Intersatellite Link (ISL) Networks: Topological Design, Routing and Network Dimensioning

Markus Werner

DLR Oberpfaffenhofen

Outline

- Why (still) ISLs ? … and what about ISLs in ATM-Sat ?
- Which ISL network topology ?
  - from the Iridium heritage to a modern (sustainable) design !
- "ATM-based" ISL routing concept:
  - a discrete-time dynamic routing framework derived from core ATM principles rather than an ATM implementation !
- Integrated ISL routing and network dimensioning
- Routing towards an ISL future:
  - ATM+IP ? ↔ all IP ? ↔ MPLS ↔ optical networks . . .
- A conclusion: Good concepts are sustainable - sustainable concepts are good!

Why (still) ISLs ?

- Iridium&ISLs: final desaster or lessons learnt (to learn) ?
- Teledesic: ongoing dream or diminishing nightmare ?

- Backbone-in-the-sky (not only “Internet-in-the-sky“) as a sustainable concept
- A sustainable ISL networking concept will pay off one (resurrection) day !

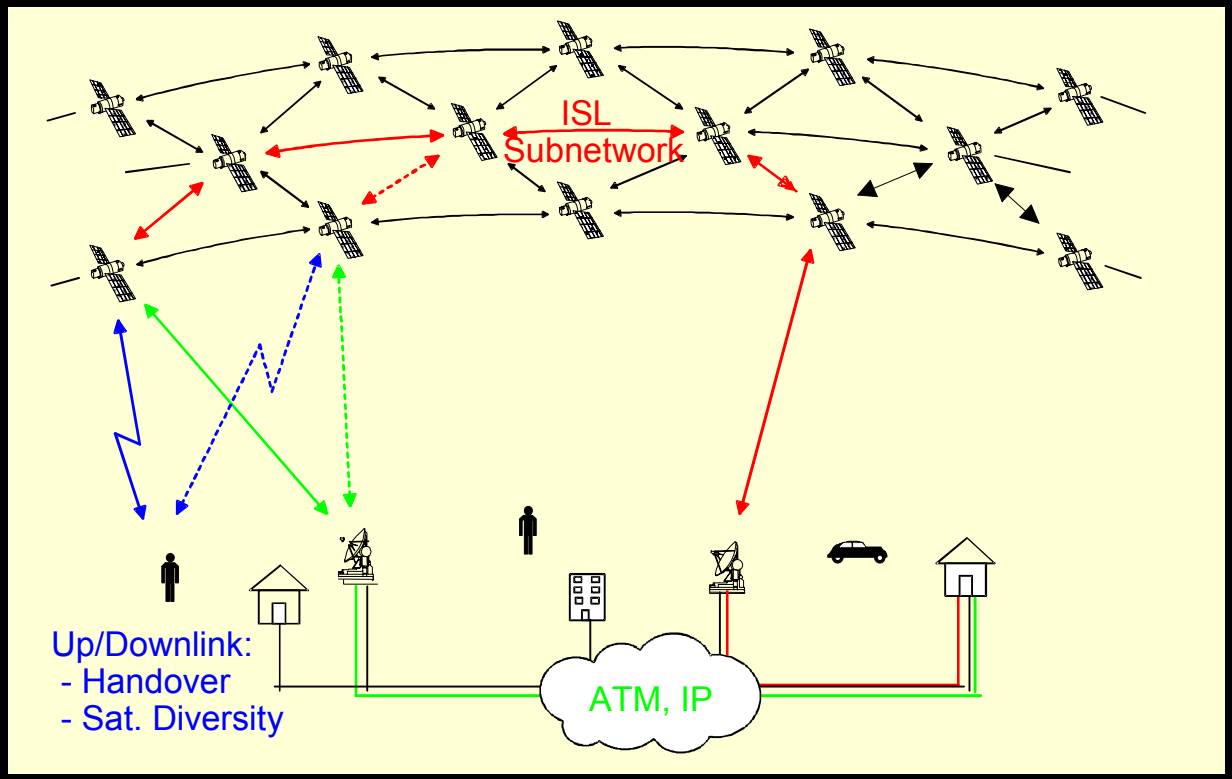
... and what about ISLs in ATM-Sat ?

- We don't have (short-term) stock options in ISL networks
- No "early-to-market" strategy, but strategic project ...
- ... consequently re-defining or just recalling the orientation/direction:

- "friendly" scenarios:
  - high-capacity multicast
  - fixed terminals
  - aggregated traffic ...
- prospective markets:
  - high quality Internet
  - particular global VPNs
  - high-speed and reliable global information distribution
  - trunking market niches ...

- driving technologies:
  - MPLS
  - optical networking
  - λ switching ...

