Delay-/ Disruption- Tolerant Networking: application to Space Communications.

Carlo Caini

University of Bologna

carlo.caini@unibo.it

Outline

- Introduction
  - Internet history
  - DTN overview
  - Satellite Communications in a nutshell
  - From PEPs to DTN
- DTN space applications
  - DTN Application to Satellite Communications
  - DTN Application to Interplanetary Communications
- Other topics
  - DTN Security
  - DTN QoS
- Conclusions

Part 1: Introduction

Internet history

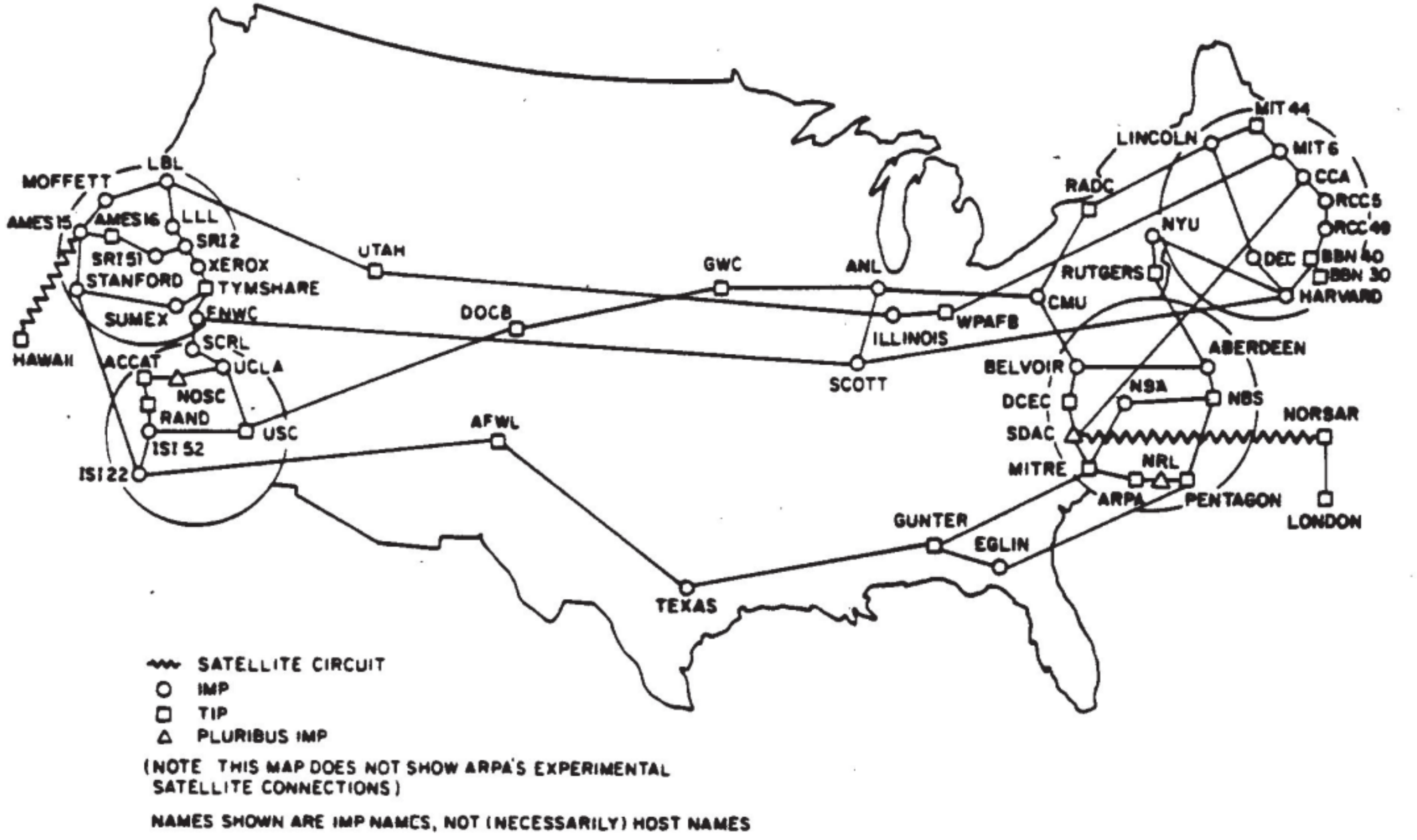
Internet origin

- What was Internet conceived for?
  - WWW, iTunes, Facebook, WhatsApp…?
- In facts, it was work shaped by the Cold War!
- Paul Baran (RAND, ARPA) became interested in the survivability of communication networks in the event of a nuclear attack (early 60's):
  - "Both the US and USSR were building hair-trigger nuclear ballistic missile systems. If the strategic weapons command and control systems could be more survivable, then the country's retaliatory capability could better allow it to withstand an attack and still function; a more stable position. But this was not a wholly feasible concept, because long-distance communication networks at that time were extremely vulnerable and not able to survive attack. That was the issue. Here a most dangerous situation was created by the lack of a survivable communication system."
- More generally, it derives from the shock caused in US by the launch of first artificial satellite, the Sputnik, by USSR in 1957.
  - "even the best (of our allies) require the assurance that we have not been surpassed scientifically and militarily by the USSR"
  - "We should accordingly plan to accomplish, ourselves, some of the next break-troughs first,… such as manned satellites or getting to the moon."
  - http://eisenhower.archives.gov/research/online_documents/sputnik.html
  - http://eisenhower.archives.gov/research/online_documents/sputnik/10_11_57.pdf

Internet basis

- Design pillars
  - Packet switching instead of circuit switching
  - Packet switching divides messages into arbitrary packets, routing decisions made per-packet.
  - Distributed & redundant architecture
- Aim
  - Provided that there is a continuous path between A (source) and B (destination), communication is possible.
  - The path among intermediate nodes is found in an automatic way
  - We will see that DTN goes further and relaxes even the continuous path constraint!

ARPANET


MOFFETT
LBL
AMES 15
AMES 16
LLL
SRI 2
SRI 51
XEROX
STANFORD
TYMSHARE
SUMEX
FNWC
HAWAII
SCRL
ACCAT
UCLA
NOSC
RAND
USC
ISI 52
ISI 22
UTAH
DOCB
GWC
ANL
AFWL
TEXAS
ILLINOIS
WPAFB
SCOTT
CMU
GUNTER
EGLIN
LINCOLN
MIT 44
MIT 6
RADC
CCA
RCC 5
RCC 49
NYU
DEC
BBN 40
BBN 30
RUTGERS
HARVARD
ABERDEEN
BELVOIR
NSA
NBS
DCEC
SDAC
NORSAR
MITRE
NRL
ARPA
PENTAGON
LONDON
SATELLITE CIRCUIT
IMP
TIP
PLURIBUS IMP
(NOTE THIS MAP DOES NOT SHOW ARPA'S EXPERIMENTAL SATELLITE CONNECTIONS)
NAMES SHOWN ARE IMP NAMES, NOT (NECESSARILY) HOST NAMES

Internet evolution

- 1960: First researches
- 1963: Memorandum for Members and Affiliates of the Intergalactic Computer Network, from J. C. R. Licklider (ARPA)
  - A joke by a visionary man (visionary=having or showing clear ideas about what should happen or be done in the future)
- 1969: The first message on the ARPANET on October 29
  - (“lo” for “log”, but after 2 characters the host crashed; 3 months after the first man on the Moon)
- 1971: ARPANET (23 nodes)
- 1973: TCP/IP Protocols, by Vinton Cerf and Bob Kahn
- 1981: 213 nodes
- 1989: 100 000 nodes
- 1991: World Wide Web birth (first web site)
  - by Berners-Lee and Robert Cailliau at CERN, HTML language, HTTP protocol
- 1996: 100 000 000 nodes
- 2001: Interplanetary Network Architecture (by V. Cerf, et alii);
- 2002: Delay-Tolerant Network Architecture: https://tools.ietf.org/html/draft-irtf-ipnrg-arch-01
- Intergalactic Network (work in progress…)
- To know more http://www.internetsociety.org/internet/what-internet/history-internet/brief-history-internet

Internet & Patents

- Internet revolution is based on open software
  - Vint Cerf: "One of the things that is peculiar and interesting about the Internet history is that the TCP-IP protocols were never patented. In fact, they were made available as widely as possible to the public as soon as possible.... The openness of those protocols and their availability was key to their adoption and widespread use.“
  - HTTP, HTML deliberately not patented by CERN
- Please, let us free…

DTN Overview

Introduction

- Some assumptions at the basis of Internet protocols (TCP/IP)
  - End-to-end connectivity
    - Communication is possible if exists at least a continuous path between source and destination
  - Short RTT
    - Loss recovery is based on ARQ (Automatic Repeat reQuest), i.e. on retransmissions from the source
  - Few Losses
    - Most due to congestion
- "Challenged networks"
  - Environments where one or more of the previous assumptions do not hold
- DTN (Delay-/Disruption- Tolerant Networking)
  - A novel networking architecture to cope with the problems of challenged networks

Background & standardization

- 1973 –Vinton Cerf and Bob Kahn work on TCP/IP
  - A Protocol for Packet Network Intercommunication, IEEE Trans on Comms, Vol Com-22, No 5 May 1974
- 1998 –Cerf at alii promoted the Interplanetary Internet (IPN)
  - IRTF IPNRG start
- 2001 –2002
  - 2001 "Interplanetary Internet: Architectural Definition" Internet draft
    - Necessity of a new architecture for space environments made clear
  - 2002 New version of the previous draft: "Delay-Tolerant Network Architecture: The Evolving Interplanetary Internet" draft-irtf-ipnrg-arch-01
    - The new architecture (re-Christianized as DTN) can be applied to other environments ("challenged networks")
  - 2002 IRTF DTNRG start
    - "It is an open research group, anyone interested can contribute simply by joining the mailing list and getting involved in the work".
- 2010 – CCSDS (Consultative Committee for Space Data Systems) standardization start
  - https://public.ccsds.org/default.aspx
- 2014 – IETF DTNWG start
  - From Research (IRTF) to Engineering (IETF)

