5th Space Internet Workshop

Dynamic Bandwidth Allocation for a Space-to-ground Relay Network

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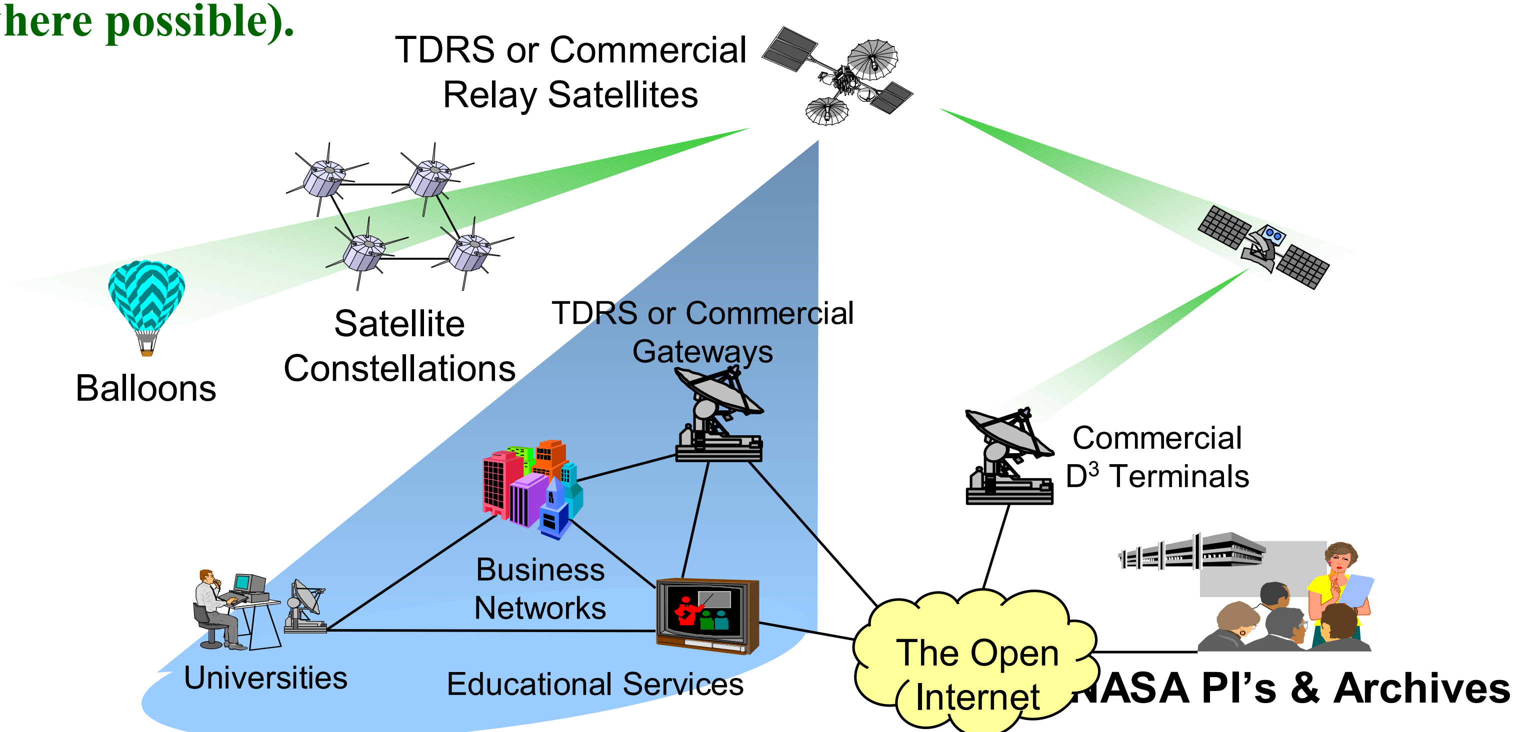
Future Mission Network Evolution

- **NASA network supports large numbers of single or constellation spacecraft with IP-addressable instruments**
- **Mission Operation gradually evolves to a dynamic concept and uses a NASA & commercial assets for communication support; direct-to-ground as well as GEO relay solutions are employed.**
- **Commercial technology and standard communication protocols are employed (where possible).**



Broadband Satellite Communication Networks

- An increasing number of single or constellation scientific spacecraft with IP-addressable instruments and the new NASA initiative for Moon, Mars and other planets
- Internet protocols connecting everybody together and leading a new development phase with wireless extensions of this network in a variety of environments
- The ability to use recent advances in communications technologies by investigators on Earth to enjoy a virtual presence in space
- Dynamic communication support for bursty mission traffic with different QoS requirements
- Commercial technology and standard protocols reducing development and deployment costs