Scenario



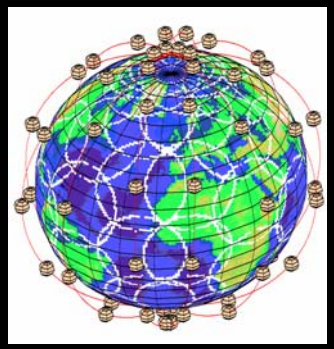
Space segment:
ISL trunk network

Air interface:
OD traffic

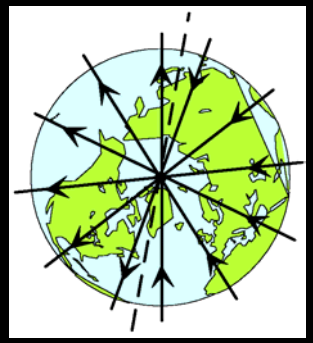
Earth segment:
Wireline backbones

Problems with (Near-)Polar Orbits: The Iridium Heritage

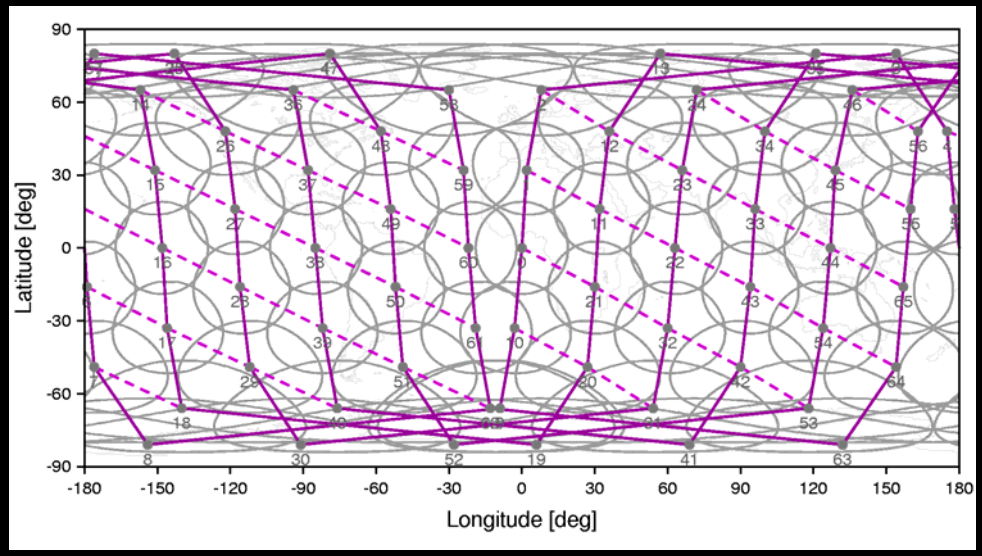
Satellite constellation:



"Seam" between counter-rotating orbits:



Snapshot of footprints and ISL topology:



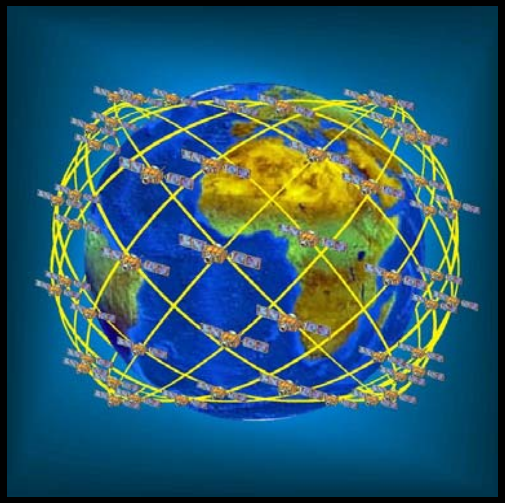
—— intra-plane ---- inter-plane ISLs

Drawback: two kinds of irregularity

- no ISLs crossing the "seam"
- deactivation of inter-plane ISLs in polar regions
  -> considerable path rerouting requirements !

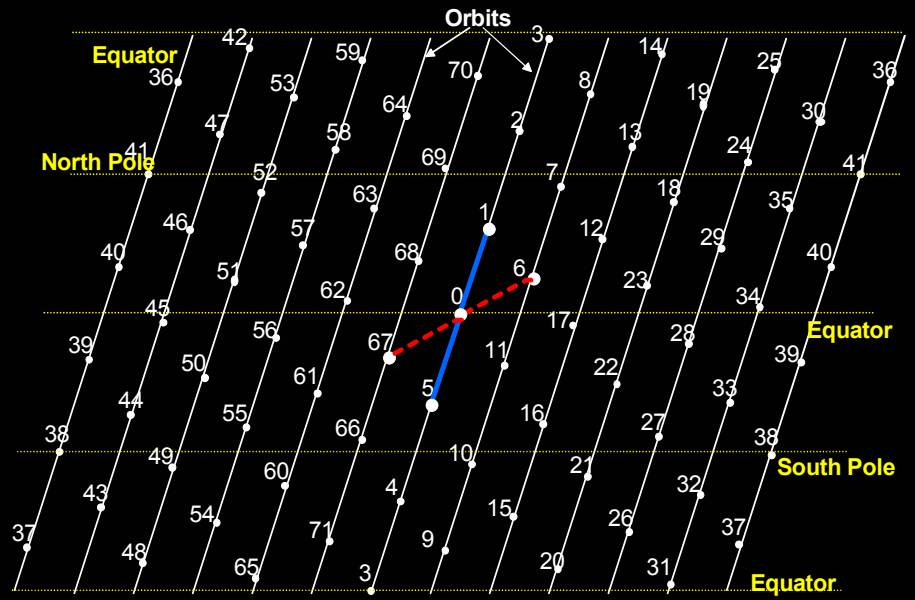
The Inclined Walker "Delta" Constellation M-Star

