMA frames along several frequency carriers.

A. Bandwidth on Demand (BoD) Process

BoD mechanisms are deemed mandatory in current and future satellite networks. They offer high flexibility in supporting traffic with different requirements without sacrificing resource utilization. The BoD process considered here is drawn from [14] and involves the BoD entity and BoD scheduler. There is at maximum one BoD entity per traffic class at each satellite terminal. Packets of the same traffic class are stored in separate queues and handled by the respective BoD entity. The BoD scheduler is responsible for efficiently distributing the timeslots amongst satellite terminals. The BoD process consists of two functions that are executed periodically.

- *Resource request process* - As long as there are new packet arrivals at their queues, the BoD entities send resource (slot) requests (RRs) to the BoD scheduler with a period of n_s TDMA frames. If $q(k)$ are the queued packets at the BoD entity at the start of the k^{th} allocation period, then the RR sent to the BoD scheduler is given by

$$RR(k)=\left[\left(q(k) - n_s \cdot a(k) - n_s \sum_{j=1}^{L_s-1} RR(k - L_s + j) - n_s \cdot w(k)\right) \Big/ n_s\right]^+ \tag{1}$$

  In (1), $a(k)$ denotes the number of timeslots per frame already allocated to the BoD entity for the next n_s frames; $w(k)$ are the owed timeslots by the scheduler from previous resource allocation periods; L_s is the *nominal system response time* in frames, namely the time from the moment a BoD entity submits a request to the moment it receives its allocation. It accounts for the propagation, transmission and processing delays at the BoD entity and BoD scheduler. The *actual system response time* may well be higher than the nominal one, if the request cannot be served in the first encountered resource allocation period but rather has to be queued and served in subsequent resource allocation periods. $[v]^+ = v$ if $v > 0$ and 0 otherwise, ensuring that no resource request will be submitted if it is zero or negative.
- *Resource allocation process* - Upon the reception of RRs, the BoD scheduler allocates timeslots to each requesting BoD entity based on the scheduling discipline and policies set by the satellite operator. It then constructs and broadcasts the burst time plan (BTP) that contains the allocation information. Figure 1 outlines the BoD process timing.

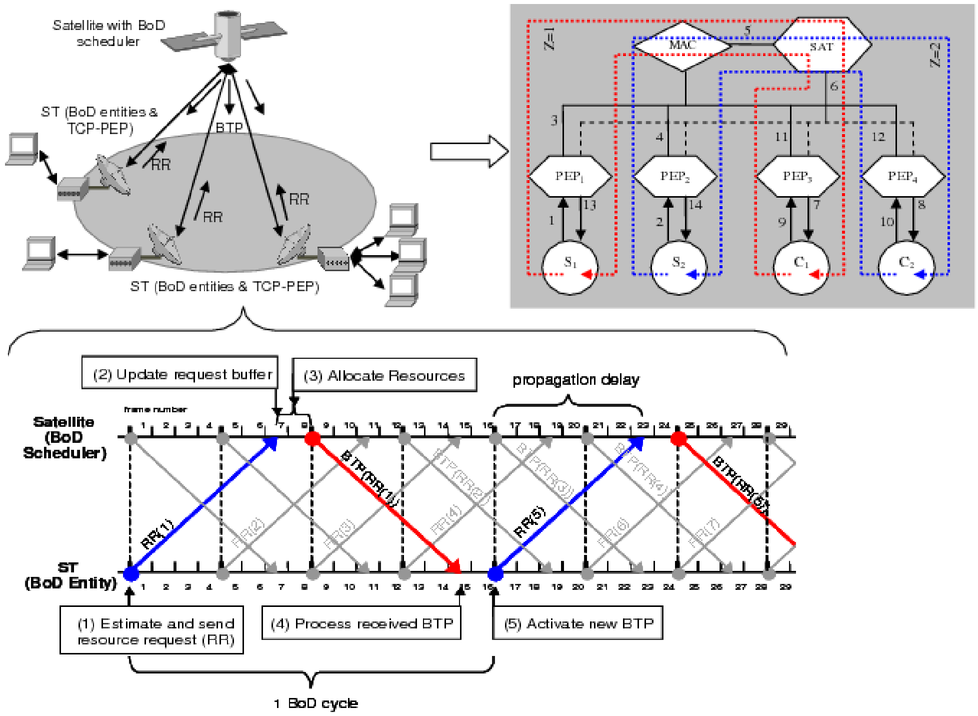


Fig. 1. BoD satellite network configuration with an example abstraction of the network for $Z = 2$ and $Y = 14$.

B. TCP-Performance Enhancing Proxy (TCP-PEP)

A TCP-PEP [15] is attached to each satellite terminal connecting to the satellite. TCP-PEP comes under a broader range of solutions proposed for enhancing the TCP performance in satellite environments; interested readers are referred to [16] and the references therein for comprehensive summaries of the problems and the respective solutions. Despite security and scalability concerns, TCP-PEPs have been widely deployed in satellite networks [17]. In general, the use of TCP-PEPs enables the deployment of specific mechanisms or even an entirely new transport protocol over the satellite links to address more efficiently their characteristics.

In our study, TCP-PEPs *split* the TCP connection into two components, the terrestrial and the satellite component. They store TCP segments and prematurely acknowledge their arrival resulting in faster progress of TCP connections [18]. We use the TCP-PEP as a tool to provide differential treatment to TCP connections of different classes and implement the PDS model. Figure 1 depicts the main physical nodes of our reference satellite network architecture.

III. Providing Proportional Performance to TCP Flows

A. The PDS model in general

Formally, consider a network supporting N service classes. Let r_i be the differentiation parameter (DP) attached to service class i, $1 \leq i \leq N$, which acts as a "tuning knob" for satellite operator to control the performance gap among service classes. If σ_i is the performance metric of interest for class i, *e.g.*, delay, throughput, packet loss, then the PDS model requires that

$$\frac{\sigma_i}{\sigma_j} = \frac{r_i}{r_j}; \quad \forall i, j \in \{1, \dots, N\}. \tag{2}$$

We follow the convention of numbering classes in decreasing priority order whereby class i has higher priority than class $i+1$ and normalize all DPs with reference to the highest priority class (*i.e.*, class 1), which is assigned DP equal to unity: $0 < r_N < r_{N-1} < \dots < r_2 < r_1 = 1$.