IRTF DTNRG& IETF DTNWG

- IRTF DTNRG
  - The Delay-Tolerant Networking Research Group (DTNRG) was a research group chartered as part of the [Internet Research Task Force (IRTF)](), concluded in April 2016.
    - https://irtf.org/concluded/dtnrg
  - «Members of DTNRG are concerned with how to address the architectural and protocol design principles arising from the need to provide interoperable communications… in performance-challenged environments»
    - Spacecraft
    - military/tactical
    - some forms of disaster response
    - Underwater
    - and some forms of ad-hoc sensor/actuator networks
    - Internet connectivity in places where performance may suffer such as developing parts of the world.
- DTN standardization continues in IETF DTN Working Group (DTNWG)
  - https://datatracker.ietf.org/wg/dtn/charter/

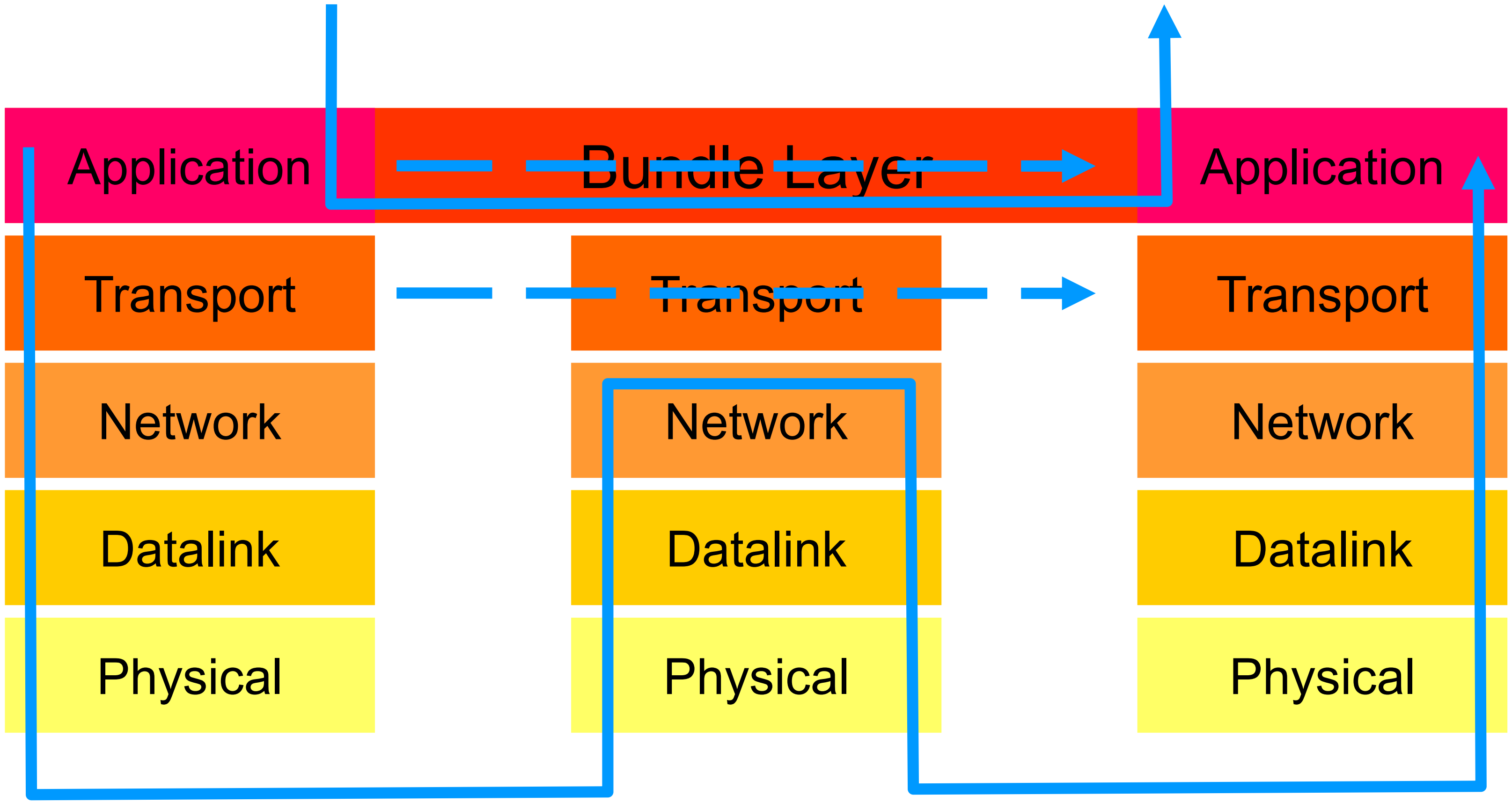
The Bundle Protocol DTN architecture

- BP DTN architecture
  - Not the sole but the most important DTN architecture
- Fundamental RFCs
  - RFC 4838: Delay-Tolerant Networking Architecture, V. Cerf et al., Apr. 2007; http://tools.ietf.org/html/rfc4838.
  - RFC 5050: Bundle Protocol Specification, K. Scott and S. Burleigh, Nov. 2007; http://tools.ietf.org/html/rfc5050
  - RFC 9171: Bundle Protocol Version 7, S. Burleigh, K. Fall, E. Birrane, Jan. 2022; https://www.rfc-editor.org/rfc/rfc9171.html
- Major current BP implementations
  - DTNME (v.1.01 beta) by NASA-MSFC (Marshall Space Flight Centre)
    - fork of DTN2 2.9
  - ION (v.4.1.1) by NASA JPL
  - IBR-DTN by University of Braunshweig
  - µD3TN by D3TN
  - Others…

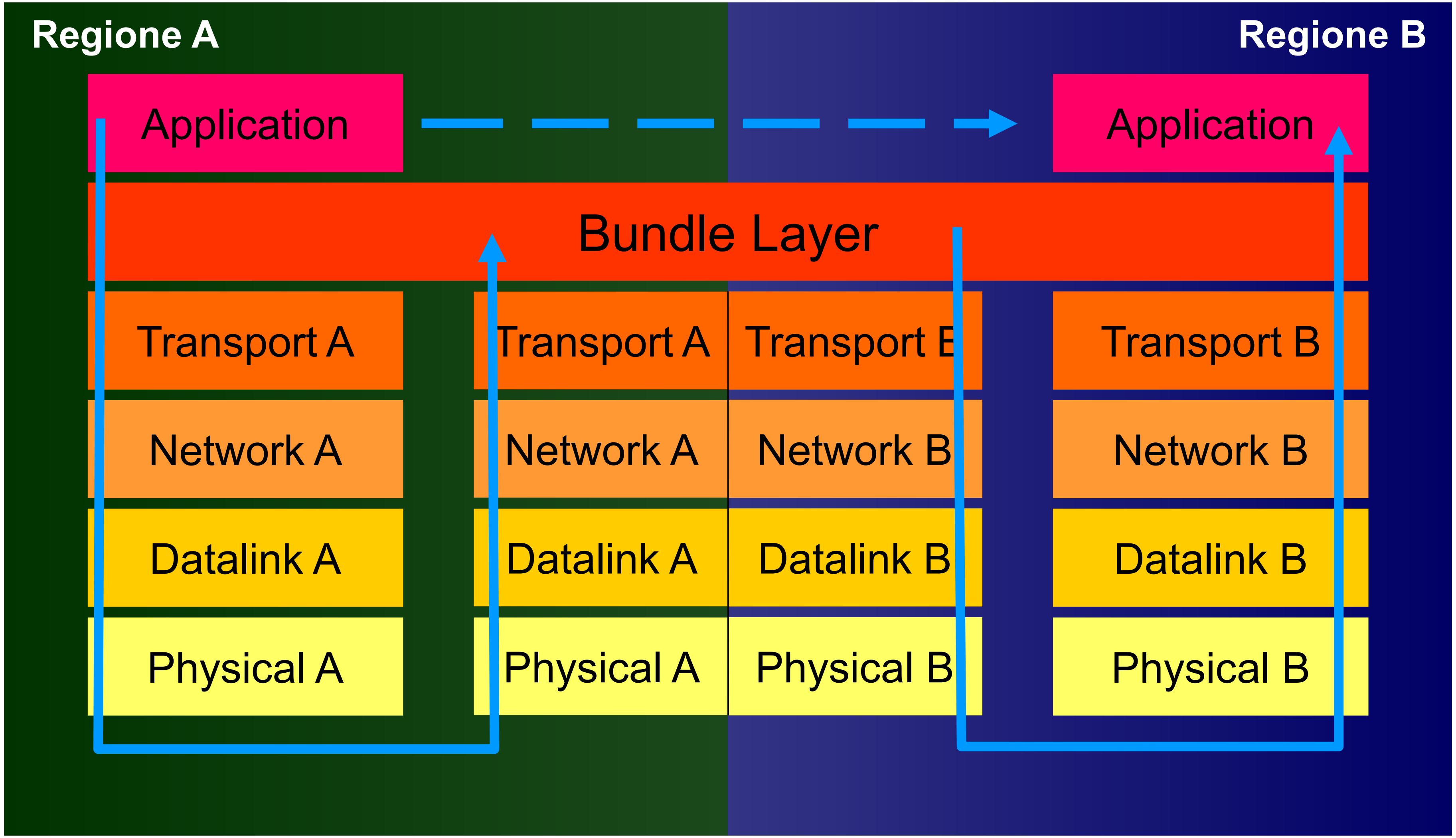
The Bundle Protocol DTN architecture

- It is based on the introduction of the Bundle layer between Application and lower layers (e.g. Transport)
  - “Bundles” are (large) data packet at this layer
  - Store (carry) and forward
    - A bundle is first received, stored, (sometimes carried) and then transmitted when possible.