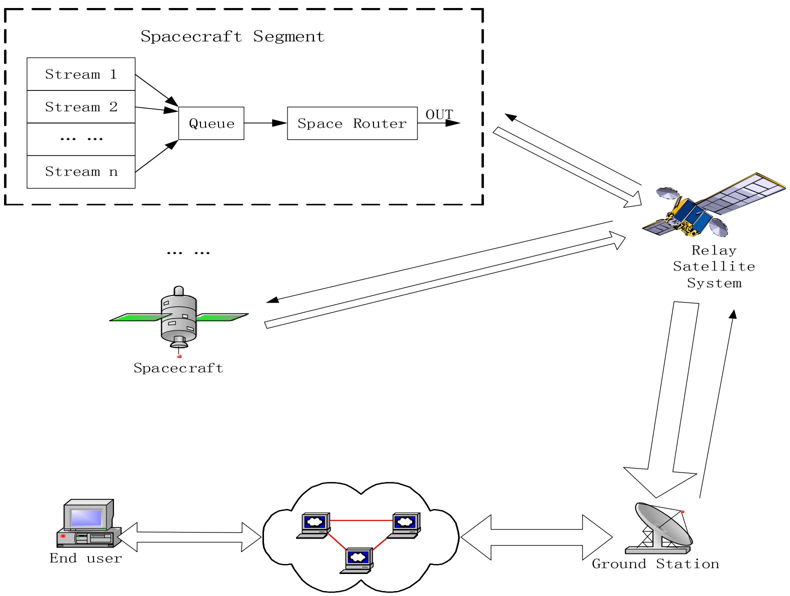
Challenges

- Large and time-varying propagation delay
- Intermittent communication links
- Highly asymmetric or unidirectional communication links
- Higher BER than most terrestrial wired links
- Multiple mobile nodes forming a dynamic network topology
- High mobility (velocity), but often very predictable, since most spacecraft move along pre-defined orbits and their locations may be easily predicted.

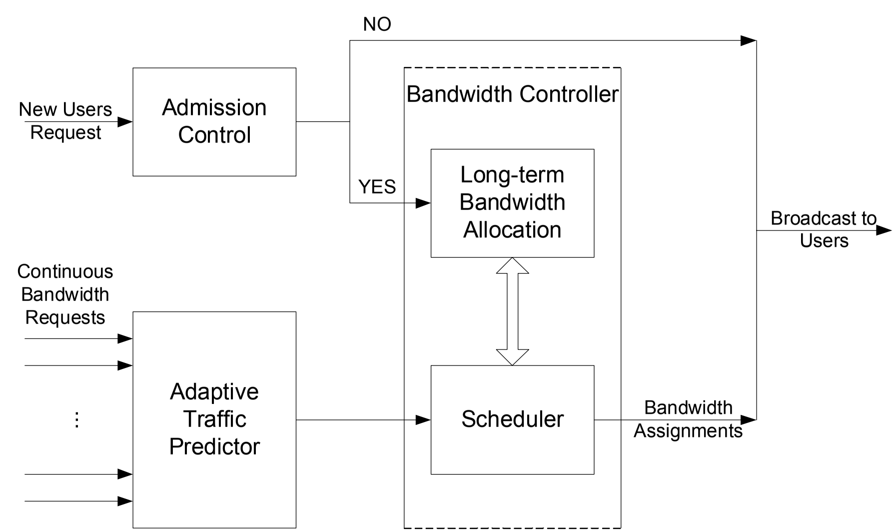
Requirements

- High resource utilization or efficiency
- Reliable Admission Control algorithm and QoS frameworks
- Efficient handover management between relay satellites
- Variable service classes
- Fairness
- Scalability
- Queue management on-board satellite
- Error compensation and prevention

Network Architecture



- Multi-access sharing among a large number of spacecraft for the downlink channel
- On-board scheduling and queuing among several streams for each spacecraft



- Admission control and initial bandwidth allocation (static, long-term)
- Dynamic bandwidth allocation determined by the scheduler in the ground station

Bandwidth Allocation at the Ground Station with NCC

Traffic Sources and Admission Control

Traffic sources:

- Existing Types: mission traffic, scientific instruments traffic, high-priority telemetry control and housekeeping traffic, real-time or non-real-time video traffic
- Mapped Types: Guaranteed bandwidth traffic, Best-effort traffic and Mixed-type traffic
- Multi-State-Multi-Mode (MSMM), MM-MSMM
- Elastic traffic modeled by minimum and maximum requested bandwidth
- Our traffic source model: minimum bandwidth (*c*), targeted bandwidth (*a*), maximum bandwidth (*b*)

Admission Control:

- The assignment must satisfy $\sum_i c_i \leq B$
- The assigned bandwidth does not exceed the requested maximum bandwidth.

Long-term Bandwidth Allocation (Rate Control)

Kelly's Model:

- **SYSTEM(U, H, A, C):**

$$\text{Maximize} \sum_{s \in S} U_s(x_s)$$
$$\text{subject to } Hy = x,\ Ay \le C$$
$$\text{over } x, y \ge 0.$$

Where, U(.) is over [0, ∞), with $U(0) = -\infty$, $U'(0) = \infty$.