B. Applying the PDS Model to the TCP Treatment in Split-TCP Satellite BoD Networks

The TCP performance metric we consider here is the average TCP throughput; we seek to provide proportional throughput to TCP flows that are classified under different service classes. Applying the PDS model into our problem, we thus require

$$\frac{\overline{thr_i}}{\overline{thr_j}} = \frac{r_i}{r_j}; \quad \forall i, j \in \{1, \dots, N\} \tag{3}$$

where $\overline{thr_i}$ is the average TCP throughput of class i. For the rest of the paper, we refer to the term $\overline{thr_i}/\overline{thr_j}$ simply as throughput ratio; while the set of $\{r_i\}$ are called *throughput differentiation parameters* (TDPs). Note that the throughput metric is relevant to both persistent TCP connections and finite TCP transfers. In the second case, (3) implies that

$$\frac{D_i \cdot Lat_j}{D_j \cdot Lat_i} = \frac{r_i}{r_j}; \quad \forall i, j \in \{1, \dots, N\} \tag{4}$$

where D_i and Lat_i are the amount of transferred TCP data and time devoted to their transfer (latency) for connections of i^{th} class, respectively.

Analytical approximations in the literature give adequate insight to the parameters affecting the TCP throughput. The *inverse square root p law* (*e.g.*, [19]) provides a simplified model of the additive increase and multiplicative decrease (AIMD) flow/congestion control of TCP.

$$thr = \frac{W \cdot MSS}{RTT} = \frac{k_o}{\sqrt{p}} \cdot \frac{MSS}{RTT} \quad (5)$$

where W is the average TCP send window, p is the packet loss probability, MSS is the maximum segment size, RTT is the round trip time and k_o is a constant depending on the nature of loss and the use of the delayed acknowledgements option. In practical implementations, the connections are bounded by the maximum TCP send window W_{max}. The throughput equation is then written as

$$thr = min\left(\frac{W_{max} \cdot MSS}{RTT}, \frac{k_o}{\sqrt{p}} \cdot \frac{MSS}{RTT}\right). \quad (6)$$

Padhye *et al.* in [20] improved the model accuracy under high loss with a more complicated formula. We will subsequently refer to it as the *Padhye formula*. Both (6) and the *Padhye formula* were initially derived with persistent TCP connections in mind. Caldwell *et al.* in [21] reused this analysis and added a model for slow-start to approximate the time devoted to TCP data transfers for finite TCP connections.

The analysis suggests that the TCP throughput is basically dependent on (a) packet loss probability, (b) maximum send window, and (c) queueing delays since the propagation and processing delay contributions to RTT may be assumed constant for a given connection path. In broadband satellite systems the links are dimensioned to yield bit error rates in the order of 10^{-10}. In fact, current generation satellite radio interfaces such as DVB-S2 do so by deploying adaptive coding and modulation techniques [22]. Moreover, splitting the TCP connection at the border of the terrestrial and the satellite network practically isolate the respective parts of the connections. Backpressure techniques and TCP window control can be used to control the data in-flight over the satellite link and limit buffer overflow over what is in most cases the bottleneck of the overall connection [23].

With the loss term p tending to zero over the satellite part of the connection, its steady-state throughput can be written as

$$thr = \frac{W_{max} \cdot MSS}{RTT} = \frac{W_{max} \cdot MSS}{RTD + dq_F + dq_R} \quad (7)$$

for persistent TCP connections, where dq_F and dq_R are the queuing delays experienced in the forward and reverse (ACK) path in the satellite network and RTD is the round trip delay. Likewise, for finite TCP transfers, the equivalent average throughput over the connection duration would be written as the ratio of the transferred data size over the time devoted to the data transfer, as derived from the analysis in [21] for $p \to 0$.

Equation (7) and its counterpart for finite TCP transfers suggest that one class of TCP connections may obtain better performance than another if one or both of the following conditions are met: a) when they experience lower delays at the MAC scheduler during the resource allocation process, and/or b) when the maximum send window of the satellite part of the TCP connections is set to a higher value. Therefore, differentiation of the TCP performance is feasible via tuning parameters at the MAC and transport layer. The difficulty arises when we want to do this consistently and quantitatively, *i.e.*, to achieve a predefined relative performance differentiation that will be robust to traffic load changes. In the following two subsections, we present our approach to this problem.

C. MAC Layer Differentiation Mechanism

The bandwidth allocation at the MAC layer is carried out by the Satellite Waiting Time Priority (SWTP) scheduler [24]. The SWTP scheduler is a variant of the WTP scheduler first proposed by Kleinrock [25]. It is a non-preemptive, work-conserving scheduler that enforces proportional queueing delays for different traffic classes at the MAC buffers. One problem with the WTP is that the achieved delays approximate the target delay ratios only under heavy load. Leung *et al.* [27] showed that the feasible delay ratios depend on the link utilization and derived the proper configuration of the scheme for a feasible target delay ratio as a function of the link utilization. The SWTP scheduler schedules RRs from BoD entities rather than individual packets as with the WTP scheduler. Formally, if Q_i is the set of newly arrived packets at the queue of the BoD entity i, *i.e.*, packets that came within the last resource allocation period, q the set cardinality, and τ_j the arrival time of packet j, $1 \leq j \leq q$, indexed in increasing order of arrival times, then the BoD entity m computes at time t the RR timestamp ts_i^m according to the arrival time of the last packet that arrived in the queue during the last resource allocation period, namely: $ts_i = t - \tau_q$.

The BoD scheduler computes the priority of each RR, $P_i^m(k)$ at k^{th} resource allocation period as

$$P_i^m(k) = r_i^D.(w_i^{RR}(k) + \alpha) \quad (8)$$

where α accounts for the propagation delay of the BTP and the processing delay in BoD entities, while $w_i^{RR}(k) = t - ts_i^m$ and ts_i^m is the timestamp encoded in each RR. The set of $\{r_i^D\}$ are called hereafter delay differentiation parameters (DDPs), r_i^D, $1 \leq i \leq M$, where M is the total number of MAC layer classes. At each allocation instance, the SWTP scheduler allocates timeslots by considering requests in decreasing priority order. Requests can be fully satisfied as long as they do not exceed the available capacity. The time slot allocation proceeds until all timeslots within the MF-TDMA frame have been allocated. Those requests that are not satisfied will be buffered onboard. The priorities of these buffered requests are recalculated in the next allocation instance to account for the additional waiting time of the pending requests at the scheduler queue.