Bundle Layer



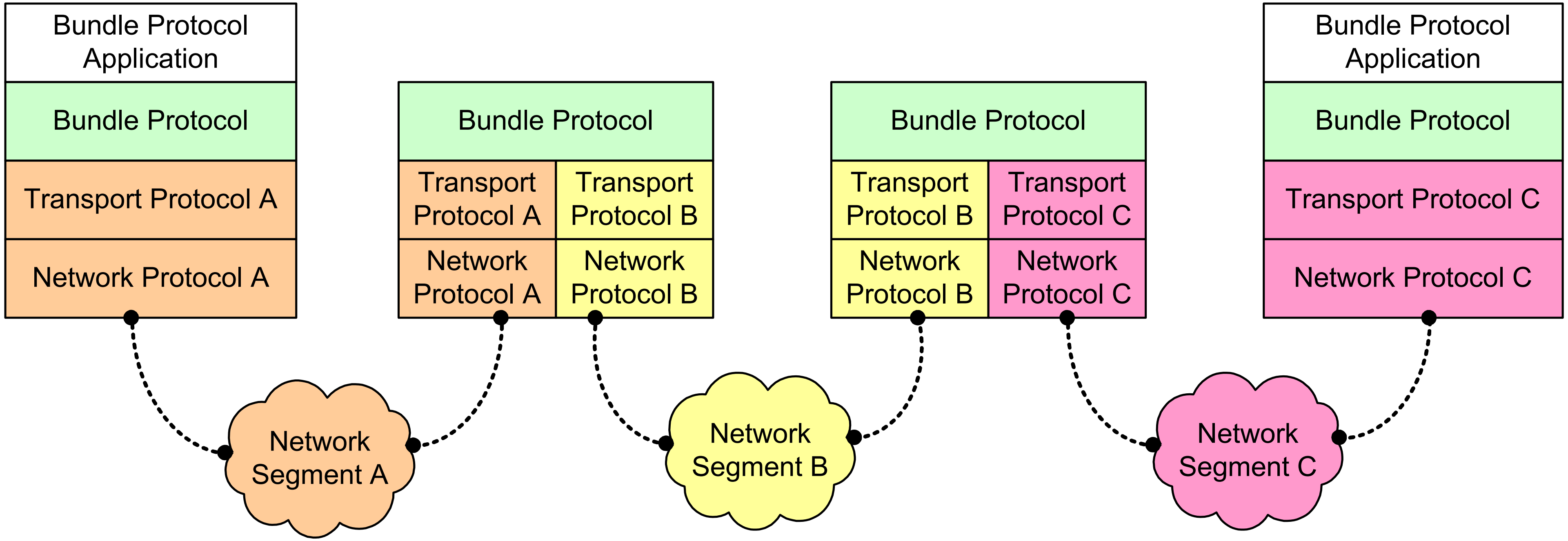
Bundle Layer



DTN as an overlay

- End-to-end path in a heterogeneous network divided into multiple DTN hops
- Transport end-to-end semantics confined inside each DTN hop
- Possibility to use different protocol stacks in different DTN hops
  - TCP or transport protocols specialized to channel characteristics of each DTN hop
- Bundle layer is not end-to-end
  - It is present in some intermediate nodes too.

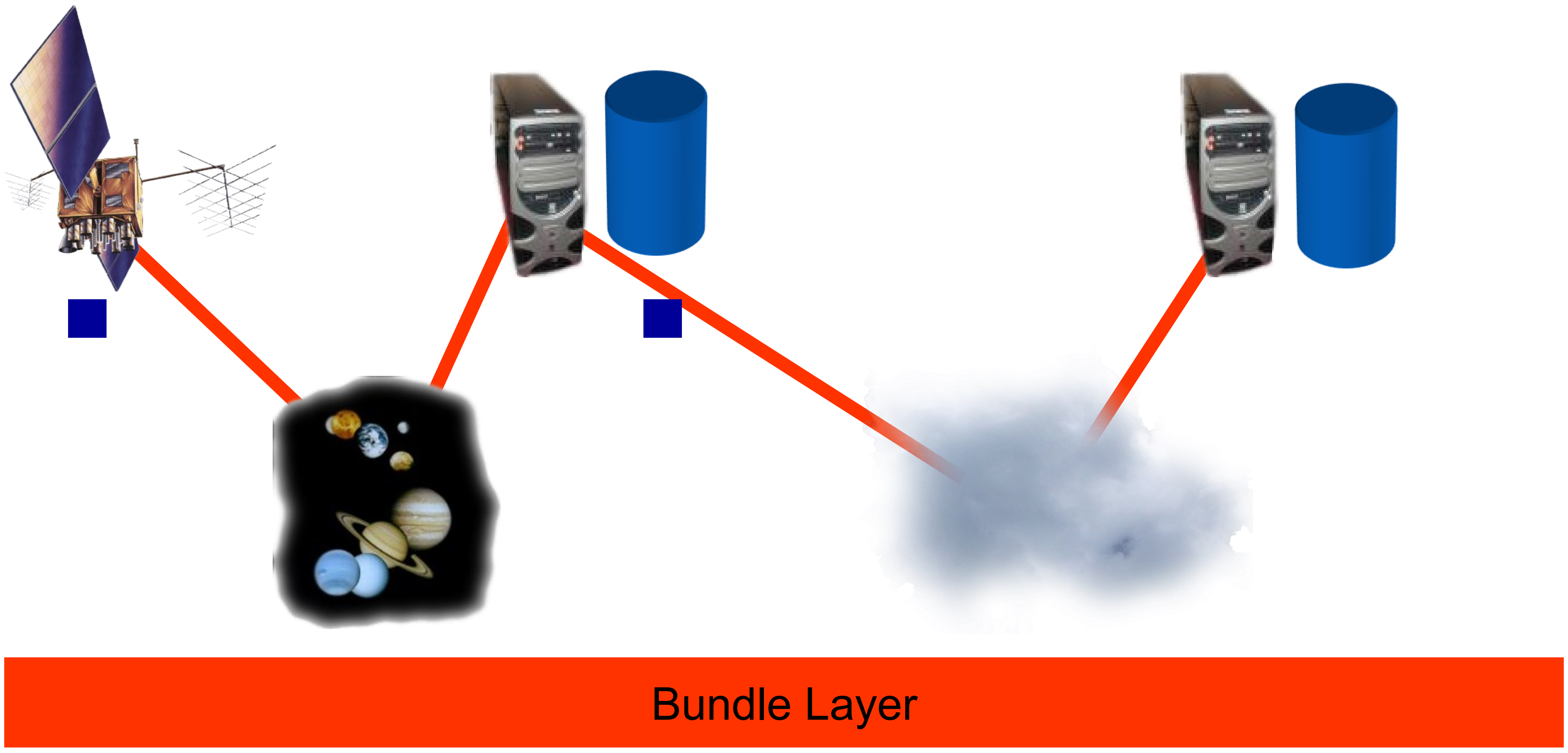
DTN overlay over a heterogeneous network



Information storage at intermediate nodes

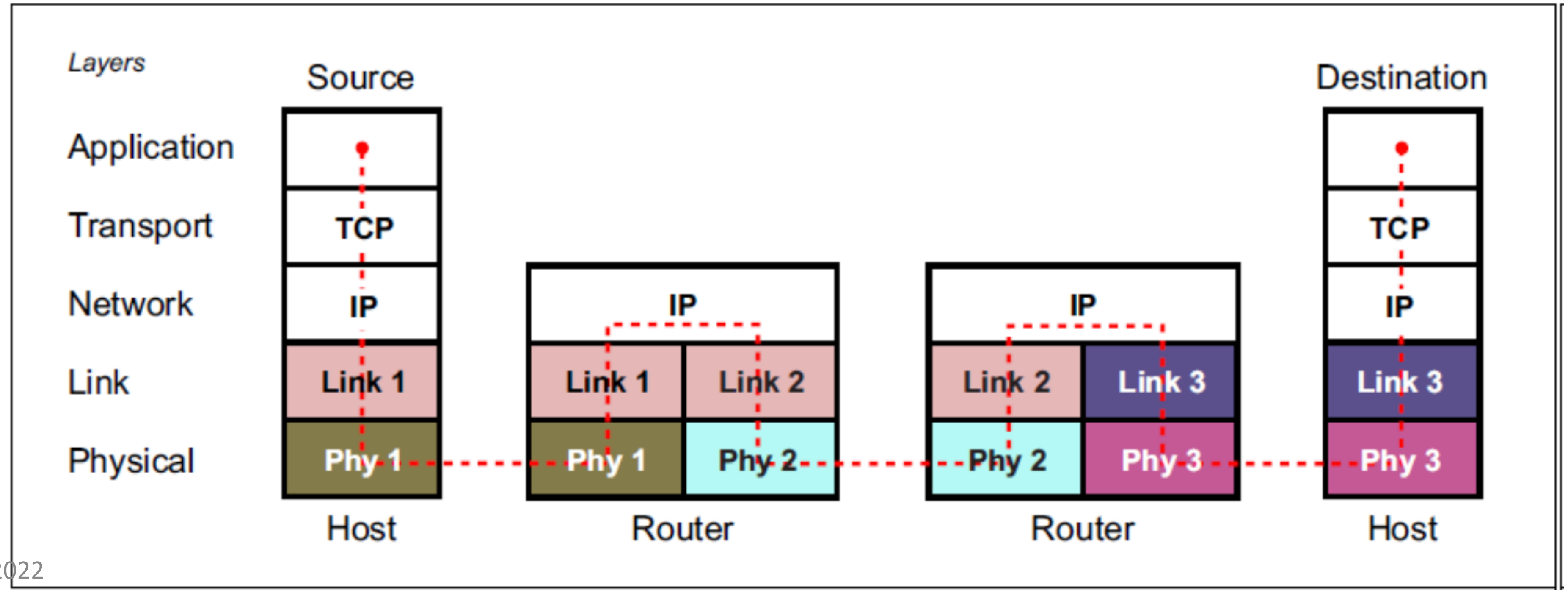
- Why necessary
  - To cope with the possible lack of a continuous end-to end-path (e.g. “data mule” applications)
  - More efficient loss recovery with long RTTs
    - Transport protocols retransmissions are no longer end-to-end, but operate on one DTN hop (shorter RTT)
- Standard mechanism
  - Bundles are stored on a local database as soon as created or received
  - Bundles may be removed once sent; they are always removed when their lifetime expires.
- "Custody transfer” option
  - It is based on a “token” passing mechanism
  - The custodian of a bundle:
    - must retransmit the bundle unless a “custody acceptance” is received before an RTO
    - cannot delete the bundle before a following node (not necessarily the next) has accepted the custody (or the bundle has expired)
  - Removed in bpv7 because of difficulty in setting the RTO