Constellation:



orbit altitude	1350 km
orbit period	113 min
# of satellites	72
# of orbits	12
inclination	47°

Planar projection (schematic):

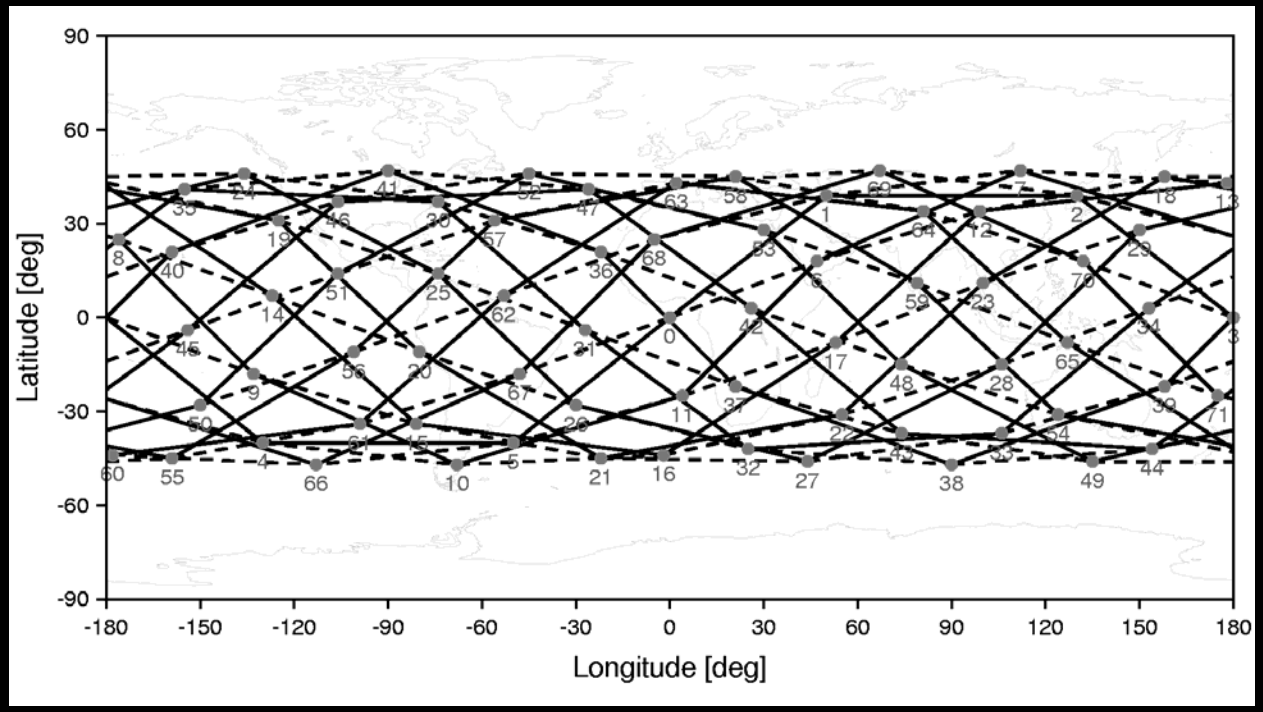


- regular phasing, phasing factor 5
- absolute symmetry of the orbital constellation
- no "seam" like in polar constellations

M-Star utilizes the promising combination of "delta" constellation pattern and optical ISLs

Reference ISL Topology for M-Star

Snapshot at *t*=0:



All links are permanently maintained over the whole orbit period !

Network Design: Concepts and Methods

- Network design = topology + routing + dimensioning
  - usually an iterative process
- ISL network design:
  - extreme challenges: dynamic topology, traffic variation
  - design process must be simple !
- Ingredients for “simple“ ISL network design:
  - hierarchical “open-loop“ design:
    `begin {topology; routing; dimensioning} end`
  - top-down decomposition
  - standard modules (shortest path search, LP optimization, ...)
  - abstraction of dynamics: discretization and virtualization