D. Transport Layer Differentiation Mechanism

We use W_{max} as the differentiation parameter for the satellite part of the TCP connections. This way our scheme becomes independent of the actual TCP variant used. Similar to section III.C, we define a set of *window differentiation parameters* (WDPs), $\{r_i^W\}$, where L is the number of transport layer classes, each mapped to a single W_{max} value. Again, applying the PDS model to the satellite domain, we can now write

$$\frac{W^{sat}_{max,i}}{W^{sat}_{max,j}} = \frac{r^W_i}{r^W_j}; \quad \forall i, j \in \{1, \ldots, L\} \tag{9}$$

where $W^{sat}_{max,i}$ is the W_{max} of the class i connections within the satellite segment, namely between the two bordering TCP-PEPs of the connection.

For simplicity, we assume that the number of service differentiation levels at MAC and transport layers is equal to the total number of TCP traffic classes supported within the network:

$$L = M = N. \tag{10}$$

Under these assumptions, the problem may be stated as follows:

"In a split-TCP capable BoD satellite network, how should one jointly set the WDPs at the TCP-PEPs and the DDPs at the MAC scheduler, so that for a given set of TDPs, $\{r_i\}$, the PDS model objective of (3) can be achieved?"

IV. Generic Framework for Analytical Performance Investigation

In this section, we introduce the main equations that capture the interaction between end sources and network elements. The formulation uses matrix notation, as in [11] and [12]. Here we expand the method for scenarios involving multiple traffic classes. Figure 1 shows how the satellite network topology can be schematically abstracted to assist the derivation of the system of equations. The figure shows two TCP server (S)-client (C) pairs connected via satellite and TCP-PEPs across the available links via separate routes. Let Y_{link} and Z_{route} be the sets of network links and routes (paths) of TCP connections, respectively. Then each element of Z_{route} is the union of one or more elements of Y_{link}. Further, Y and Z are their cardinalities; $Y = |Y_{link}|$ and $Z = |Z_{route}|$. Each network path is traversed by a finite number of TCP connections of class i, n_i, which contribute to the actual load seen by all links on this path. The aggregate per link load, summed over all N traffic classes can be expressed as

$$\mathbf{b} = \sum_{\mathbf{i=1}}^{N} \mathbf{b_i} = \sum_{\mathbf{i=1}}^{N} \left(\mathbf{s^T_{F,i}} \cdot \overline{\mathbf{V^i_F}} + \mathbf{s^T_{R,i}} \cdot \overline{\mathbf{V^i_R}} \right) \tag{11}$$

where $\overline{\mathbf{V^i_F}}$ and $\overline{\mathbf{V^i_R}}$ are the $Z \times Y$ *traffic-thinning* matrices for the forward and reverse paths of the TCP connections. Each row of the matrices corresponds to one path. The row element (z, y) expresses the thinning that traffic of path z is subject to when crossing link y. Thinning may be due to link loss or link buffer overflow and is different for each traffic class, depending on the respective scheduling disciplines and buffer management policies deployed on each link.

The $1 \times Z$ vectors $\mathbf{s_{F,i}}$ and $\mathbf{s_{R,i}}$ denote the total send rate for the forward and reverse paths, measured in bytes, respectively, of class i connections across the Z paths in the network. Note that one or more TCP connections may share the same path, so that the vector of the per-path aggregate send rates of class i connections can be written as the product of the number of connections over the path, n_i, times the send rate SR achieved by each connection,

$$\mathbf{s_{F,i}} = \mathbf{n_i} .\cdot \mathbf{SR_i}(\mathbf{W_{max,i}}, \mathbf{MSS_i}, \mathbf{p_i}, \mathbf{RTT_i}) \tag{12}$$

$$\begin{aligned} \mathbf{s_{R,i}} =& \mathbf{n_i} .\cdot \mathbf{SR_i}(\mathbf{W_{max,i}}, \mathbf{MSS_i}, \mathbf{p_i}, \mathbf{RTT_i}) \\ & .\cdot (\mathbf{1} - \mathbf{p_i}) .\cdot \mathbf{u} .\cdot \frac{\mathbf{MSS^{ACK}_i}}{\mathbf{MSS_i}} \end{aligned} \tag{13}$$

where the notation $.\cdot$ denotes element-wise multiplication. The TCP send rate formulas, $SR(\cdot)$, are functions of the TCP maximum send window, W_{max}, and the maximum segment size MSS; the send rates in the reverse path are functions of the ACK packet size, MSS^{ACK}, the *residual* send rates of TCP connections, and the use of the delayed ACK option of TCP, captured in vector $\mathbf{u}$. The vector $\mathbf{p_i}$ represents the end-to-end path losses experienced by TCP senders of class i on the network paths.

Finally, the overall RTTs of class i TCP connections, including the propagation, queuing and processing delays suffered by TCP segments in the forward direction (from TCP server to client) and ACK packets in the reverse direction (the path of ACK packets) are given by the vector

$$\mathbf{RTT_i} = (\overline{\mathbf{A_F}} + \overline{\mathbf{A_R}}) \cdot \mathbf{dq_i} + \mathbf{RTD} \tag{14}$$

where $\overline{\mathbf{A_F}}$ and $\overline{\mathbf{A_R}}$ are the $Z \times Y$ *routing matrices* for the forward and reverse paths, respectively. Both matrices are binary; their $(z, y), 1 \leq z \leq Z, 1 \leq y \leq Y$, element is unity when link y is included in path Y and zero otherwise. The $Y \times Z$ $\mathbf{RTD}$ vector refers to the round-trip propagation delays and $\mathbf{dq_i}$ is the $Y \times Z$ vector of queueing/MAC access delays experienced by class i packets at the output buffers of the Y links. Queueing delays are directly dependent on the offered load and the link capacities. Thus we derive the vector $\mathbf{dq_i}$ through formulas f of input load, $\mathbf{b}$, and link capacity vectors, $\mathbf{c}$:

$$\mathbf{dq_i} = f(\mathbf{b}, \mathbf{c}). \tag{15}$$

Summarizing, input data to this approach are the satellite network topology, as captured in the routing matrices, the TCP connection parameters, and the network link capacities. These are then used by the equations that approximate the TCP throughput and the performance (delay, loss) at the network links. The solution of this system of equations gives the steady-state solution for the achieved end-to-end TCP throughputs and the delay/loss experienced at network links.

V. Analytical Models and Fixed-point Formulation

The starting point of our derivation is (15). Writing (15) for the shared satellite link lying in the path of all TCP connection classes, we get:

$$dq_i^{sat} = f_i^{sat}\left(\sum_{j=1}^{n_i} SR_i(W_{max,i}, MSS_i, p_i, RTT_i) \cdot \left(1 + \frac{(1+p_i)\cdot u \cdot MSS_i^{ACK}}{MSS_i}\right), c^{sat}\right) \quad (16)$$

The missing blocks for the system of Equations (11)-(16) are the analytical expressions $f_i^{sat}(\cdot)$ for the access delays experienced by different traffic classes over the satellite link, and $SR_i(\cdot)$ for the TCP send rates. We address them in the following two subsections.