- **Fairness:**

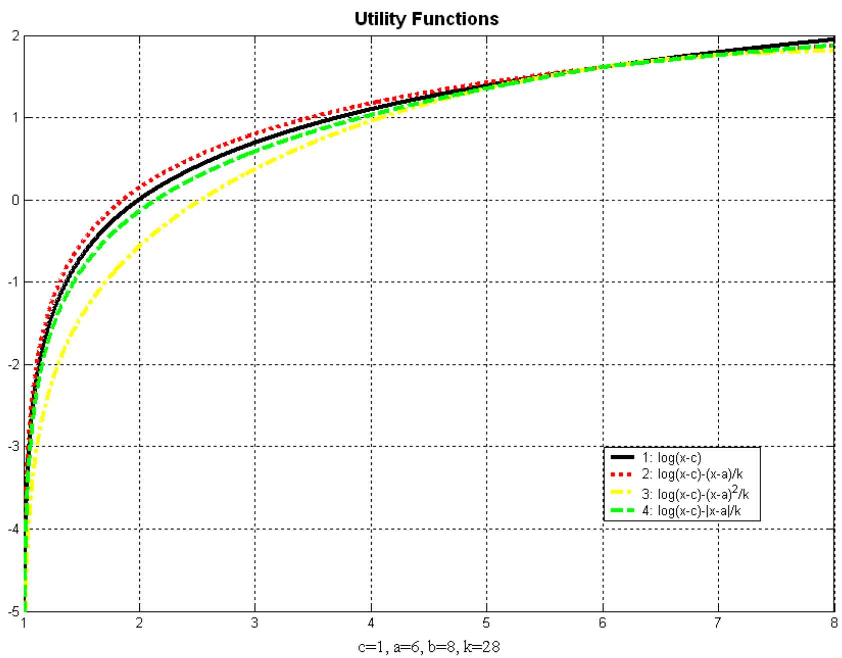
$$U_{(\alpha)}(x) = -(-\log x)^{\alpha},\ 0 < x < 1,\ \alpha \geq 1.$$

Max-min fairness, when $\alpha \to \infty$;

Proportional fairness, when $\alpha = 1$.

$$\sum_{s \in S} \frac{x_s^* - x_s}{x_s} \le 0 \qquad \sum_{s \in S} \frac{\delta x_s}{x_s} \le 0$$

Utility Functions Discussion

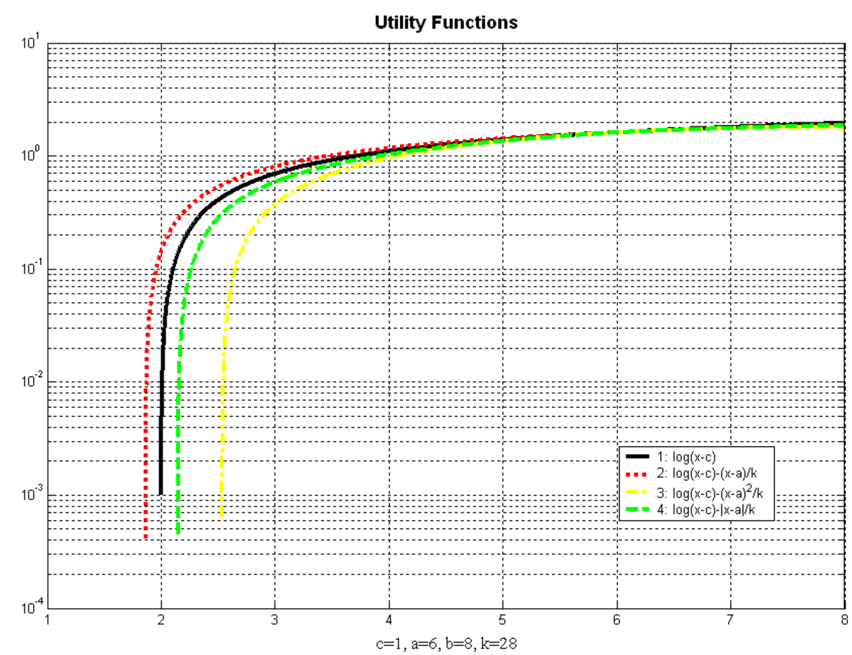


B: $U(x) = log(x-c)$

R: $U(x) = log(x-c) - (x-a)/k$

Y: $U(x) = log(x-c) - (x-a)^2/k$

G: $U(x) = log(x-c) - |x-a|/k$



Minimum Bandwidth $$\sum_{s\in S} \frac{\delta x_s}{x_s - c_s} \leq 0$$

Targeted Bandwidth $$\sum_{s\in S} U_s'(x_s)\cdot \delta x_s \leq 0$$

Pseudo-Proportional Fairness $$\sum_{s\in S} \frac{\delta x_s}{x_s - c_s} \leq \sum_{s\in S} \frac{1}{k_s}$$

Long-term BW Allocation (Problem)

Optimization Problem:

$$\max \sum_{i=1}^{N} [m_i \cdot \log(x_i - c_i) - \frac{x_i - a_i}{k_i}]$$

$$\text{subj. to: } x_i \geq c_i,\ x_i \leq b_i$$

$$Ax \leq B$$

$$i = 1, 2, \ldots, N$$

With assumption: $Ax_c < B$, where $x_c = [c_1, c_2, \ldots, c_N]^T$.