Discrete-Time Dynamic Routing Framework

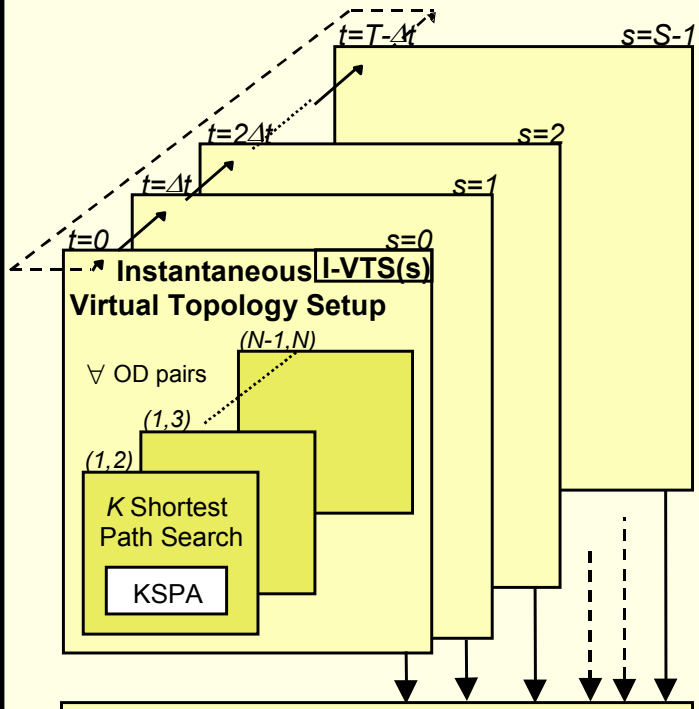
Topological Design

Permanent Physical Topology Design **P-PTD**

Topological design of ISL network
with permanent (non-switched) physical links
for Walker delta constellations

Off-line Routing Framework

Discrete-Time VirtualTopology Design **DT-VTD**



Capacity Dimensioning

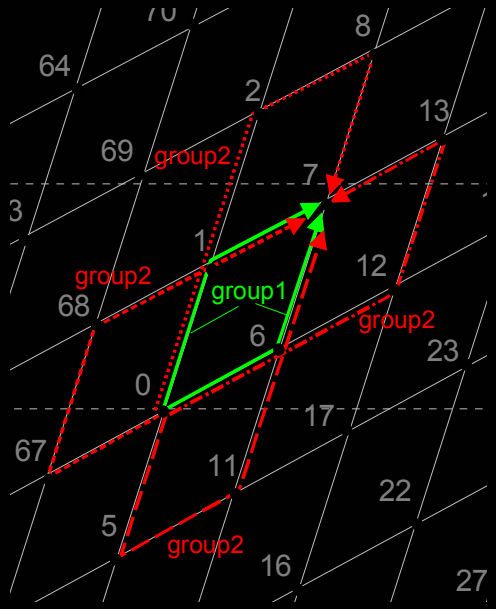
Discrete-Time Multi-Step Dimensioning **DT-MSD**

or *or*

Single-step dimensioning + post-processing	Linked single-step dimensioning	Multi-step dimensioning: Dynamic optimiz.

Path Grouping for Origin-Destination (OD) Pairs

Hop-based path grouping for example OD pair:



Clear path group separation by cost ranges (costs = accumulated propag. + processing delays)

- **PG separation extends over all steps; no overlaps of cost ranges!**
- **Ordering of paths (KSPA) can only vary within a group**

➡ **Select *k** = *k*(OD) such that *k**-path set always forms a complete path group**

Network Dimensioning: Target Functions

ISL capacity requirements → Bandwidth & RF power

Satellite capacity requirements → Processing power & buffer sizes

Bandwidth & RF power, Processing power & buffer sizes → DC power → Size & weight of satellite → System costs

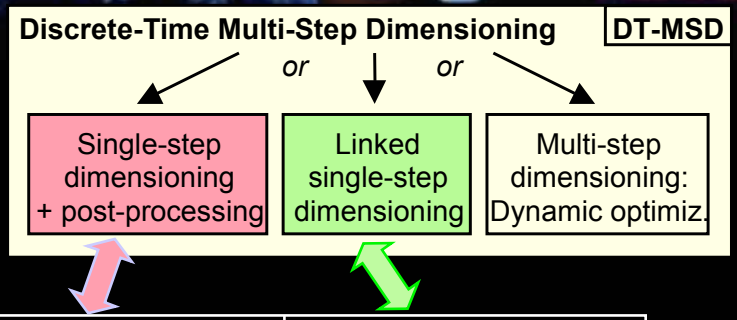
- LEO constellation dynamics --> every sat/link encounters worst case sometime
  --> all sats/links to be dimensioned accordingly

→ Candidate target functions: TF1: Minimize worst case link (WCL) load

TF2: Minimize worst case node (WCN) load

- positive "side effect": better utilization of installed network capacity

Network Dimensioning: Approaches



	isolated step	history-based
Equal Sharing (ES)	iES	hES
Bounded Optimization (BO)	iBO	hBO
Full Optimization (FO)	iFO	hFO

ES: *Equal sharing* of total OD traffic between <u>all</u> *k* OD paths

FO: *Linear optimization* of OD traffic distribution on *k* alternative paths *without specific constraints*

BO: *Linear optimization* of OD traffic distribution on *k* alternative paths *with additional constraints*

LP Optimization Approach: Isolated Step

For each time step $s = 1 \ldots S$:

iFO

minimax problem

minimize

$$\max_{\forall l} \{n_l(\mathbf{n_p})\}$$

subject to

$$n_w = \sum_{p, p \in P_w} n_p \ , \ \forall w$$

linear optimization problem

minimize

$$n_{\max}(\mathbf{n_p})$$ minimize WCL capacity

subject to

link capacity constraint

$$n_{\max} \geq n_l = \sum_{w, w \in W} \sum_{p, p \in P_w} \delta_l^p n_p \ , \ \forall l$$

$$n_w = \sum_{p, p \in P_w} n_p \ , \ \forall w$$ OD/path capacity constr.