A. Analytical Model of the SWTP Scheduler

Analytical models for satellite MAC have several restrictions. Almost all of them assume Poisson traffic arrivals and uniform traffic distribution across satellite nodes. Very few, if any, address dynamic traffic prioritization mechanisms. This shortage of models in literature is effectively a hard constraint to our approach and generally to any analytical effort to predict MAC-level performance.

For our SWTP scheduler, we exploit Kleinrock's analysis for time-dependent priorities queue in [25] and the complementary work on the scheduler characterization in [27]. A clean closed-form expression for average queueing delay for class i, dq_i[1], is derived in [25] for the WTP scheduler as

$$dq_i = \frac{[dq_o/(1-\rho)] - \sum_{j=1}^{i-1}\rho_j dq_j[1-(r_i^D/r_j^D)]}{1-\sum_{j=i+1}^{N}\rho_j[1-(r_j^D/r_i^D)]}; \quad i = 1, \ldots, N \quad (17)$$

where dq_o is the mean residual service time observed by a packet and the link utilization, ρ, is the sum of utilizations due to the individual traffic classes, $\rho = \sum_{i=1}^{N}\rho_i$. If $\overline{x_i}$ is the mean service time of class i and $\overline{x_i^2}$ its second moment, then $dq_o = \sum_{i=1}^{N}(\rho\overline{x_i^2}/2\overline{x_i})$.

Compared to the original algorithm, our SWTP scheduler differs in two aspects: (1) unlike in terrestrial networks, there is non-negligible propagation delay between the allocation time and the actual packet transmission time and (2) in the BoD system, the time when the BoD scheduler is actually computing the priority no longer corresponds to the packet scheduling instance. Also, assuming fixed packet size, then $\overline{x_i^2} = (\overline{x_i})^2$. Taking these into account, we rewrite dq_o as

$$dq_o^{'} = \sum_{i=1}^{N}((\rho_i\overline{x_i}/2) + RTD). \quad (18)$$

Figure 2 compares the original and adapted analytical models for utilization 80%. In Figure 2(a), we compare the two by varying the WDP setting for three DDP sets. The throughput ratios approximated from the original model overlap with each other for all the computed DDP sets. Conversely, with the adapted model, we see distinct separation among the different DDP set values. Apparently, without our adaptations, the original analysis in [25] is unresponsive to changes of the DDP knob. Further, Figure 2(b) reinforces our observation that the results from the original analysis are solely dictated by the WDP knob. From the equations above, we can compute the queueing delays for all service classes if we know the load from each class, ρ_i, which is dependent on the number of TCP connections in each class and their respective send rates.

[1]The convention used for numbering classes in [25] is reversed compared to ours in this paper, hence the difference in the equation.

B. Analytical Model of the Transport Layer Differentiation

The TCP send rate is governed by the congestion window (*cwnd*), whose value is determined by the slow-start and congestion avoidance phases, as well as the fast retransmit and fast recovery algorithms. For short-lived TCP connections, it is important to model slow-start accurately. For persistent TCP connections, which mainly operate in the congestion avoidance phase, the contribution of the slow-start phase may be negligible. Thus, they require different treatment. In the following, we focus on persistent TCP connections and discriminate between two scenarios:

1) Error-free satellite links: We use (7) in this work with modifications to reflect the effect of our mechanism on different classes of TCP connections.

$$SR_i = \frac{W_{max,i}^{sat}\cdot MSS}{RTD + 2dq_i^{sat}}. \quad (19)$$

The satellite link utilization can then be written

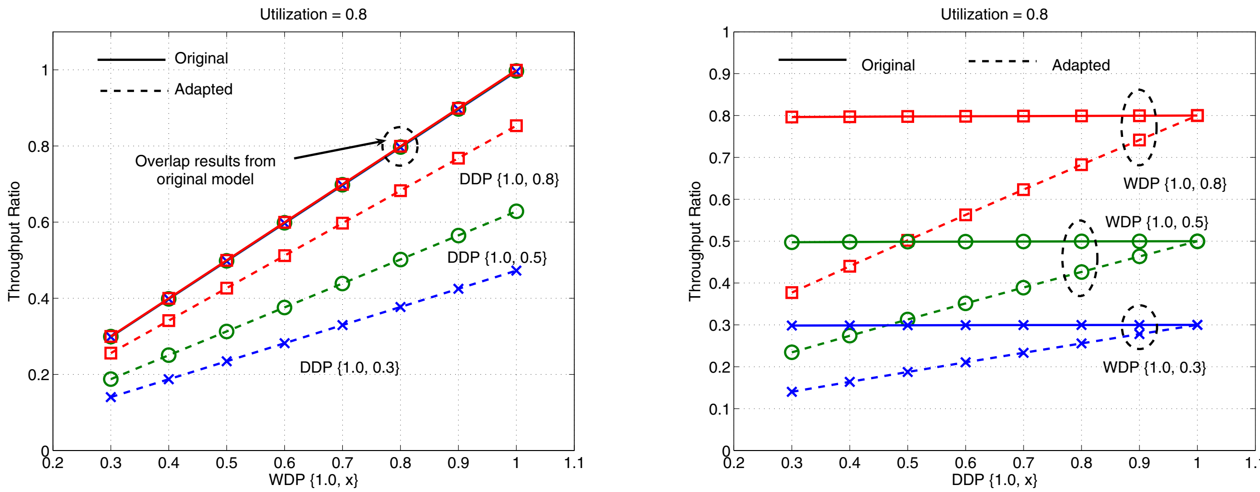
$$\rho = \left[\frac{(1+f)}{c^{sat}}\right]\sum_{i=1}^{N}\frac{n_i\cdot W_{max,i}^{sat}}{RTD + 2dq_i^{sat}} \quad (20)$$

where $f = MSS_i/MSS_i^{ACK}$ is the contribution of ACK packet traffic to the overall satellite link load.

2) Error-prone satellite links: The derived *inverse square root p law* for TCP throughput in [19] addresses packet loss due to buffer overflow, exhibiting periodicities. The TCP throughput under random loss has also been widely investigated. For example, Lakshman and Madhow formulate the problem in fixed-point terms in [26] for TCP Tahoe and Reno variants, whereas Casetti and Meo in [28] derive a continuous Markov Chain for the congestion window evolution of Reno connections. Nevertheless, both approaches call for use of numerical methods, which complicate their direct use in our analytical framework.