Alternatively:

$$\max \prod_{i=1}^{N} (x_i - c_i)^{m_i} \cdot e^{-\frac{x_i - a_i}{k_i}}$$

Lagrangian:

$$L(x, \lambda, \beta, \mu) = \sum_{i=1}^{N} [m_i \cdot \log(x_i - c_i) - \frac{(x_i - a_i)}{k_i}] - \sum_{i=1}^{N} \lambda_i (c_i - x_i) - \sum_{i=1}^{N} \beta_i (x_i - b_i) - \sum_{l=1}^{L} \mu_l [(Ax)_l - B_l],$$

$$x_i \geq 0,\ \lambda_i \geq 0,\ \beta_i \geq 0,\ \mu_i \geq 0,\ i = 1, \ldots, N,$$

Long-term BW Allocation (Solution)

Solution: $\forall i = 1, \ldots, N, \quad \forall l = 1, \ldots, L,$

$$x_i = c_i + \min\left[(b_i - c_i),\ \frac{m_i}{\frac{1}{k_i} + \sum_{l=1}^{L} \mu_l A_{l,i}} \right]$$

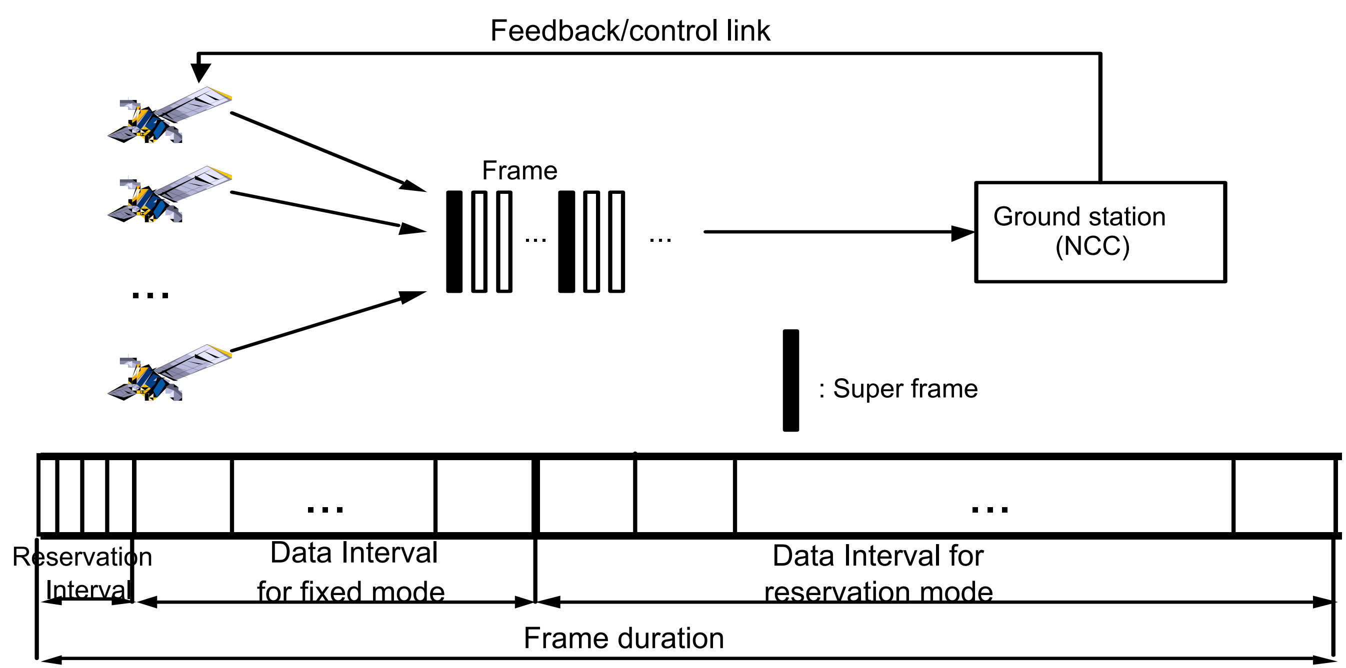
$$Ax \le B,\ (Ax - B)_l \cdot \mu_l = 0,\ \mu_l \ge 0.$$

Remarks:

- **m_i is the weight for the source *i*.**
- **The Lagrange multiplier μ_l is the implied cost for link *l*.**
- **k_i is the desired attenuation parameter for the source *i*.**

Hybrid-mode TDMA Protocol with Short-term Bandwidth Allocation

- Besides the control slots, use the "piggy-back" method to send the information in the data slots
- "Out-of-date" collected information in NCC because of the long propagation delay (Need estimation)



Short-term Bandwidth Allocation (1)

- Two different levels of scheduling:
  - Burst-level scheduling: performed only once during each frame and allocates timeslots to a stream within a frame in a contiguous fashion.
  - Packet-level scheduling: performed during each timeslot and one timeslot is assigned at a time.
- Burst-level scheduling is more practical and stable for our long delay satellite communications network.
- The scheduler generates a bandwidth allocation table (BAT) and sends it back to all the spacecraft. A BAT contains several information fields such as User_ID, First_slot, and Last_slot.