Bundle transfer



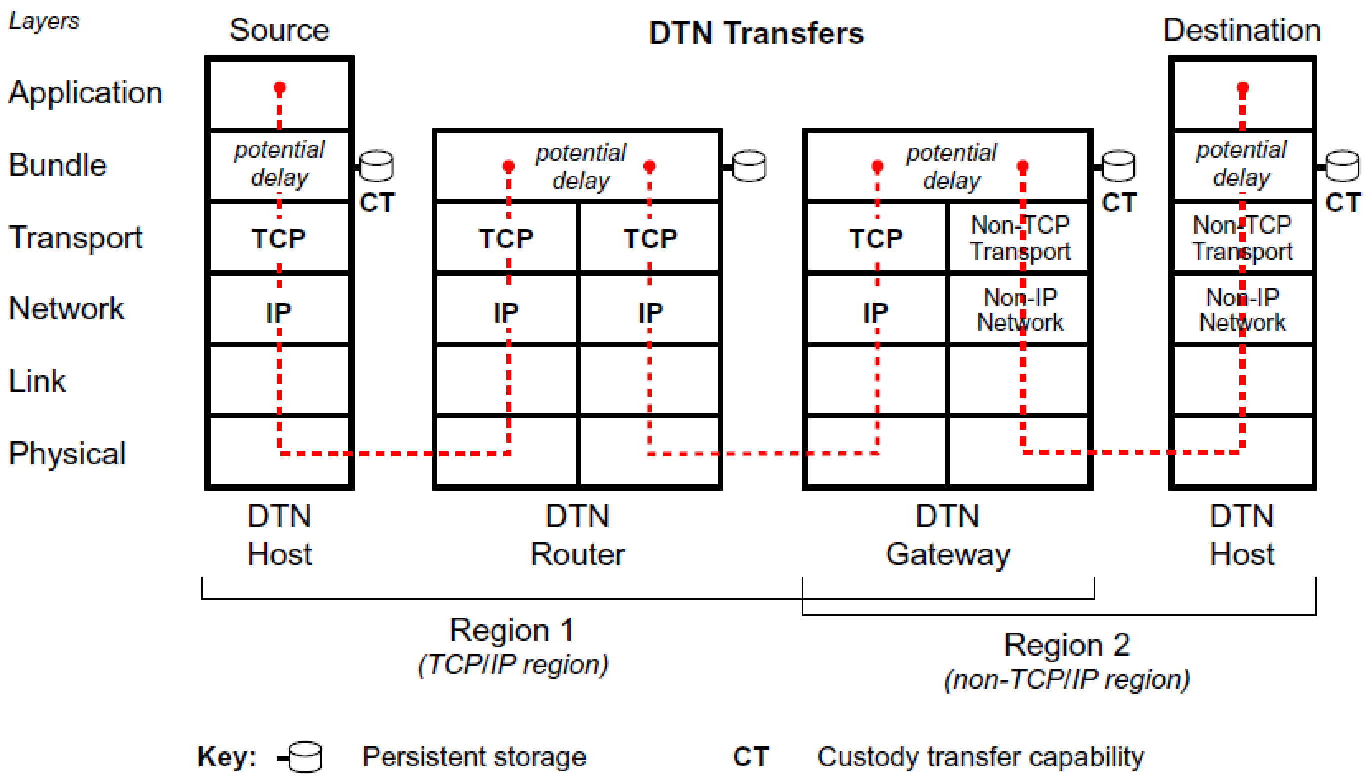
The TCP/IP architecture

- Transport is end-to-end
- Intermediate nodes (routers) have just the first 3 layers
- If you do not know the TCP-IP architecture, or the ISO-OSI model, please study this on a good Computer Networks book (e.g. by Tanenbaum) asap.



The DTN architecture

- Transport is no longer end-to-end (it is end-to-end only inside one DTN hop)
- Note: between two DTN nodes, we can have many intermediate Layer 3 routers (not reported)



CT is not the main database, there is always a local database but it's not CT. CT was from a previous version of the protocol.

Bundle fragmentation (proactive)

- Proactive fragmentation
  - In networks with intermittent scheduled (periodic) connectivity, it allows large bundles to be divided “a priori” into multiple fragments compatible with the “contact volume”.
    - The contact volume is the maximum amount of data that can be transferred on a DTN hop at each “contact” (opportunity of Tx from node A to node B). It is calculated as the product of contact duration and nominal Tx speed
  - Useful in deep space or LEO systems
  - Not implemented in DTN2/DTNME; implemented in ION (udpcl)

Bundle fragmentation (reactive)

- Reactive fragmentation
  - Works a posteriori, when disruptions interrupt an on going bundle transfer
  - Not to retransmit already received data, the partially transmitted bundle is split into two “fragments”. The first contains data already sent, the second the remaining data. At link re-establishment, only the second fragment is transmitted.
  - Bundle fragments are treated as ordinary bundles and consecutive fragmentations are possible.
  - Reactive fragmentation is useful for large bundles when disruptions may be relatively frequent and unpredictable, as in satellite communications with mobile terminals.
  - Implemented in DTN2/DTNME but not in ION

Late binding (advanced)

- Late binding is one of the most difficult concept in DTN
  - Its implications are subtle to understand
  - Consequences are revolutionary
- E.g. you can send bundles to “future” nodes
  - You can send a bundle from your desktop to the smartphone that you are going to buy tomorrow… (e.g. dtn://mynextsmartphone.dtn)
- How?
  - The bundle is DTN-routed on the basis of the destination EID (a name, without any topological meaning). The last node on the path can take it in its database until a new node, claiming to be “dtn://mynextsmartphone.dtn” opens a connection to it. Maybe the following day…

Routing

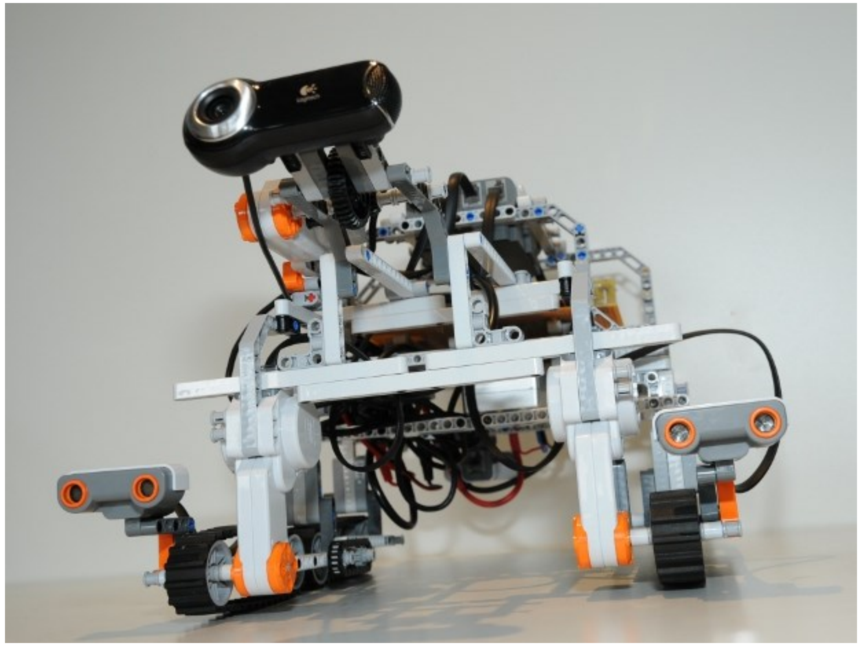
- Routing in DTN is a really challenging issue (and a hot research topic)
- DTN routing schemes have to deal with these major problems which prevents the use of Internet routing algorithms
  - Network can be partitioned (e.g. data mule)
  - Links may be intermittent (a path can be available only for limited intervals)
  - Storage at intermediate nodes is limited
  - Routing information exchanges among nodes are impaired by delays and disruptions
- Possible routing objectives
  - delivery delay
  - probability of bundle delivery
  - storage management (new)
- Routing schemes must adapt to the peculiarities of the different DTN networks
  - Not just one routing scheme but many solutions
- See the QoS section