The *Padhye formula*[2] instead provides a computationally cheaper approximation for the TCP send rate. Instead of (19) and (20), we now have (21) (see next page) for the TCP send rate, and

[2]Padhye *et al.* look into TCP operation at the level of a round, with each round corresponding to the transmission of the whole window of TCP segments. Two of their main modelling assumptions are that losses between different rounds are independent and losses within the same round are correlated (*e.g.*, if one packet of the current window of data flying gets lost, then all subsequent get lost). Whereas this could be seen as an attempt to capture the burst loss pattern often related to DropTail routers, it does not hold for Random Early Drop (RED) schemes. On the contrary, the model could fit very well the loss patterns viewed over a wireless link if the duration of burst loss is mapped to the coherence time of the wireless channel.



(a) (b)

Fig. 2. Comparing the approximated differentiation between the original WTP equations and our adapted analytical model at utilization = 0.8; (a) Original model unable to predict differentiation for different settings of DDP; (b) The results from original model are dominated by the effect of WDP knob alone.

$$SR_i = min\left(\frac{W^{sat}_{max,i}}{RTT_i}, \frac{1}{RTT_i\sqrt{\frac{2up}{3}} + T_o\, min\left(1, 3\sqrt{\frac{3up}{8}}\right) p(1+32p^2)}\right) \quad (21)$$

$$\rho = \frac{1}{c^{sat}} \cdot \sum_{i=1}^{N} n_i \cdot SR_i \cdot [1 + f \cdot (1 - p_i)] \quad (22)$$

for the satellite link utilization, respectively, where T_o is the TCP base timeout value, u accounts for the use of delayed acknowledgments and $RTT_i = RTD + 2 \cdot dq_i^{sat}$.

C. Fixed-Point Formulation and Solution Existence/Uniqueness

In this section, we explore the existence and uniqueness of the solution for the system of Equations (17)-(20) for error-free satellite links and system of Equations (17)-(18) and (21)-(22) for the non error-free satellite links.

With some algebraic manipulations, the two sets of equations can be written in the form $\mathbf{dq} = \mathbf{f}(\mathbf{dq})$, *i.e.*, we get fixed-point equations on the vector dq. Making statements for the solution of these equations by drawing on known results from fixed-point theory is not straightforward; for example, since dq does not vary in the closed interval $[0,1]^N$, we cannot invoke Brouwer's theorem [29] to directly enforce the solution existence. Moreover, the complexity of the equations for arbitrary N does not permit a rigorous proof via their algebraic treatment.

Nevertheless, we can make the following remarks. Consider the function $\rho = f_1(dq_1, dq_2, \ldots, dq_N) = f_1(\mathbf{dq})$ yielding the link utilization from the MAC point of view. The function f_1 is *strictly monotonically increasing* in $\mathbf{dq}$; its minimum value is obtained for $\mathbf{dq} = 0$ and equals $f_1(\mathbf{0}) = f_1^{min} = 0$; whereas as $\{dq_i\}$ grow larger, $f_1(\mathbf{dq})$ tends asymptotically to its maximum value, *i.e.*, unity: $f_1^{max} = lim_{\mathbf{dq}\to\infty} f_1(\mathbf{dq}) = 1$. The plot of f_1 is an (N+1)-dimensional surface.

On the other hand, the function $\rho = f_2(dq_1, dq_2, ..., dq_N) = f_2(\mathbf{dq})$, for the link utilization according to the TCP equations, as (20) suggests, is *monotonically decreasing* in $\mathbf{dq}$. Its maximum value is obtained for $\mathbf{dq} = 0$ and equals to equation (23) (see next page) whereas it tends to 0 as $\{dq_i\}$ grow to infinity, namely $f_2^{min} = lim_{\mathbf{dq}\to\infty} f_2(\mathbf{dq}) = 0$. In general, the intersection of the two surfaces is a (N+1)-dimensional curve. However, when fixing all other parameters, $\{\rho_i\}$ values univocally determine the $\{dq_i\}$ values, each one of them cutting one dimension from the intersection curve and eventually yielding a unique point $\{\rho^*, \mathbf{dq}^*\}$ in the (N+1)-dimensional space.

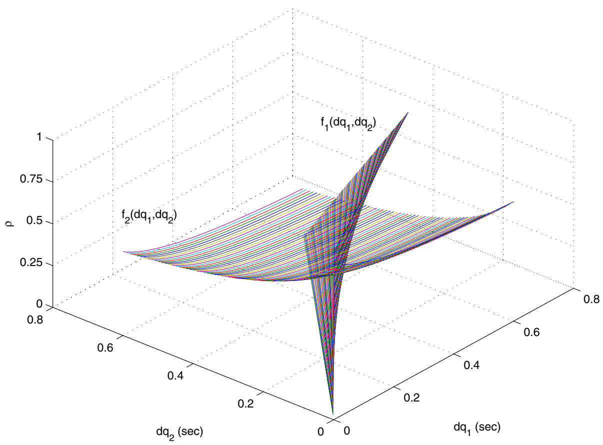
In other words, under given $\{W_{max,i}, N_i, RTT_i, p_i, f, b_i, \rho_i\}$ values, the intersection of the two (N+1)-dimensional surfaces f_1 and f_2, which are oppositely monotonical over $\{dq_i\}$ with $f_2^{max} = f_2(0) > f_1(0) = f_1^{min}$ and $lim_{\mathbf{dq}\to\infty} f_2(\mathbf{dq}) = f_2^{min} < f_1^{max} = lim_{\mathbf{dq}\to\infty} f_1(\mathbf{dq})$, $\{\rho, dq_1, dq_2, \ldots, dq_N\}$ is a single point in the (N+1)-dimensional space of $\{\rho, \mathbf{dq}\}$. We exemplify this for $N = 2$ in Figure 3.

Note that in all problem settings that were numerically solved with MATLAB, we did not run across more than one solution, irrespective of the point chosen in the initialization step; in the worst case, convergence was achieved within a couple of decades of iterations.