Short-term Bandwidth Allocation (2)

Problem Formulation:

$$\text{Minimize} \quad \sum_{k \in M_a} \sum_{l \in C} v_{kl} (D_{kl} - s_{kl})^+$$

subject to:

$$s_{kl} \le \min(U_{kl}, D_{kl}), \qquad k \in M_a, l \in C$$

$$s_{kl} \ge L_{kl}, \qquad k \in M_a, l \in C$$

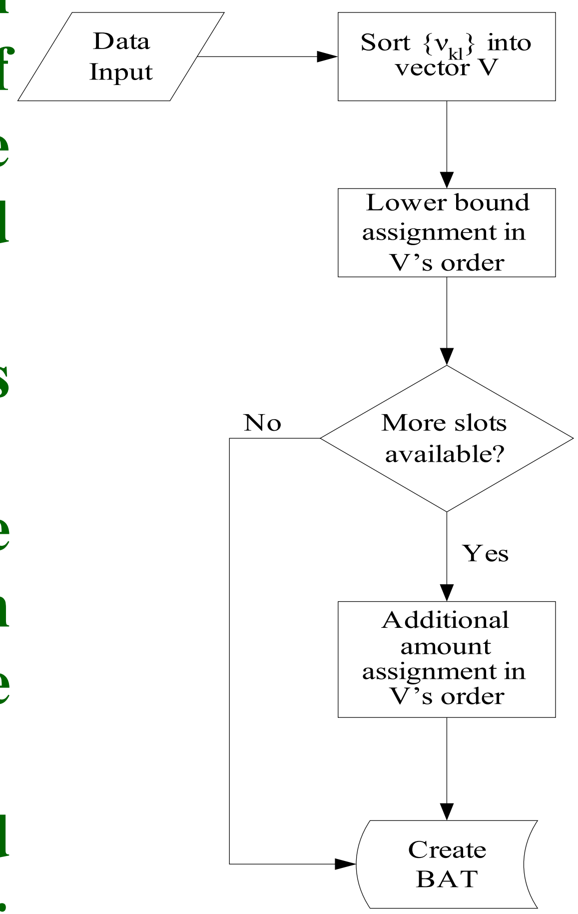
$$\sum_{k \in M_a} \sum_{l \in C} s_{kl} \le N,$$

$$\forall s_{kl} \in \{0, 1, 2, \ldots, N\}$$

- U_{kl} **and** L_{kl} **can be assigned according to the service requirements of the streams and the practical condition of the whole channel.**
- **The multiple-frame bandwidth assignment for user *i* is in the range of (**$x_i \times$ **frames –** L_i**,** $x_i \times$ **frames +** U_i**).**

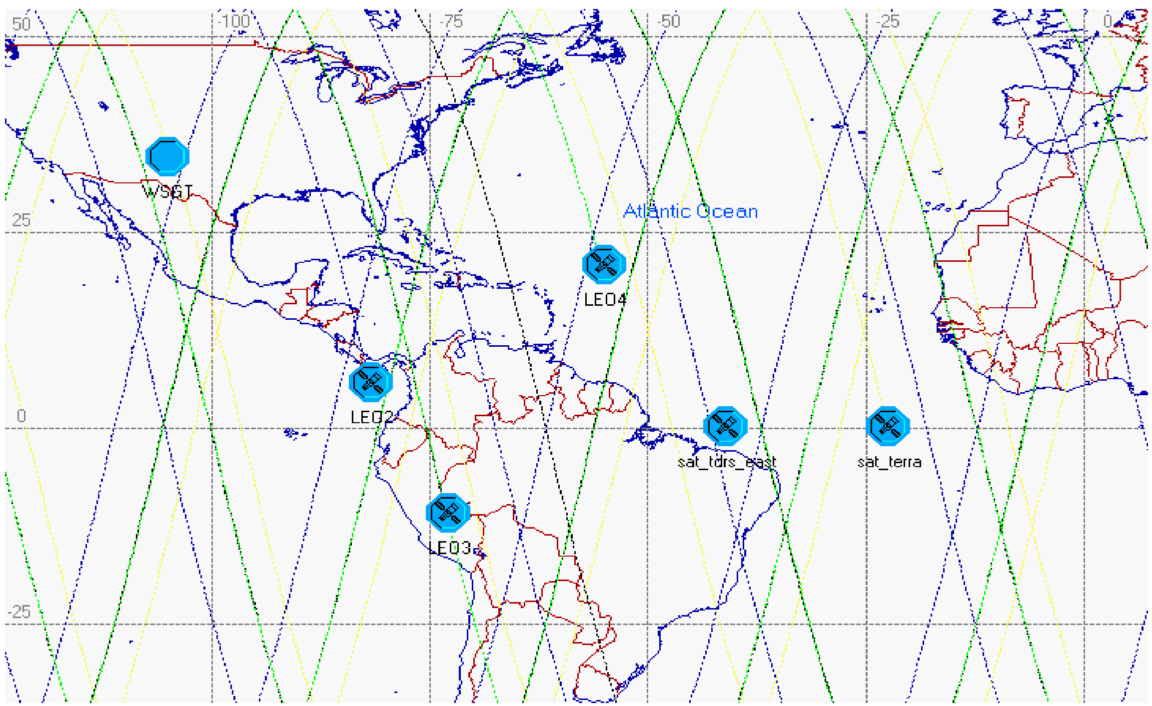
Short-term Bandwidth Allocation (3)

- Controls applied to deal with variations in traffic dynamics and with the presence of multiple services, in order to guarantee different performance requirements and avoid congestion.
- Direct algorithm for distinct penalties $\{\nu_{kl}\}$ and definite known demands $\{D_{kl}\}$
- Computation or estimation of the demands from the recent or long-term collected information during multiple frames (stability)
- To users with same penalties, fairness and maximum throughput considered together