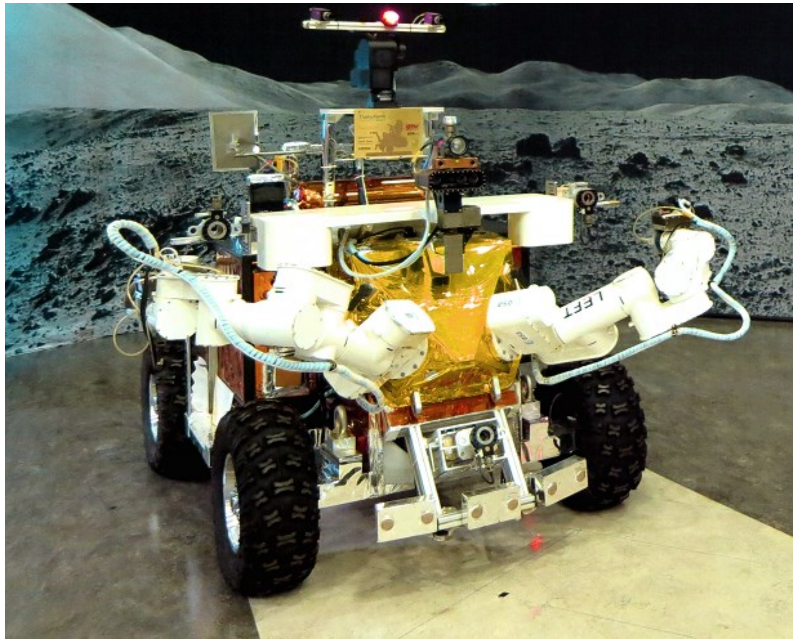
DTN Experiments in space

- Epoxy experiment by NASA (one DTN node in deep space)
- Experiments from the International Space Station
  - https://www.nasa.gov/mission_pages/station/research/experiments/explorer/Investigation.html?#id=717
  - Multi-purpose End-To-End Robotic Operations Network (METERON, by ESA, NASA, DLR…)
  - https://www.nasa.gov/feature/goddard/2018/disruption-tolerant-networking-to-demonstrate-internet-in-space
- Experiments on satellites
  - UK part of the Disaster Monitoring Satellite (DMC)
  - MITRE (Tactical Networks)
  - NASA-D3TN

DTN & LEGO & on (ESA Meteron)

- Lego robot controlled by ISS via DTN (2013 ESA experiment)
  - “The experimental DTN we’ve tested from the space station may one day be used by humans on a spacecraft in orbit around Mars to operate robots on the surface, or from Earth using orbiting satellites as relay stations.”
- Other experiments with larger robots (Eurobots) are going on from ISS via DTN
  - http://blogs.esa.int/meteron/
  - http://esamultimedia.esa.int/multimedia/virtual-tour-iss/





Bundle Protocol DTN architecture RFCs

- Fundamental RFCs
  - RFC 4838: Delay-Tolerant Networking Architecture, V. Cerf et al., Apr. 2007
    - http://tools.ietf.org/html/rfc4838.
  - RFC5050: Bundle Protocol Specification, K. Scott and S. Burleigh, Nov. 2007
    - http://tools.ietf.org/html/rfc5050.
  - RFC 9171: Bundle Protocol Version 7, S. Burleigh, K. Fall, E. Birrane, Jan. 2022
    - https://www.rfc-editor.org/rfc/rfc9171.html
- Other RFCs
  - RFC 6255: Delay-Tolerant Networking Bundle Protocol IANA Registries, M. Blanchet, May 2011, http://tools.ietf.org/html/rfc6255
  - RFC 6256: Using Self-Delimiting Numeric Values in Protocols W. Eddy, E. Davies, May 2011 http://tools.ietf.org/html/rfc6256
  - RFC 6257: Bundle Security Protocol Specification, S. Symington et al. May 2011 http://tools.ietf.org/html/rfc6257
  - RFC 6258: Delay-Tolerant Networking Metadata Extension Block, S. Symington, May 2011 http://tools.ietf.org/html/rfc6258
  - RFC 6259: Delay-Tolerant Networking Previous-Hop Insertion Block, S. Symington, May 2011, http://tools.ietf.org/html/rfc6259
  - RFC 6260: Compressed Bundle Header Encoding (CBHE), S. Burleigh, May 2011 http://tools.ietf.org/html/rfc6260
  - RFC 9172: Bundle Protocol Security (BPSec) E. Birrane, K. McKeever, Jan. 2022 http://tools.ietf.org/html/rfc9172
  - RFC 9173: Default Security Contexts for Bundle Protocol Security (BPSec), E. Birrane, A. White, S. HeinerK. Jan. 2022 http://tools.ietf.org/html/rfc9173
  - RFC 9174: Delay-Tolerant Networking TCP Convergence-Layer Protocol Version 4,. B. Sipos, M. Demmer, J. Ott, S. Perreault, Jan. 2022 http://tools.ietf.org/html/rfc9174

Other references of the "DTN Overview" section

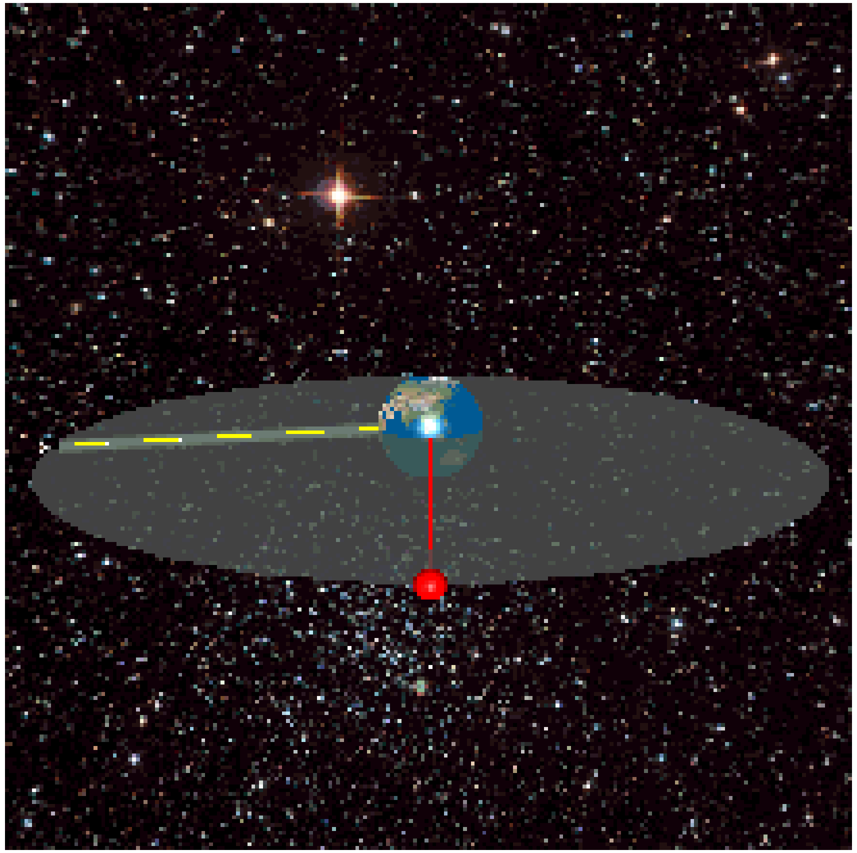
- A. McMahon, S. Farrell, "Delay- and Disruption-Tolerant Networking", IEEE Internet Computing, vol. 13, no. 6, pp. 82-87, Nov./Dec. 2009.
  - DOI: 10.1109/MIC.2009.127
- K. Fall, S. Farrell, "DTN: an architectural retrospective", IEEE J. Select. Areas in Commun., vol.26, no.5, pp. 828-836, June 2008.
  - DOI: 10.1109/JSAC.2008.080609
- J. Wyatt, S. Burleigh, R. Jones, L. Torgeson, S. Wissler, "Disruption Tolerant Networking Flight Validation Experiment on NASA's EPOXI Mission", in Proc. First Int. Conf. on Advances in Satellite and Space Commun., Colmar, France, 2009, pp. 187-196.
  - DOI: 10.1109/SPACOMM.2009.39
- W. Ivancic, W.M. Eddy, D. Stewart, L. Wood, J. Northam, C. Jackson, , "Experience with Delay-Tolerant Networking from Orbit", Int. J. Satell. Commun. Netw., vol. 28, no. 5-6, pp. 335-351, Sept. –Dec. 2010.
  - DOI: 10.1109/ASMS.2008.37
- C. Caini, H.Cruickshank, S. Farrell, M. Marchese, "Delay- and Disruption-Tolerant Networking (DTN): An Alternative Solution for Future Satellite Networking Applications," Proceedings of the IEEE , vol.99, no.11, pp.1980,1997, Nov. 2011
  - DOI: 10.1109/JPROC.2011.2158378
- F. Warthmann, "Delay-Tolerant Networks (DTNs), A tutorial v.3.2"
  - http://ipnsig.org/wp-content/uploads/2015/09/DTN_Tutorial_v3.2.pdf
- CCSDS Bundle Protocol Specification, 734.2-B-1, Blue Book, September 2015.
  - https://public.ccsds.org/Pubs/734x2b1.pdf.

Satellite Communications in a nutshell

Geostationary Earth Orbit (GEO)

From Wikipedia https://en.wikipedia.org/wiki/Geostationary_orbit

- A circular orbit 35,786 kilometers (22,236 mi) above the Earth's equator and following the direction of the Earth's rotation.
    - Orbital radius is 42164 km
    - Earth's equatorial radius 6378 km
    - GEO altitude 35,786 kilometers
- An object in such an orbit has an orbital period equal to the Earth's rotational period (one sidereal day), and thus appears motionless, at a fixed position in the sky, to ground observers.
- Communications satellites and weather satellites are often given geostationary orbits, so that the satellite antennas that communicate with them do not have to move to track them, but can be pointed permanently at the position in the sky where they stay.