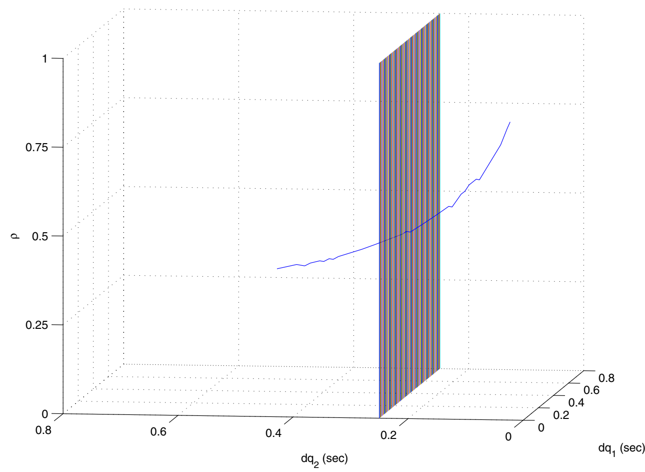
VI. Performance Evaluation and Method Validation

Having formulated all the required components of our analytical method, we show how we use it to achieve a given set of target TCP throughput ratios. Our fixed-point approximations

$$f_2^{max} \quad = \quad f_{2|\mathbf{dq}=0} = min\left(1, \frac{1}{c^{sat}} \cdot \sum_{i=1}^{N} n_i \cdot SR_i(W_{max,i}, MSS_i, p_i, RTT_i | dq_i = 0) \cdot [1 + f \cdot (1 - p_i)]\right) \tag{23}$$



(a)



(b)

Fig. 3. Graphical solution of equations (17)-(20) for $N = 2$. In the general case, the 3-dimensional surfaces $f_1(dq_1, dq_2)$ and $f_2(dq_1, dq_2)$ intersect along a 3-dimensional line (a). Specific per-class utilization values ρ_1 and ρ_2 , point to constant values of dq_1, dq_2 respectively, according to (20). For example, the plane corresponding to a given dq_2 value intersects the 3-line to a single point, which is the solution of the equations.

require inputs regarding both the satellite network and users, such as the vector representation of the network topology, policies regarding the treatment of network traffic, and number of TCP connections from different service classes. These are used to compute the required WDP and DDP sets, which in turn are used to configure the transport and MAC layers in the satellite network. Ideally, the achieved throughput ratios thr_i/thr_j obey the target TDPs.

A. Configuring Differentiation Parameters with the Fixed-point Approximations

The tuning knobs available to the satellite operator are the WDP and DDP sets; they control the differentiation at transport and MAC layer, respectively. Their combined effect determines the performance spacing. We exemplify the approach for $N = 2$.

For the transport layer differentiation, besides the WDP set, $\{r_i^W\}$, the fixed-point approximations must also compute the *exact* values of the $W_{max,i}$. If the network is lightly loaded, the satellite operator would assign higher $W_{max,i}$ values to the TCP connections to avoid bandwidth wastage. Otherwise, the satellite operator wants to limit the overall input load of TCP connections in the network by setting the $W_{max,i}$ to proportionally lower values.

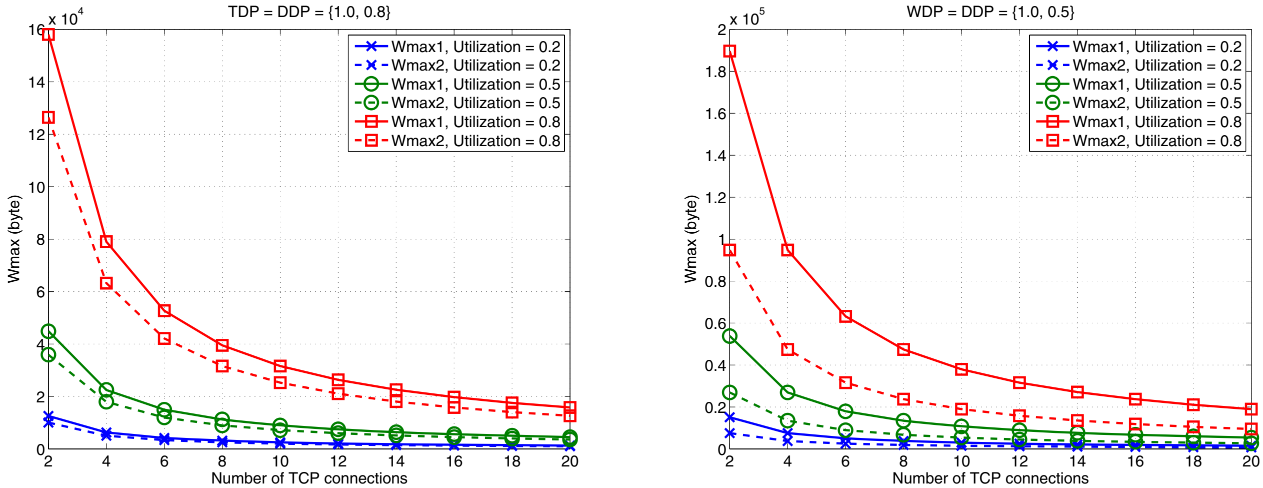
Figure 4 plots the $W_{max,i}$ values computed by the fixed-point method for a range of utilization requirements when $n_1 = n_2$. The results are rather intuitive and logical:

- The higher the number of connections, the lower the computed W_{max} for any utilization value
- The higher the satellite link utilization needed, the bigger the W_{max} values

In addition to that, the W_{max} values are also proportional for the classes according to the WDP settings. The fixed-point method approximates a throughput ratio for each set of these settings. Hence, the satellite operator can match the required performance spacing and apply the parameters to the real network.

B. Simulation Setup

We use simulation to validate our analytical method. We extend the *ns2* [30] with BoD capabilities, the SWTP scheduler and include a new TCP-PEP agent that splits TCP connections. Our transport layer differentiation mechanism is built into this agent. The simulation parameters are listed on Table I. We simulate a star network topology as shown in Figure 1, where the bottleneck is assumed to be at the satellite part of the topology. The terrestrial links are configured to be 2048 kbps while the satellite up/downlinks are set to 512 kbps. TCP NewReno with the delayed acknowledgements option turned off is used for our experiments. The TCP segment size is 576 bytes and each segment is fragmented into 48 byte MAC frames with 5-byte header at link layer. The link buffer is set to be large enough to absorb the TCP bursts, thus avoiding link layer losses. Each TDMA frame period is 24 ms and four TDMA frames form a super-frame. Each point in the graphs represents the average value of 30 simulation runs; each run corresponds to the same setting, only each TCP connection starts randomly within a window of 1 s. For each simulation, we utilize a different predefined "good" seed of the *ns2* for generating the connection start times. The graphs also plot the 95% confidence intervals of the computed averages.



(a) (b)

Fig. 4. W_{max} values computed by the fixed-point method for two differentiation settings under different link utilization values; solid and dashed lines correspond to class 1 and class 2 connections, respectively.