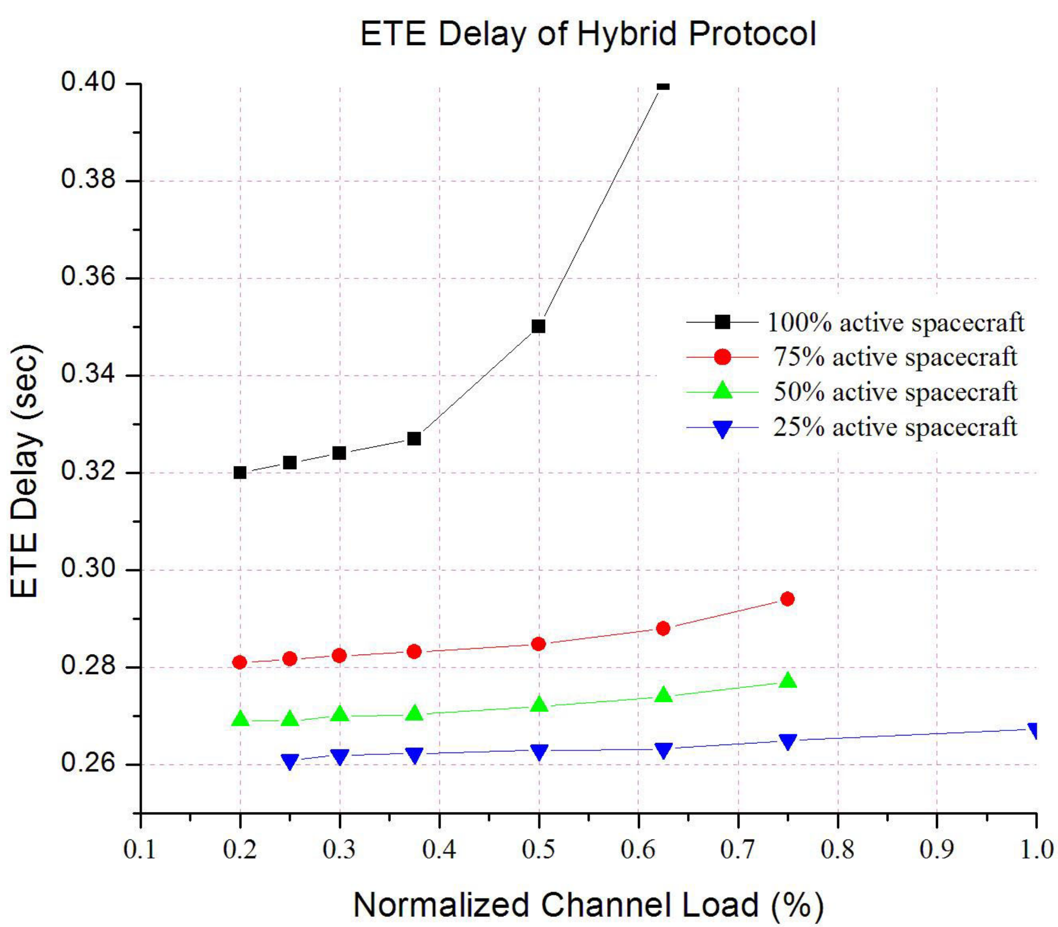


Simulation Configuration

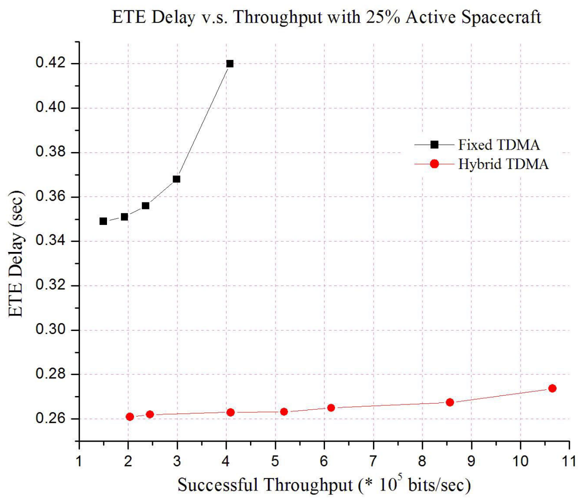
- RTD = 0.48~0.62 sec, Frame duration = 0.1372 sec
- Number of data slots per frame = 64, number of control slots per frame = 4.
- Channel capacity = 2Mbps, error-free