Derivation of geostationary altitude

$$F_{newton} = \frac{G m_{sat} m_{earth}}{r^2}$$

$$F_{centripetal} = m_{sat} \omega^2 r$$

$$F_{newton} = F_{centripetal}$$

$$\frac{G m_{earth}}{r^2} = \omega^2 r$$

$$\frac{\mu}{r^3} = \omega^2 \qquad \mu = G m_{earth}$$

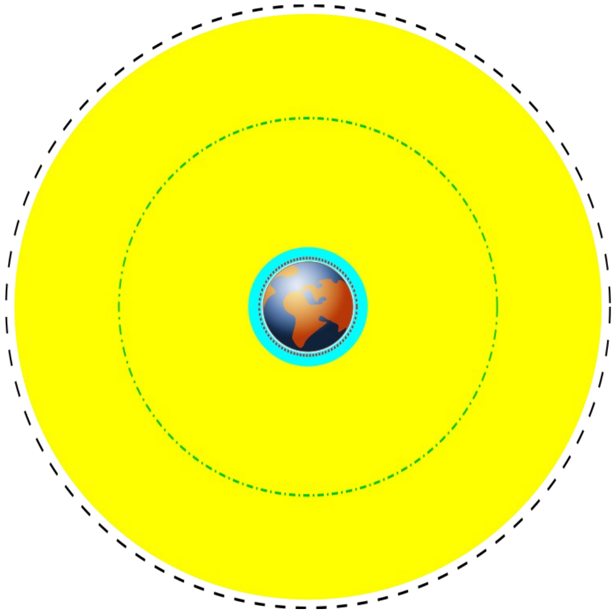
$$r = \sqrt[3]{\frac{\mu}{\omega^2}}$$

GEO sats

- Advantages
  - To an observer on Earth they appear fixed in the Sky (no tracking necessary)
  - 3 satellites at 120° on the GEO orbit can provide an almost full coverage of the Earth
- Disadvantages
  - High free-space attenuation due to the long distance
  - High propagation delay (about 125 ms from Earth to sat, i.e. RTT>500ms)
  - The inclination angle of the antenna on Earth decreases with the latitude
  - Lack of coverage of polar regions

Distances from Earth

English	Marker	Distance above earth (km)	Distance from center of earth (km)
Earth	Blue/brown image	0	6370
Low Earth Orbit (LEO)	Cyan area	160 to 2,000	6,530 to 8,370
Medium Earth Orbit (MEO)	Yellow area	2,000 to 34,780	8,370 to 41,150
International Space Station (ISS)	Red dotted line	370	6,741
Global Positioning System (GPS) satellites	Green dash-dot line	20,230	26,600
Geostationary Orbit (GEO)	Black	35,794	42,164



https://en.wikipedia.org/wiki/Low_Earth_orbit

Distances from Earth

- A perfectly scaled diagram showing the orbital altitudes of several satellites (LEO, MEO, GEO).
  - https://en.wikipedia.org/wiki/Low_Earth_orbit#/media/File:Orbitalaltitudes.jpg

Low Earth Orbit (LEO)

- Advantages
  - Low attenuation
  - Short propagation delay (and RTT)
  - The short distance allows for high resolution images of the Earth
- Disadvantages
  - They move fast in the sky
  - Global coverage requires constellations of tenths of satellites
- If the orbit is polar all the regions of the Earth can be covered by one satellite (not simultaneously of course)
  - good for Earth Observation
  - Typical orbital period=100m
  - LOS (Line of Sight) Window= few minutes (e.g. 8)

Some GEO Sat Com Providers

- GEO
  - Inmarsat (full constell.; global coverage but polar regions)
    - http://www.inmarsat.com/
    - http://en.wikipedia.org/wiki/Inmarsat
  - Thuraya (single GEO satellite; coverage of some continents)
    - http://www.thuraya.com/
    - http://en.wikipedia.org/wiki/Thuraya

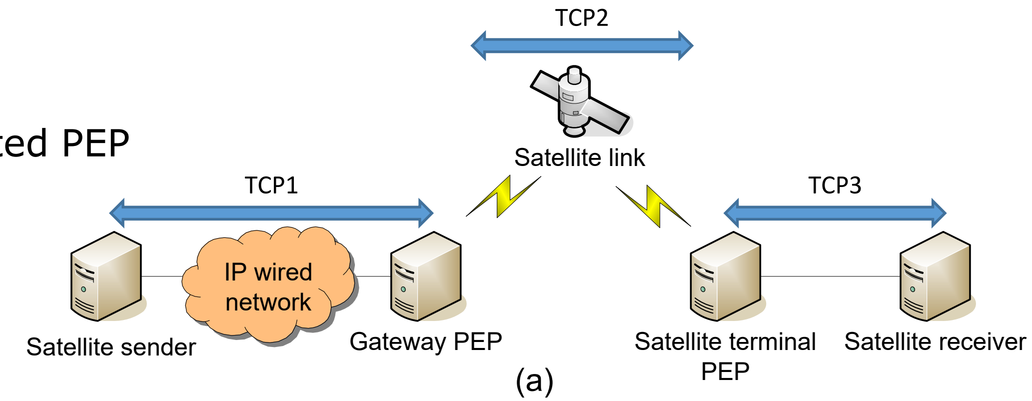
Some LEO Sat Com Providers

- First LEO providers
  - Iridium (66LEOs, true global coverage, optical inter sat links)
    - http://www.iridium.com
    - http://en.wikipedia.org/wiki/Iridium_satellite_constellation
  - Globalstar (24 LEOs, coverage of continents, no Oceans…;)
    - no inter sat links
    - Emergency message service for Iphone 14
    - http://eu.globalstar.com/en/
    - http://en.wikipedia.org/wiki/Globalstar
- LEO mega constellations
  - OneWeb (648 LEOs planned, 464 launched Oct. 2022; no inter sat links)
    - Failed in 2020; project sold to the UK government and to an Indian company; last launches blocked by Russia at the beginning of Ukrainian war; launches will restart from INDIA
    - https://www.oneweb.world/
    - https://en.wikipedia.org/wiki/OneWeb
  - Starlink (12000 LEOs planned, 2300 operational Oct. 2022; by SpaceX; optical inter sat links)
    - By 6 April 2022, SpaceX had sent over 5000 Starlink terminals to Ukraine to allow Ukrainians access to the Starlink network; more than 22000 operational in autumn 2022; 700000 users worldwide
    - https://www.starlink.com/
    - https://en.wikipedia.org/wiki/Starlink_(satellite_constellation)
  - «space debris» problem is still an open issue
  - Visibility is a new issue… (LEOs more visible than stars at night?)

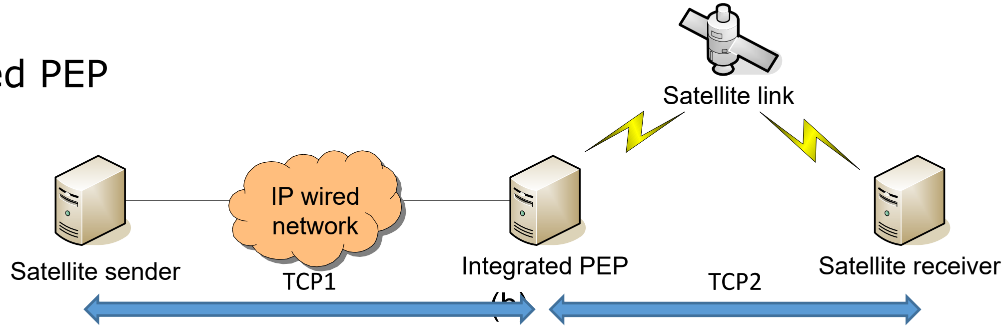
From PEPs (Performance Enhancing Proxies) to DTN