TABLE I
SIMULATION PARAMETERS

Parameter	Simulation Value
Number of classes	2
Simulation time	150 s
Terrestrial link	2048 kbps
Satellite up/downlink	512 kbps
MAC frame size	48 bytes
MAC frame header	5 bytes
TDMA frame period	24 ms
Super-frame period	96 ms or 4 TDMA frames
Rate granularity	16 kbps
Timeslot per TDMA frame	32
TCP segment size	576 bytes
TCP type	NewReno
TCP timer granularity	100 ms
TCP timestamp option	On
TCP Delayed Acknowledgements Option	Off

C. Analytical Method Validation: DDP

Since two tuning knobs are available, we examine them separately. We first investigate how the DDP set affects the TCP throughput ratios and compare them with the predicted ratios by the fixed-point approximations. The results are given in Figure 5.

We carry out simulations under low, moderate and high load conditions to ensure that our solution can indeed approximate the target performance spacing. From Figure 5, we see that the simulation results closely match the analytical results. At low load the simulated throughput ratio is practically constant for all DDP values, confirming that for low load the SWTP scheduler has almost no impact. We can also explain this mathematically. Substituting (19) to (8), we have

$$\frac{r_i}{r_j} = \frac{W^{sat}_{max,i}}{W^{sat}_{max,j}} \cdot \frac{RTD + 2dq^{sat}_j}{RTD + 2dq^{sat}_i}. \tag{24}$$

For $i < j$, and ignoring the $W^{sat}_{max,i}$ terms for the moment, we can see that the bigger the difference between dq^{sat}_i and dq^{sat}_j, the bigger the throughput ratio will be. Since dq^{sat}_i and dq^{sat}_j are almost equal at low load, the gradient for given WDP is expected to be near zero. In other words, at low load, the transport layer differentiation mechanism alone suffices to produce the required performance spacing. The analytical curves follow this trend, although they appear to be slightly more sensitive to the DDP changes than the simulation curves.

As the load increases, we see in Figures 5(b) and (c) that the gradients of the curves increase, signifying the increasing impact of DDPs on the differentiation. The analytical approximations do track closely the simulation results across the DDP parameter space. The deviation between the two sets of curves is higher for medium link utilization values. This is where the inaccuracy of the used source and resource models becomes more evident. For example, the TCP model does not take into account the effect of the slow-start phase of TCP connections; whereas, the assumption of Poisson packet arrivals in (17) cannot capture the burstiness of TCP traffic. In short, the more realistic the models used, the more precise the match of the fixed-point approximations with the simulation results will be.

D. Analytical Method Validation: WDP

We repeat the procedure in section VI.C, this time varying the WDP values instead of the DDP values. The results are presented in Figure 6. Overall, the simulated results follow closely the general trend of the analytical results and call for similar remarks. At low load, the simulated throughput ratios overlap for different DDP settings since, as mentioned earlier, the SWTP scheduler has minimal impact at low load. The analytically obtained curves capture this trend adequately.

Likewise, the trend is captured, only with less accuracy, for medium link utilization and at saturation area underlining the potential for improvement from the use of better models for the behavior of TCP sources and MAC protocol.

Finally, we compute the simulated average throughput of each class from 30 simulation runs and compare with the mean

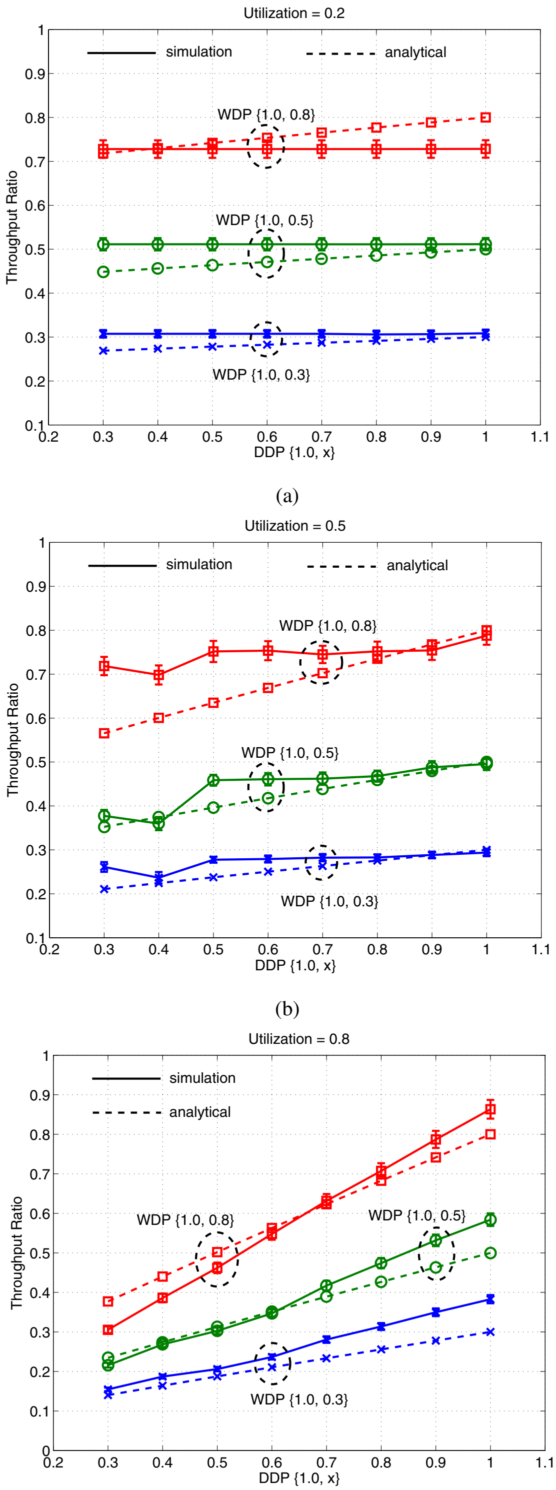


Fig. 5. Analytical approximations versus simulation results under varying DDP settings for three levels of utilizations; (a) Utilization = 0.2, (b) Utilization = 0.5, (c) Utilization = 0.8.