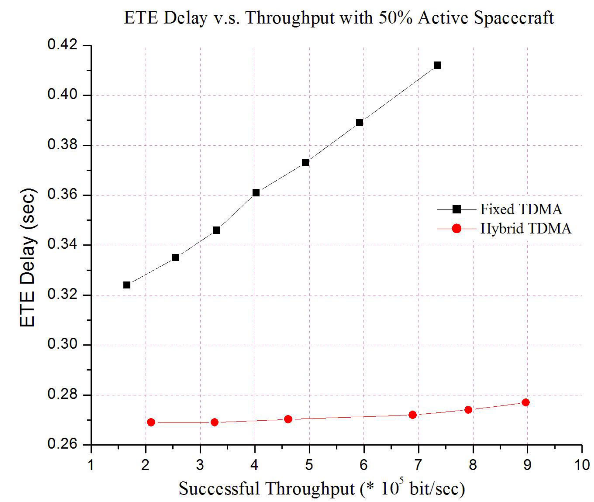


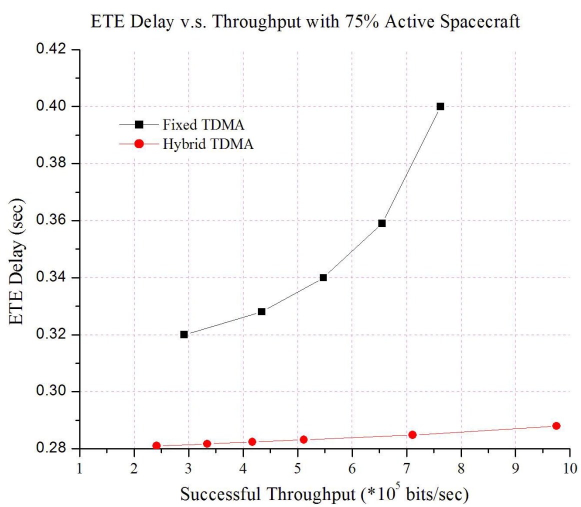
Performance of Hybrid-mode TDMA

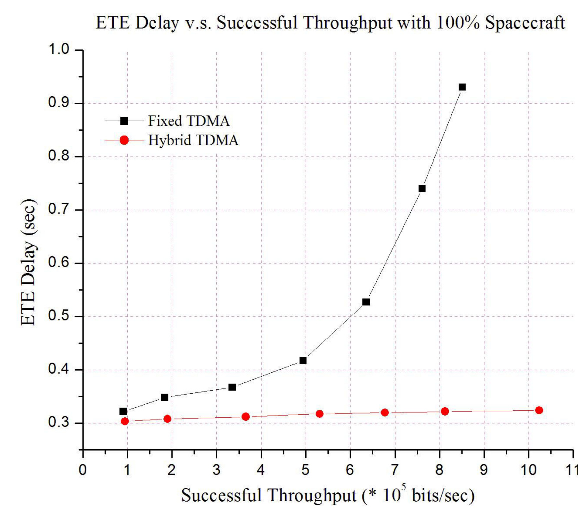


Hybrid-mode VS Static TDMA

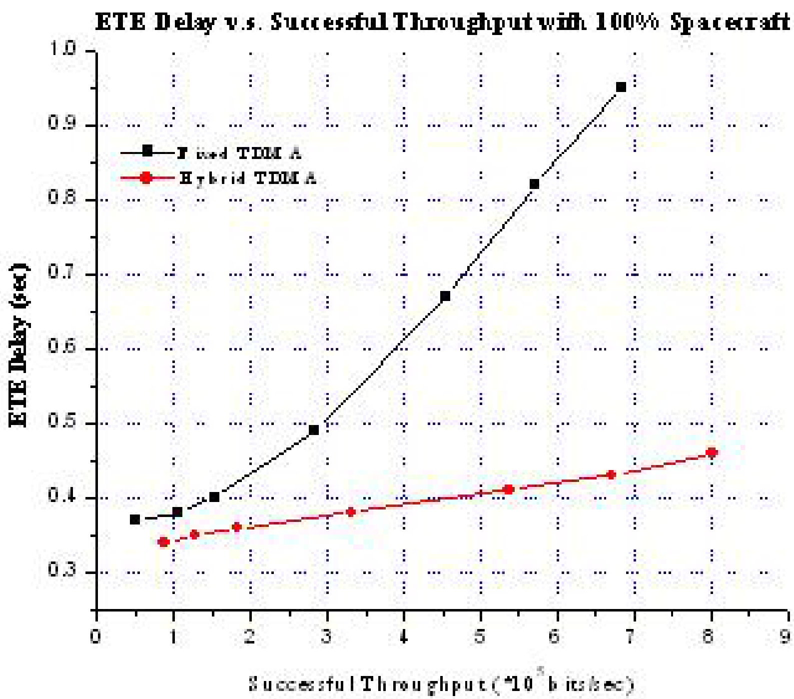




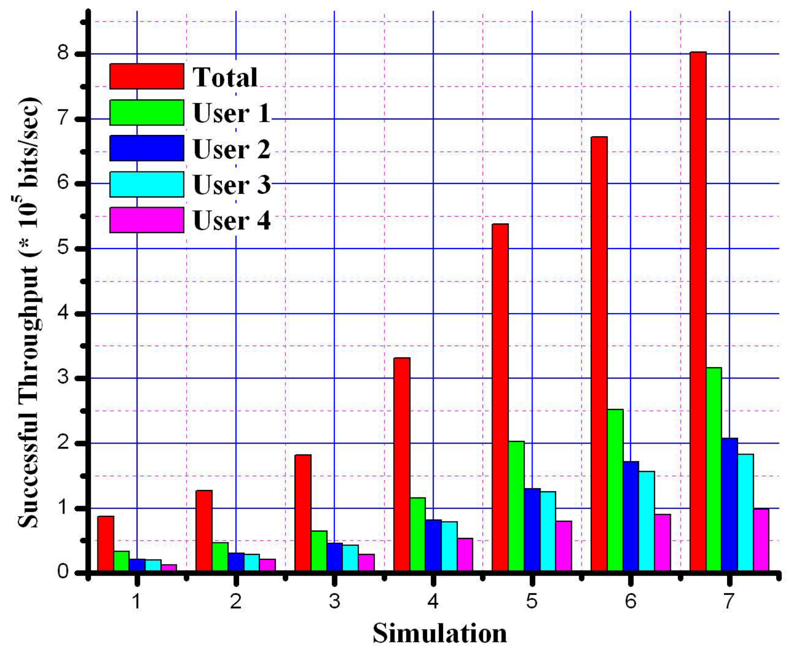




Hybrid-mode VS Static TDMA



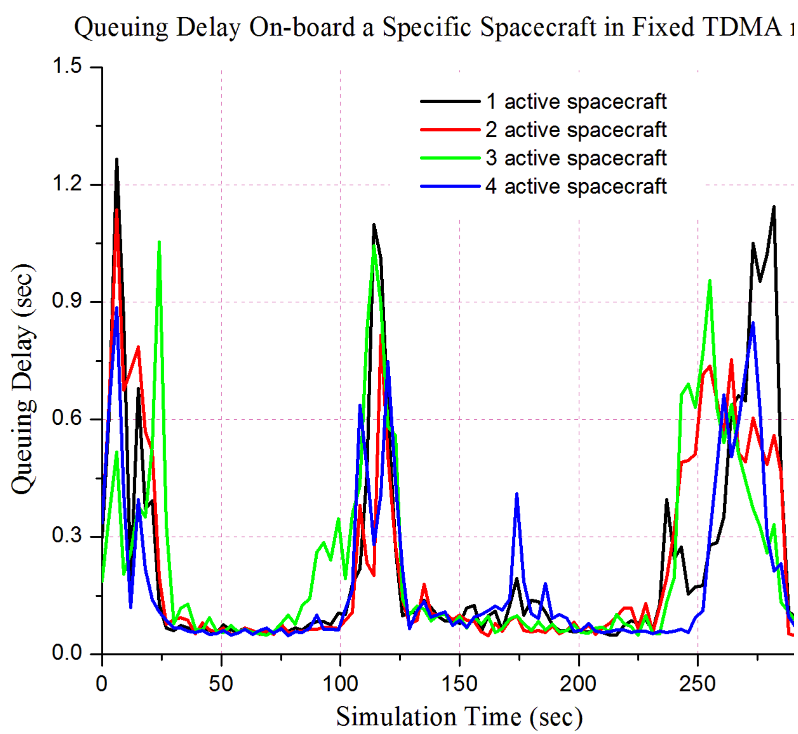
ETE Delay vs. Throughput

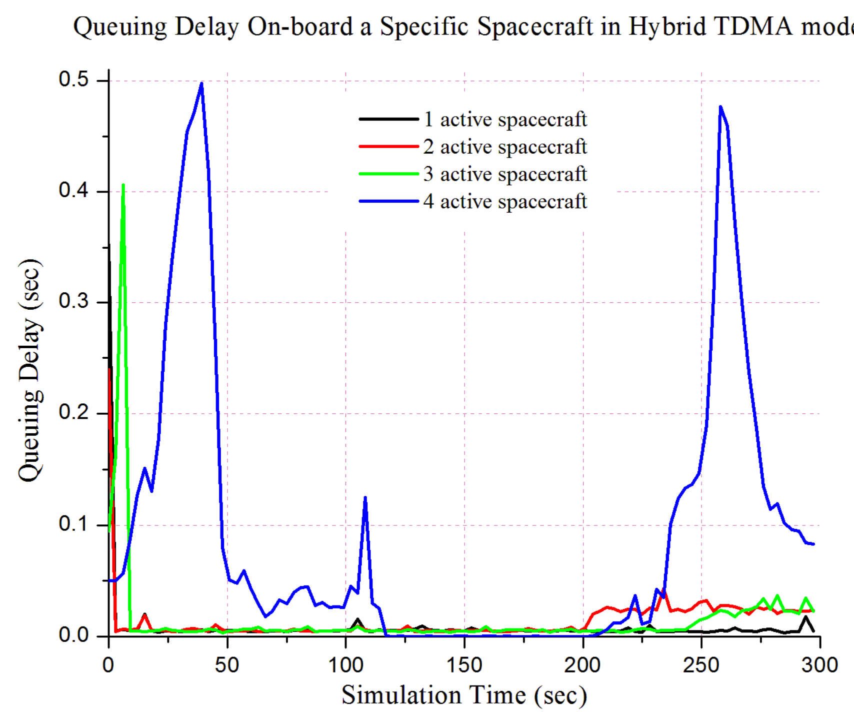


Fairness among Users

Note: The ratio of expectations of traffic loads of four users is 3:2:2:1.

Queuing Delay On-board





Future Work

- In a real system spacecraft will use finite queues on-board instead of infinite queues.
- The effects of changing the period of performing the long-term bandwidth allocation need to be investigated.
- Use our results to study design trade-offs for a future broadband relay satellite constellation with on-board switching and inter-satellite links between relay spacecraft.
- To formulate rate-control system models (single flow or multi-flow) with heterogeneously time-varying large propagation delays, and then study its stability and other behavior.