From PEPs to DTN

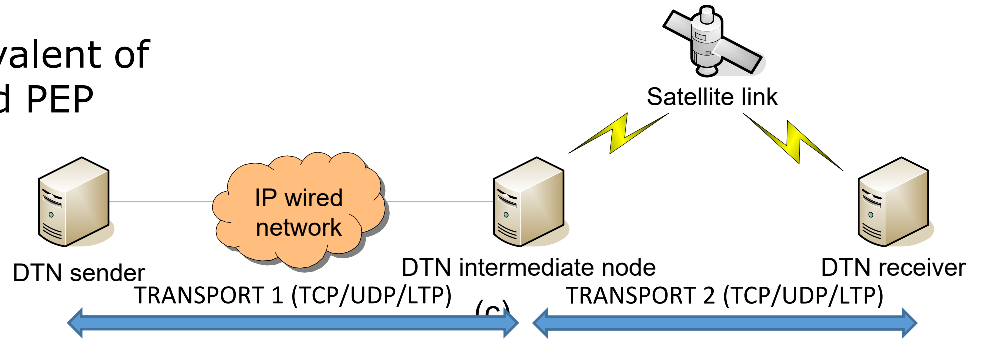
Distributed PEP



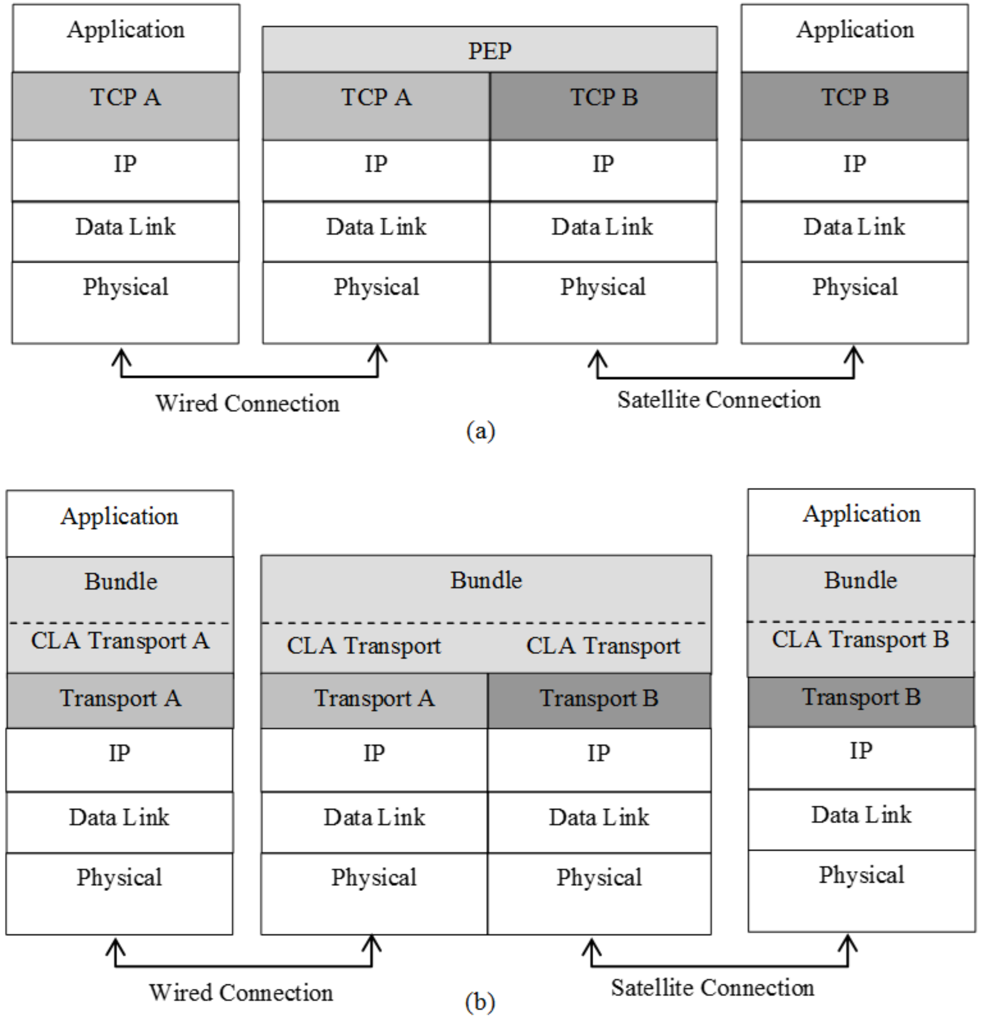
Integrated PEP



DTN equivalent of
Integrated PEP



TCP-splitting PEP and DTN protocol stack comparison



PEPs vs. DTN

- Integrated PEPs and DTN commonalities:
  - Two transport layer connections
    - wired and satellite
  - Possible use of a TCP variant suitable for sat links.
  - The two characteristics above are instrumental for good performance
- Differences:
  - DTN not transparent: BP must be installed on end-nodes.
  - TCP-splitting violates end-to-end TCP semantics
    - PEPs operate at Transport or Application layer although they are intermediate nodes
    - In DTN the end-to-end role of TCP is redefined by the BP insertion.
  - TCP-splitting is incompatible with IPsec (see security section)

References of the “From PEPs to DTN” section

- J. Border, M. Kojo, J. Griner, G. Montenegro, Z. Shelby, “Performance Enhancing Proxies Intended to Mitigate Link-Related Degradations”, Internet RFC 3135, June 2001.
  - http://www.rfc-editor.org/rfc/rfc3135.txt
- Technical Report on Performance Enhancing Proxies (PEPs) for the European ETSI Broadband Satellite Multimedia (BSM) working group. ETSI Report TR 102 676 (Sept. 2009)
  - http://portal.etsi.org
- C. Caini, R. Firrincieli, and D. Lacamera: PEPsal: a Performance Enhancing Proxy for TCP satellite connections, IEEE Aerospace and Electronic Systems Mag.. Vol.22, no. 8, pp. b-9, b-16, Aug. 2007.
  - DOI: 10.1109/MAES.2007.4301030
- C. Caini, P. Cornice, R. Firrincieli, and D. Lacamera, “A DTN Approach to Satellite Commun.”, IEEE J. Select. Areas in Commun., vol. 26, no. 5, pp. 820-827, Jun. 2008.
  - DOI: 10.1109/JSAC.2008.080608
- C. Caini, H.Cruickshank, S. Farrell, M. Marchese, "Delay- and Disruption-Tolerant Networking (DTN): An Alternative Solution for Future Satellite Networking Applications," Proceedings of the IEEE , vol.99, no.11, pp.1980,1997, Nov. 2011
  - DOI: 10.1109/JPROC.2011.2158378

Part 2: DTN Space Applications

DTN Application to SATs

Motivations for DTN

- Challenges in GEO satellites
  - Long propagation delay (RTT=600ms)
    - TCP performance severely impaired
  - Possible high losses
  - Disruption with mobile terminals (Tunnels, etc…)
- Challenges in LEO satellites
  - Intermittent scheduled connectivity due to the motion of satellites
  - Multiple gateway stations on Earth pose routing problems
    - However, LEO contacts are known a priori, thus routing can take advantage of this.

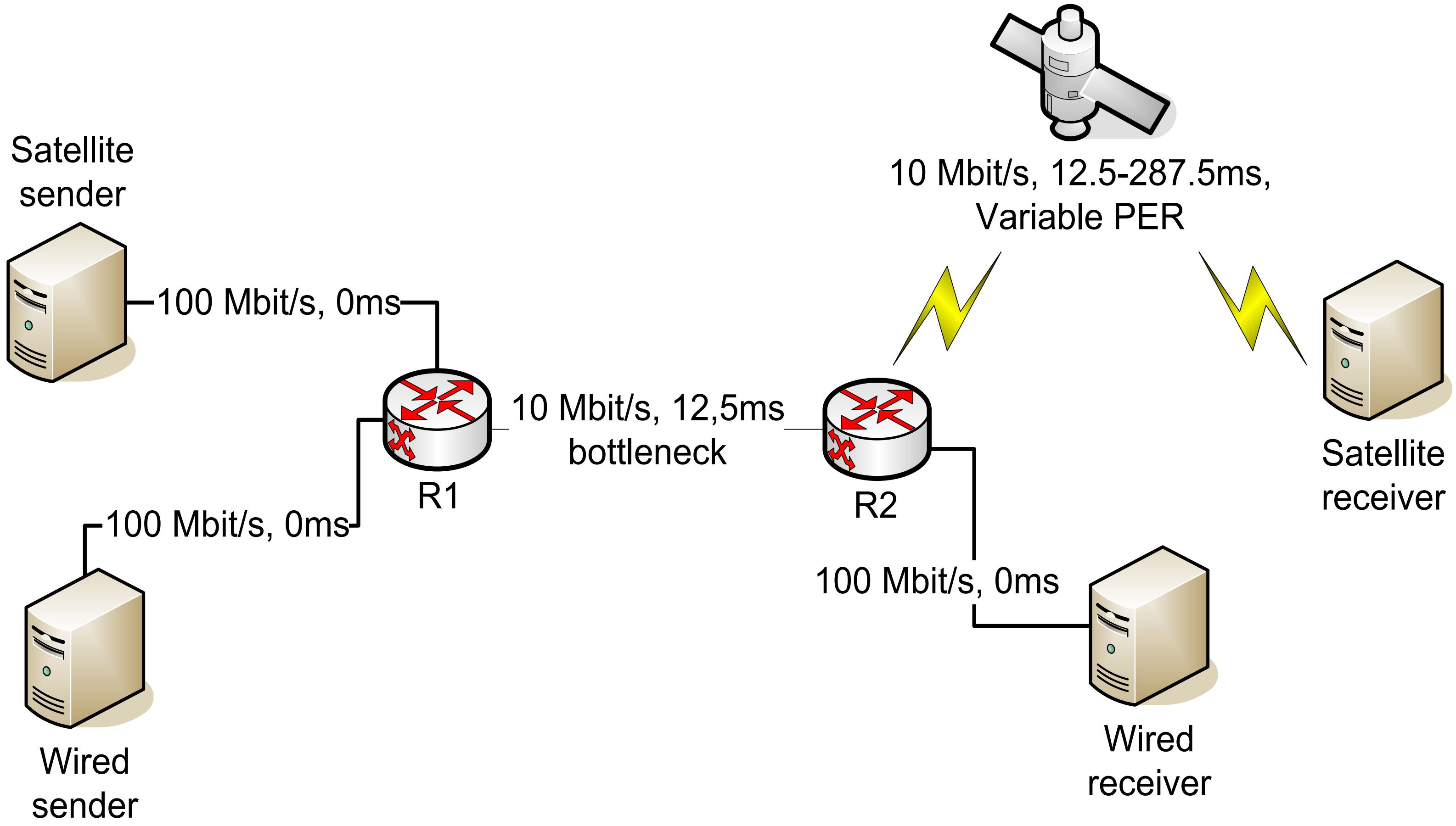
Performance experiments: aim, scope and… fundamental remarks!