iBO

$$0 \leq n_p \leq \alpha n_w \ , \ \alpha \in [0 \ldots 1] \ , \ \forall p$$ path cap. upper bounds

for k=3:

7668 optimization variables

144 constraints

2556 constraints

7668 constraints

Post-processing : Take maximum of all S minimax values

Performance of Isolated Step Optimization

from here, all numerical examples assume network-uniform traffic, i.e., a normalized symmetrical traffic load of 1 between all OD pairs

Worst Case Link (WCL) Load: iES - iBO - iFO

History-Based Optimization: Rationale

- Modeling deficiencies of isolated step approach:
  - assumes uncorrelated demand pair capacities
  - neglects "history" of single calls
  - implicitly assumes that all calls are freely (re)routable in each step

  ⇒ isolated step optimization results are "too good" (considering QoS)

- History-based approach:
  - guarantees that remaining (old) calls stick to the once chosen path:

    → avoid uncontrolled delay offset
    → reduce dropping probability
    → avoid unnecessary signaling
  - takes care of incoming rerouted calls (from other OD pairs; sat. handover!)

History-Based Optimization: Modeling

With ODT(s) = OD demand pair Traffic at step s:

total ODT(s) = new ODT(s) + rerouted ODT(s) + remaining ODT(s)

freely (re)routable

old ODT(s)

- Call model:
  - determines the ratio between old and new traffic
  - classical Erlang model: Poisson arrival, negative exponential holding time
- Rerouting model:
  - sub-classifies the old traffic into remaining and rerouted
  - based on a handover model for serving satellites (source/destination)

From Isolated Step to History-Based Optimization

FO

BO

isolated step approach

minimize

$n_{\max}(\mathbf{n_p})$ — minimize WCL capacity

subject to — link capacity constraint

$$n_{\max} \geq n_l = \sum_{w, w \in W} \sum_{p, p \in P_w} \delta_l^p n_p \ , \ \forall l$$

$$n_w = \sum_{p, p \in P_w} n_p \ , \ \forall w$$

OD/path capacity constr.

$0 \leq n_p \leq \alpha\, n_w \ , \ \alpha \in [1/k \ldots 1] \ , \ \forall p$

upper path cap. bounds

history-based approach

unchanged

plus:

lower path capacity bounds

$n_p^{\text{rem}} \leq n_p \ , \ \forall p$

$n_p^{\text{rem}} \leq n_p \leq \alpha\, n_w \ , \ \ldots$

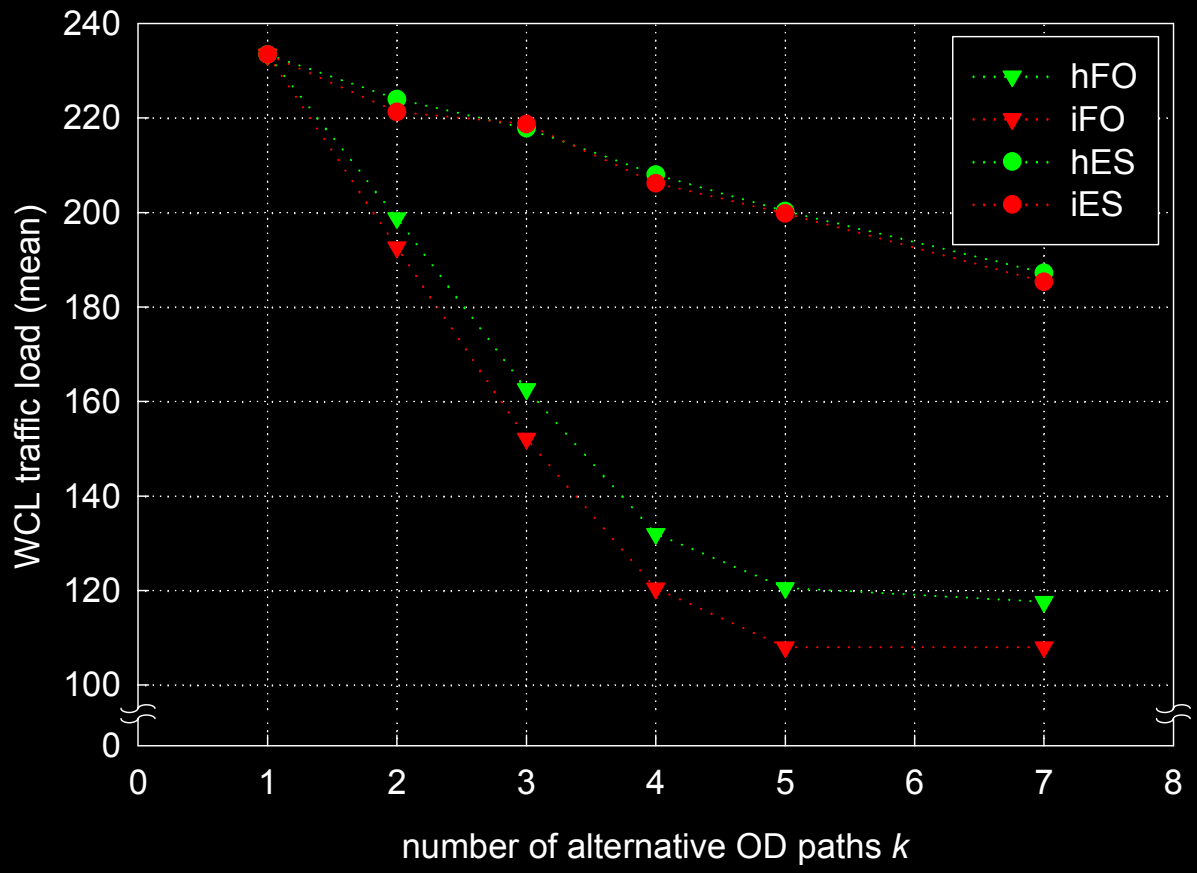
lower and upper path cap. bounds

in other words:

$$n_p^{\text{opt}} = 1 - n_p^{\text{rem}} = n_p^{\text{new}} + n_p^{\text{rer}}$$

WCL Load: Isolated Step vs History-Based

(mean call holding time: 3 min)



Link Load over Time

for shortest path routing (no optimization):

north

south

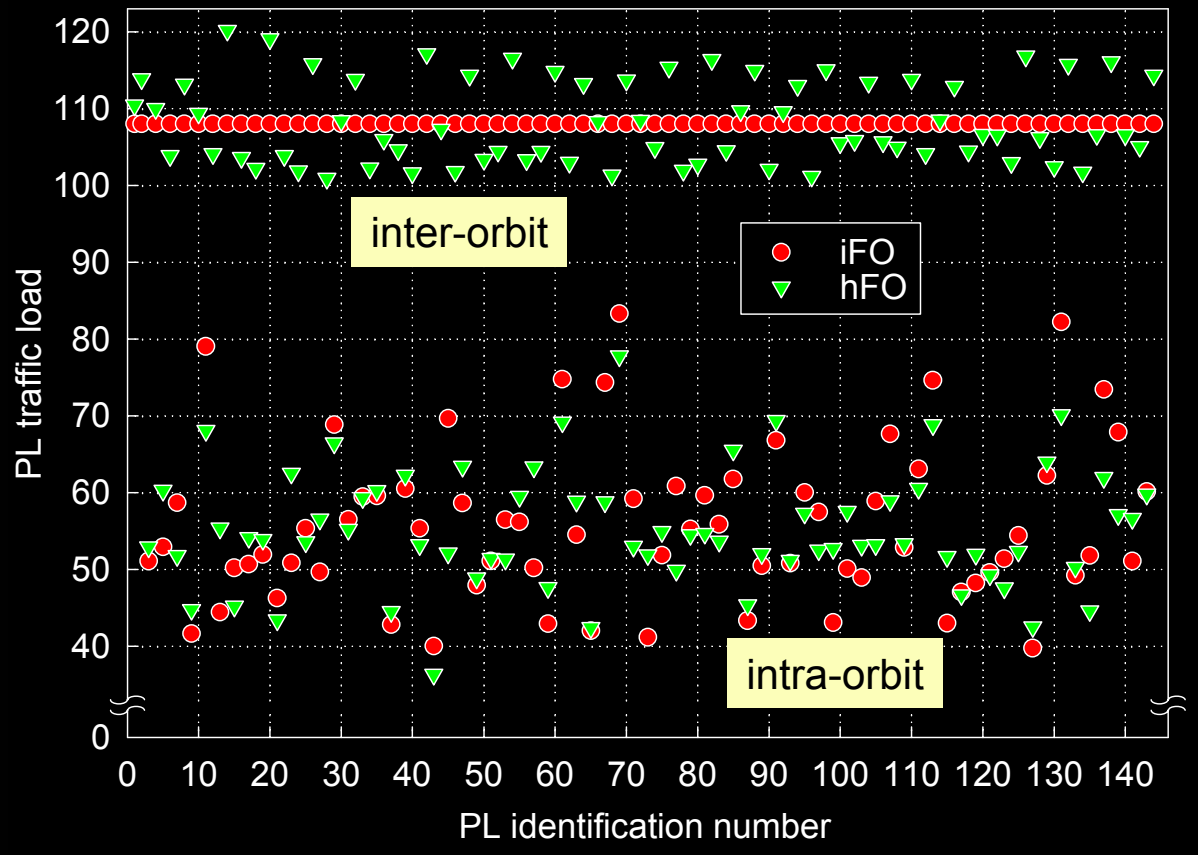
equator

equator

- periodic behaviour: peaks at higher latitudes (shorter inter-orbit links)
- inter-orbit ISLs are the critical ones

