Multi-terminal dynamic bandwidth allocation in GEO Satellite Networks

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Satellite Networks

Pros
- Easy deployment
- Cost-effective
- Mobility
- Broadcasting
- Geographical coverage

Cons
- In GEO links propagation delay is very high (RTT $\sim 500$ ms).
- High delay*bandwidth systems are critical for TCP flows.
- The bandwidth is scarce, so a careful management is needed.
Quality of Service (QoS)

**QoS metrics**
- Bandwidth
- Delay
- Jitter
- Packet Loss

<table>
<thead>
<tr>
<th>Application</th>
<th>Required Band</th>
<th>Sensitivity to</th>
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Internet Engineering Task Force (IETF) proposals
- Integrated Services (IntServ)
- Differentiated Services (DiffServ)
### Quality of Service (QoS)

#### QoS metrics
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#### Application Sensitivity Table

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Internet Engineering Task Force (IETF) proposals
- Integrated Services (IntServ)
- Differentiated Services (DiffServ)
Satellite Gateways (SGs) can be divided in different priority classes, e.g.
- Gold
- Silver
- Bronze
In order to compute the bandwidth requests, each SG use 2 blocks:

- Traffic Predictor
- Bandwidth Controller
Buffers (FIFO queues)

Input packets are divided into \( n \) buffers (FIFO queues), according to the DiffServ policy. (e.g. EF, AF, BE classes \( \implies n = 3 \))

\[
\begin{align*}
y(t) &\in \mathbb{R}^n \quad \text{vector of queue sizes} \\
w(t) &\in \mathbb{R}^n \quad \text{vector of input flows} \\
v(t) &\in \mathbb{R}^n \quad \text{vector of output flows}
\end{align*}
\]

at sample time \( t \)

\[
y(t + 1) = y(t) + w(t) - v(t)
\]
Scheduler

\( v(t) \): bandwidth assigned at time \( t \) to the SG from the NCC

\( v(t) \in \mathbb{R}^n \): transmission flows at time \( t \) for the \( n \) service classes

\[
\mathbf{v}(t) = \begin{bmatrix}
  b_1 \\
  b_2 \\
  \vdots \\
  b_n
\end{bmatrix} v(t), \quad b_i \geq 0, \quad \sum_{i=1}^{n} b_i \leq 1
\]

Several scheduling policies can be adopted, e.g.

- WFQ - Weighted Fair Queueing
- Priority Scheduling
- Weighted Round Robin
Traffic Predictor

\( \hat{\mathbf{w}}(t + k|t) \): predictions, at time \( t \), of the input traffic flows at time \( t + k \), based on the available data \( \mathbf{w}^{t-1} \triangleq \{\mathbf{w}(k), k \leq t - 1\} \).

Several predictors can be used:

- **ARMA** predictor *(not self-similar)*
- **FARIMA** predictor *(self-similar)* based on a *fractionally integrated* ARMA model
- **Maximum Likelihood** predictor
Bandwidth Controller

The **bandwidth request** \( u(t) \) for the time \( t + \delta \), where \( \delta \) is the Round Trip Delay, is based on the data already known at time \( t \) and assuming that the request is always satisfied, i.e.

\[
\nu(t) = u(t - \delta)
\]

state: \( x(t) = [y'(t), u(t - 1), \ldots, u(t - \delta)]' \in \mathbb{R}^{n+\delta} \)

Predictive model for time evolution of queue sizes:

\[
\begin{align*}
x(t + k + 1) &= Ax(t + k) + Bu(t + k) + Ew(t + k) \\
y(t + k) &= Cx(t + k)
\end{align*}
\]

Predictions \( \hat{w}(t + k|t) \) are used in place of \( w(t + k), k \geq 0 \).
$u(t)$ is chosen to trade-off small queue sizes (i.e. low traffic delays) vs. bandwidth waste

$\implies$ **Cost minimization of**

$$J = \sum_{k=0}^{H-1} \left[ y'(t+\delta+k) \cdot Q \cdot y(t+\delta+k) + r \cdot u^2(t+k) \right]$$

subject to the constraints:

$$\begin{cases} 
y_{\text{min}} \leq y(t+\delta+k) \leq y_{\text{max}} 
\quad k = 0, 1, \ldots, H - 1 

u_{\text{min}} \leq u(t+k) \leq u_{\text{max}} 
\end{cases}$$
Receding Horizon control strategy

Receding Horizon control is used to compensate the model uncertainties.

- Being \( u(t), \ldots, u(t + H - 1) \) the optimal solution at time \( t \)
- we apply the request \( u(t) \) discarding \( u(t + 1), \ldots \)
- at time \( t + 1 \) we repeat the process with the new data.
Other control strategies

**Predictive only**
Bandwidth request is based only on Predictor forecasting:

\[ u(t) = \hat{w}(t + \delta | t) \]

**Reactive controller**
Bandwidth request is computed using a Smith Predictor:

\[
\begin{align*}
  u(t) &= w(t) + K \left[ y(t) - \sum_{k=t-\delta}^{t-1} \left( u(k) - \left( 1 - \frac{\delta^*}{\delta} \right) w(k) \right) \right] \\
\end{align*}
\]

where \( \delta^* \geq \delta \) is a parameter representing the desirable queueing delay while \( K \) is a gain which, for stability, must belong to the interval (0, 1].
The bandwidth is shared among SGs following a simple rule:

- $u_i \triangleq u_i(t - \delta/2)$: bandwidth requested from SG$_i$
- $v_i \triangleq v_i(t + \delta/2)$: bandwidth assigned to SG$_i$
- $C$: link capacity (max. bandwidth $\times$ sampling time $T$)

Constraints:

- $\sum_{i=1}^{N} v_i \leq C$
- $v_i \leq u_i \quad i = 1, 2, \ldots, N$
Bandwidth assignment policy

- if $\sum_{i=1}^{N} u_i \leq C$ set $v_i = u_i$
- if $\sum_{i=1}^{N} u_i > C$ set $v_i = v_i(u_1, u_2, \ldots, u_N)$
- function $v_i(u_1, u_2, \ldots, u_N)$ depends on the assignment policy

Weighted Proportional Assignment (WPA)
Shares out the link capacity $C$ proportionally to the requests with weights $\alpha_i > 0$ depending on the class of SG$_i$ (e.g. Gold, Silver and Bronze SGs).

$$v_i = \frac{\alpha_i u_i}{\sum_{j=1}^{N} \alpha_j u_j} C$$
Satellite Systems
Quality of Service (QoS)
Dynamic Bandwidth Allocation (DBA)

**Traffic delays, simulated congestion**

- Faster recovery (1 vs. 6 min of Pred)
- Lower steady-state than Smith’s
Bandwidth waste, simulated congestion

- Comparable band waste with Pred ($\approx 0.5\%$)
- Smith’s band waste is $\approx 12\%$
Traffic delays, simulated congestion, SGs classes

WPA weights:

\[ \alpha_g = 1.0 \]
\[ \alpha_s = 0.8 \]
\[ \alpha_b = 0.6 \]

- NCC algorithm can provide different QoS to each SG class.

Chisci, Fantacci, Francioli, Pecorella

Multi-terminal dynamic bandwidth allocation in GEO Sat.
**Conclusions**

**DBA for GEO satellite systems based on**
- predictive control algorithm run in parallel in each Gateway
- bandwidth assignment algorithm in the NCC

**Interesting results in terms of**
- multiple traffic classes management with different QoS
- low bandwidth waste
- high performance in steady state and after congestion

**Future developments**
- different assignment policies in the NCC
- self-similar traffic predictors
- game-theoretic approach to DBA
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