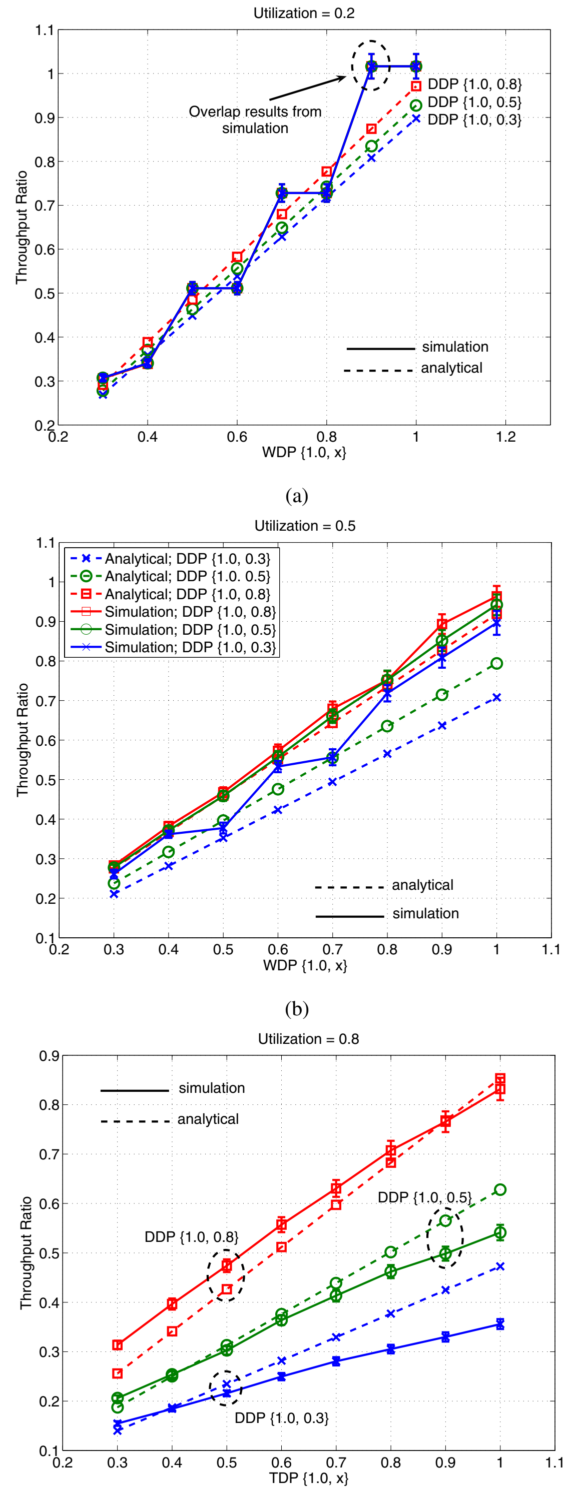


Fig. 6. Analytical simulations versus simulation results under varying WDP settings for three levels of utilizations; (a) Utilization = 0.2, (b) Utilization = 0.5, (c) Utilization = 0.8.

throughput predicted by our fixed-point method in Table II. Based on the results, we see that at low load, the predicted throughput performance is very close to the simulated values. Nevertheless, at moderate and high load, the prediction is more conservative as it almost consistently computes a lower throughput level for each class.

VII. Summary and Conclusions

In this paper, we study service differentiation for TCP traffic in the context of BoD GEO satellite networks. As a first contribution, we demonstrate how a specific service differentiation framework, *i.e.*, the PDS model, can be achieved in

TABLE II
COMPARISON OF SIMULATED AND PREDICTED TCP THROUGHPUT UNDER DIFFERENT UTILIZATION AND DIFFERENTIATION PARAMETERS

	Differentiation Setting		**Simulated average TCP throughput**	**Predicted average TCP throughput**
Utilization (%)	**WDP set, $\{r_i^W\}$**	**DDP set, $\{r_i^D\}$**	**(class1, class2) in byte/s**	**(class1, class2) in byte/s**
0.2	{1.0, 0.3}	{1.0, 0.8}	(3458.16, 1052.26)	(3089.48, 900.13)
	{1.0, 0.5}	{1.0, 0.5}	(2754.43, 1400.50)	(2725.93, 1263.67)
	{1.0, 0.8}	{1.0, 0.3}	(2381.24, 1724.52)	(2322.12, 1667.49)
0.5	{1.0, 0.3}	{1.0, 0.8}	(11335.46, 3190.39)	(7818.98, 2155.04)
	{1.0, 0.5}	{1.0, 0.5}	(10153.37, 4633.91)	(7143.29, 2830.74)
	{1.0, 0.8}	{1.0, 0.3}	(8426.94, 6025.47)	(6371.14, 3602.89)
0.8	{1.0, 0.3}	{1.0, 0.8}	(14442.16, 4505.16)	(12707.28, 3251.16)
	{1.0, 0.5}	{1.0, 0.5}	(14598.55, 4394.18)	(12154.22, 3804.22)
	{1.0, 0.8}	{1.0, 0.3}	(14580.98, 4429.16)	(11588.61, 4369.83)

such a network via implicit cross-layer mechanisms involving both the MAC and transport layers. We deploy the SWTP scheduler at the MAC layer to regulate the satellite resource and TCP-PEPs at the border of the satellite network to configure variables of the TCP connections over the satellite link. The two mechanisms are complementary. The transport-layer mechanism dominates at low load, where the capacity of SWTP to provide differentiation is limited; in contrast, the scheduler takes on the differentiation task at higher load, where the maximum TCP window constraint appears to be inactive.

The second contribution of this paper is methodological. We describe a framework, drawing on analytical approximations of the performance of TCP sources and MAC layer available in literature, which enables the prediction of the satellite network performance. The method is generic as it is also applicable to other network types and could include various protocols and mechanisms. It requires two kinds of inputs - information on network topology, and analytical models of MAC- and transport-layer protocols. Satellite operators could use this method in the dual tasks of performance analysis and network dimensioning, to improve over rules of thumb that are often viewed as best practice today.

In the work presented here, we have used this methodology to configure the transport and MAC layer for realizing the PDS model. As we have discussed, its effectiveness eventually depends on the accuracy of the mathematical models used for the MAC and transport layer protocols. Although we have shown here that the currently available models in the literature are reasonably capable to approximate the achieved differentiation, we point out that the method predictions can be further improved if more realistic analytical models for the performance of MAC or transport protocols become available.

From a broader research perspective, our study contributes to the investigation of service differentiation mechanisms over wireless networks. We show how TCP-PEPs provide added flexibility to satellite operators for managing the traffic over their network. Additionally, we illustrate the effect of TCP traffic prioritization at the satellite MAC layer. Our results add to extensive argumentation in favor of modest cross-layer approaches in wireless networks.

In the real world, service differentiation is always tightly coupled with charging considerations. For a service differentiation framework to be successful, the satellite operator has to be able to deploy, configure and maintain it in a cost-efficient manner, whereas the customers must be able to easily understand how the charging scheme reflects the differentiation. Finally, the framework must reflect the price. We have attempted to take these requirements into account in this paper.

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