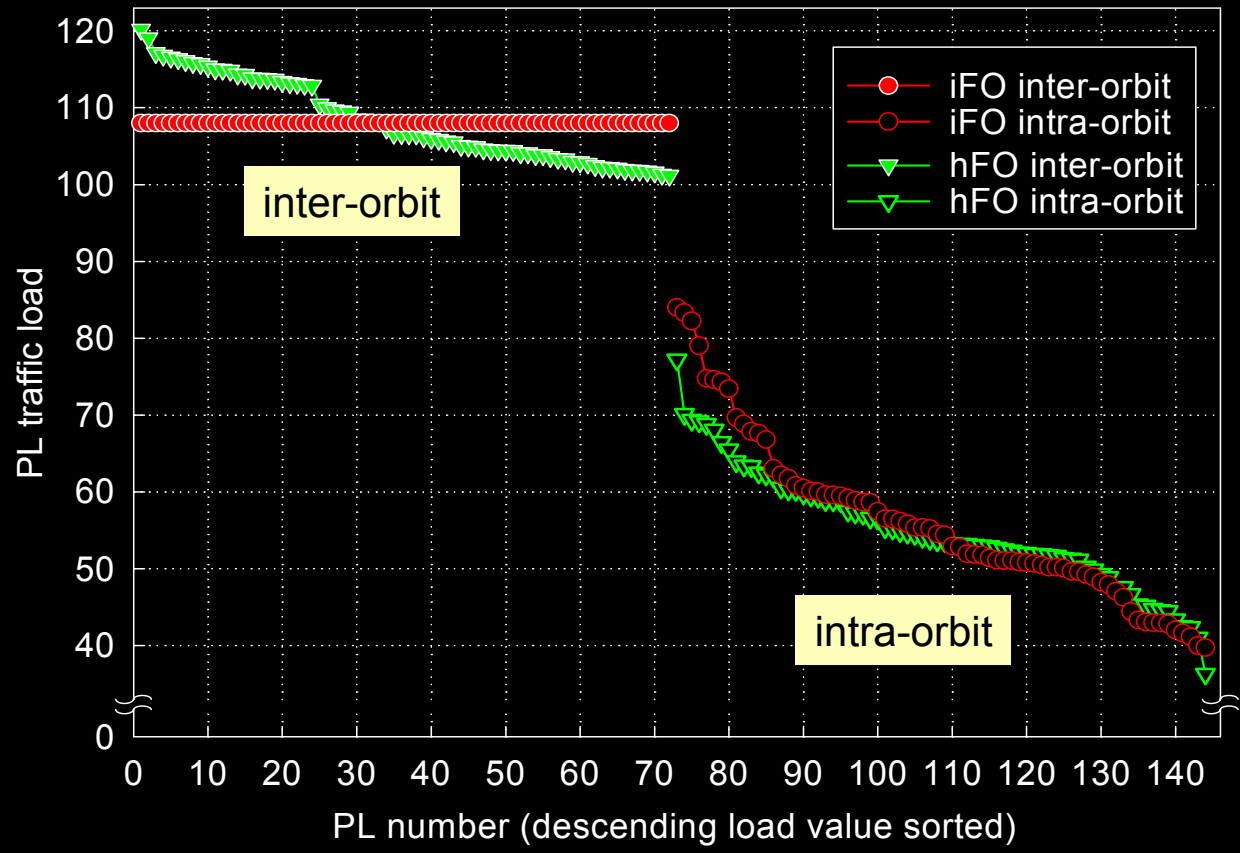
Link Load Distribution in the Network: hFO vs iFO

Snapshot at *t*=0:



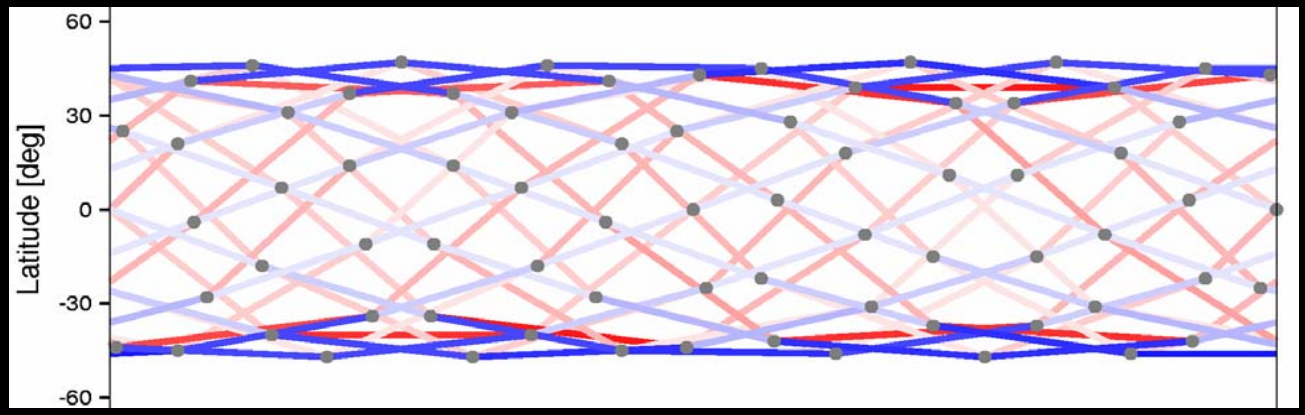
Link Load Distribution in the Network: hFO vs iFO

Snapshot at *t*=0:

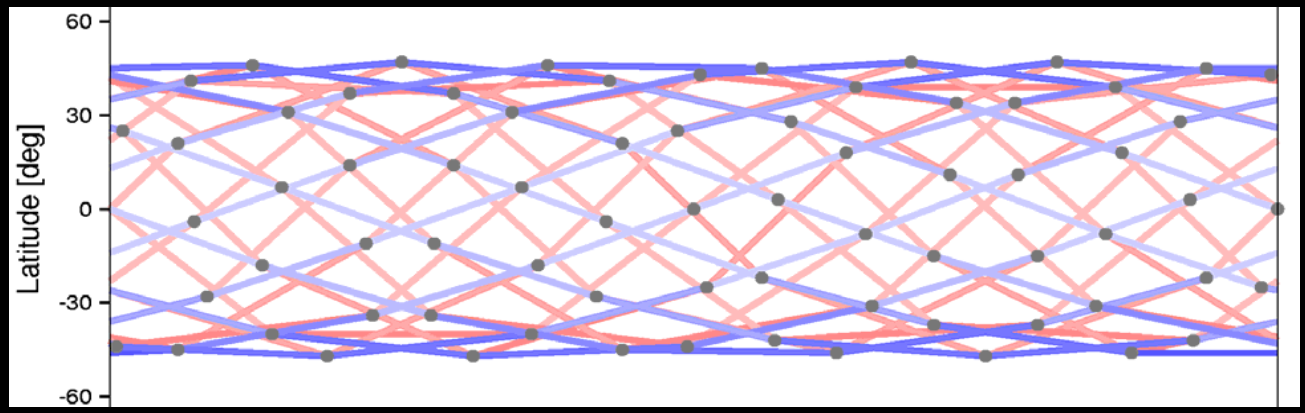


... and all that on the map:

without optimization (shortest path routing):



with optimization (multipath/alternate routing):



Conclusions (on Work Done)

- ✓ Network design process for LEO ISL networks:
- ✓ Topological design and dynamic routing framework
- ✓ Network dimensioning: (a) heuristic design rules,
- ✓ (b) LP optimization approach
- ✓ Advanced history-based approach shows limited reduction of optimization gain
- ✓ Simple isolated step approach remains a low-complexity method for "quick-and-dirty" dimensioning

A Motivation for Ongoing Work: Connection-Oriented (CO) vs Connectionless (CL) ?

Looking from a CO engineer's point of view:

- ISL topologies are (deterministically) dynamic
- end user connections must be handed over between serving satellites

==> "connections" must be broken up and rerouted in predictable steps

Looking from a CL engineer's point of view:

- ISL topologies are dynamic (-> routing updates ?!); YES, BUT:
- ISL dynamics is predictable, periodic
- ISL topologies are regular (in terms of nodes and links)

==> use nice properties, become "a bit more CO"?

Looking from an unbiased engineer's point of view:

==> Combine benefits, be SCO (sub-connection oriented)!

Packet-Oriented ISL Networking

- Ongoing joint research area of Institut Jožef Stefan (IJS) Ljubljana and DLR
  - partly within COST 252 Action
  - ISL network simulator on packet level implemented at IJS:
    - Dijskstra SPA for route calculation
    - traffic adaptive components using queue status information
    - generic on-board packet generation approach
    - interface to up/donwlink modules and corresponding traffic input
- Some results:
  - constraint-based routing combines topology and load information
  - adaptive routing concept and protocol implementation verified
  - some performance studies (routing update invterval, WCL load, ...)
  - alternate link routing proposed for “optimized” flows ...
- ... but still pure IP ... no systematic traffic engineering ... -> IP over ATM??

Multi-Protocol Label Switching (MPLS)

- THE solution for future packet-switched backbones (?)
- THE way to integrate ATM and IP (?), combining the benefits
  - calculate CO paths (ATM) using routing protocols like OSPF (IP)
  - establish these Label Switched Paths (LSPs) using MPLS unique protocols
  - allow frame and cell forwarding on the same link & in the same router
- Appeal of and issues for MPLS-based ISL networking
  - MPLS is a technique dedicated to backbones
  - a “blue-sky“ ISL network may be an ideal basis to exploit the fully potential of MPLS in a homogeneous global MPLS domain
  - each satellite acts as edge router (serving ground) and core router (transit)
  - importance of traffic engineering; potential use of proposed dimensioning methods, alternate routing approaches ...
  - use OSPF and LDP protocols within the proposed routing framework ?!

Optical ISL Networking

- Key role of optical communications for current/future backbone networks
  - (D)WDM - (dense) wavelength division multiplex
  - wavelength-routing or λ-switching
  - form optical transport network (OTN) by circuit-switched lightpaths
- For future ISL backbones:
  - low mass, size and power consumption of optical ISL terminals
  - PAT requirements for inter-plane ISLs can be met by laser technology
  - space OTN concepts are really close to the developed connection-oriented routing and dimensioning framework
- Research on space OTN has been initiated
  - lightpath assignment, (even more) simplified routing, new dimensioning issues, interoperation between optical and electronic domain (esp. for efficient resource utilization, flexible traffic flow multiplexing, ...)

Another Conclusion

Good concepts are sustainable –

sustainable concepts are good

(and both are required)

Just do it !