- Aim
  - To show the effectiveness of the DTN architecture in some selected satellite applications
- Scope (scenarios)
  - GEO satellite
    - with fixed terminals
    - with mobiles terminals
  - LEO satellite
    - Data mule
    - Earth observation
- Fundamental remarks
  - DTN conceived to cope with “challenges”
    - Long delays, disruptions, intermittent channels, absence of a continuous path between end nodes, etc…
  - In comparisons, the more challenging the scenario, the better for DTN!
    - The higher the competitive advantage over competitors

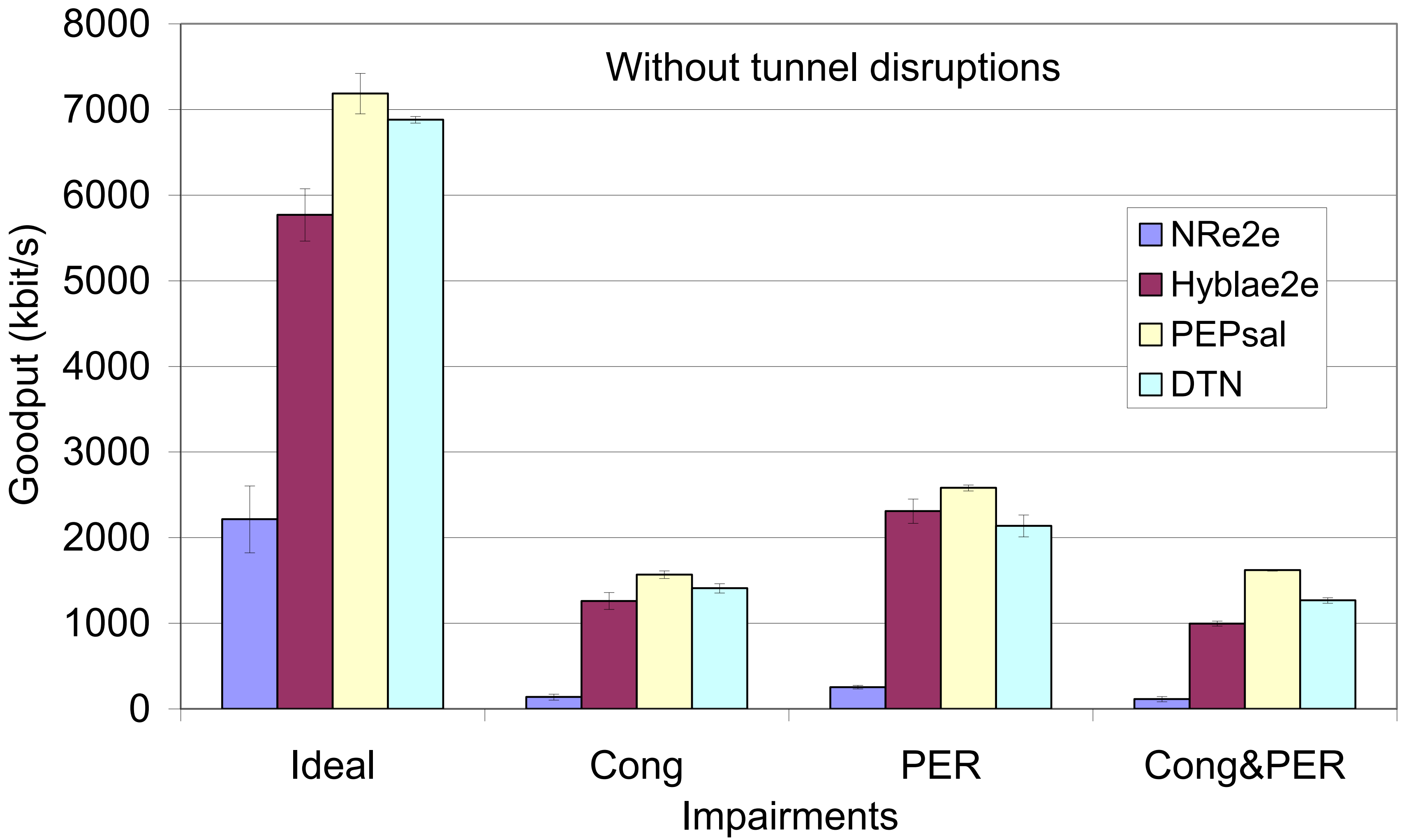
GEO satellites with fixed terminals (no disruptions)

- Aim of this experiment
  - to assess the performance achievable in the absence of disruptions (continuous channel)
- Performance metric
  - Goodput on a 180s satellite data transfer
- Techniques compared
  - end-to-end New Reno
  - end-to-end Hybla
  - PEPsal (an integrated TCP-splitting PEP)
  - DTN
- Environments (with increasing challenges)
  - ideal
  - Congestion
  - PER (Packet Error Rate, =1%)
  - PER (1%) plus congestion

GEO satellites with fixed terminals: the TATPA testbed



GEO satellites with fixed terminals



GEO satellites with fixed terminals

- First, New Reno performance is severely affected by PER and Congestion
- Hybla e-2-e, PEPsal and DTN offer much better performance
  - Reasons are detailed in Caini 2011 “Delay- and Disruption-Tolerant Networking (DTN): An Alternative Solution for Future Satellite Networking Applications”
- DTN presents a limited disadvantage with respect to PEPsal. This is a very good result because:
  - This scenario, being the less challenging, is the most unfavorable to DTN!
  - Goodput is not the only metric to be considered.
    - Side advantages of DTN (security, general solution…)

GEO satellites with mobile terminals (railway tunnel disruptions)

- Aim of experiments
  - to assess the performance achievable in the presence of disruptions due to railway tunnels (disrupted channel)
- Performance metric
  - Goodput on the trip between Bologna and Florence
- Techniques compared
  - end-to-end New Reno
  - end-to-end Hybla
  - PEPsal
  - DTN
- Environments (with increasing challenges)
  - ideal
  - Congested
  - PER (=1%)
  - PER (=1%) plus congestion

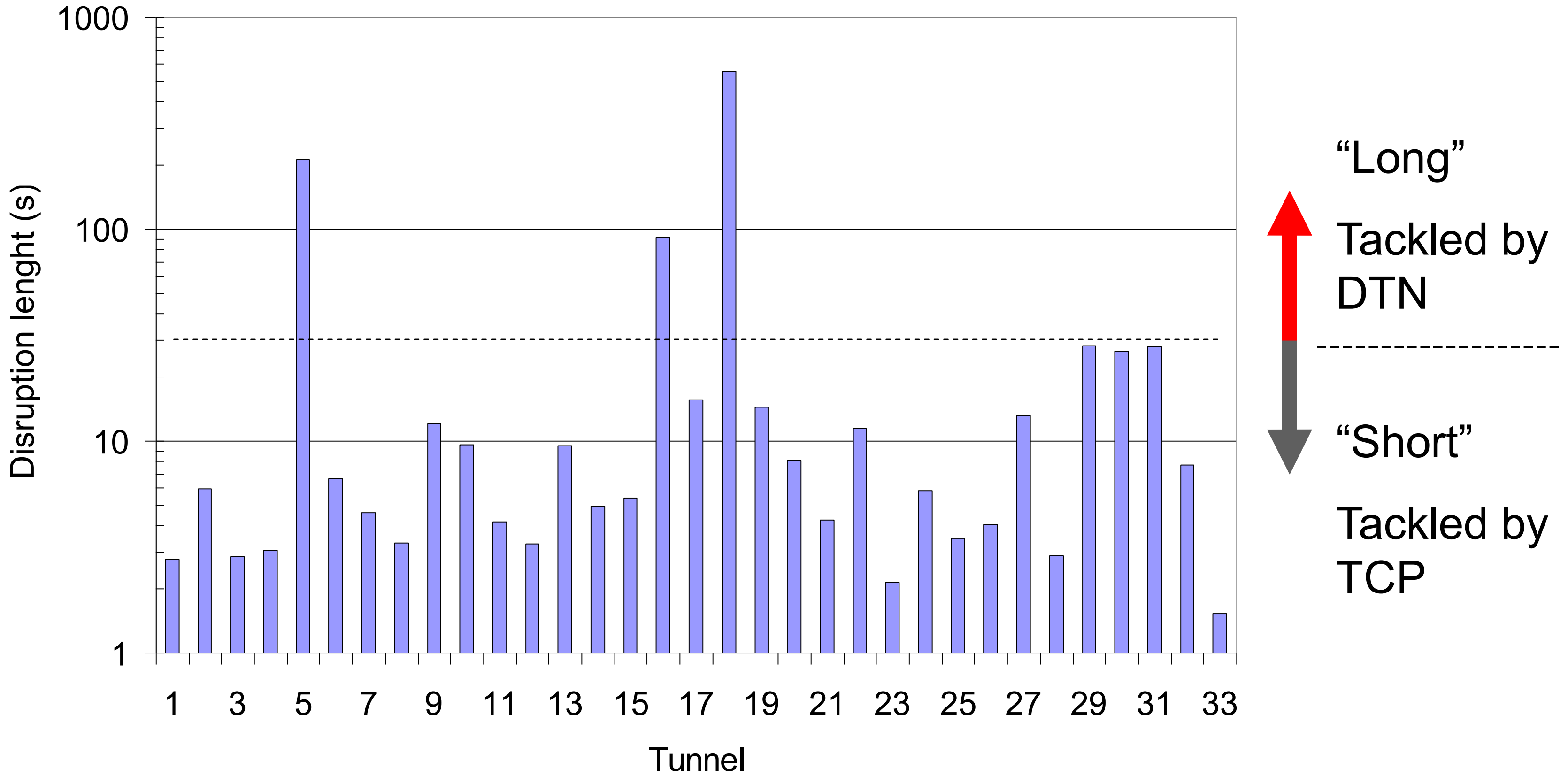
GEO satellites with mobile terminals: “short” and “long” disruptions

- Bundle protocol (BP) with TCP as convergence layer adapter (CLA)
  - BP DTN2 and Linux defaults

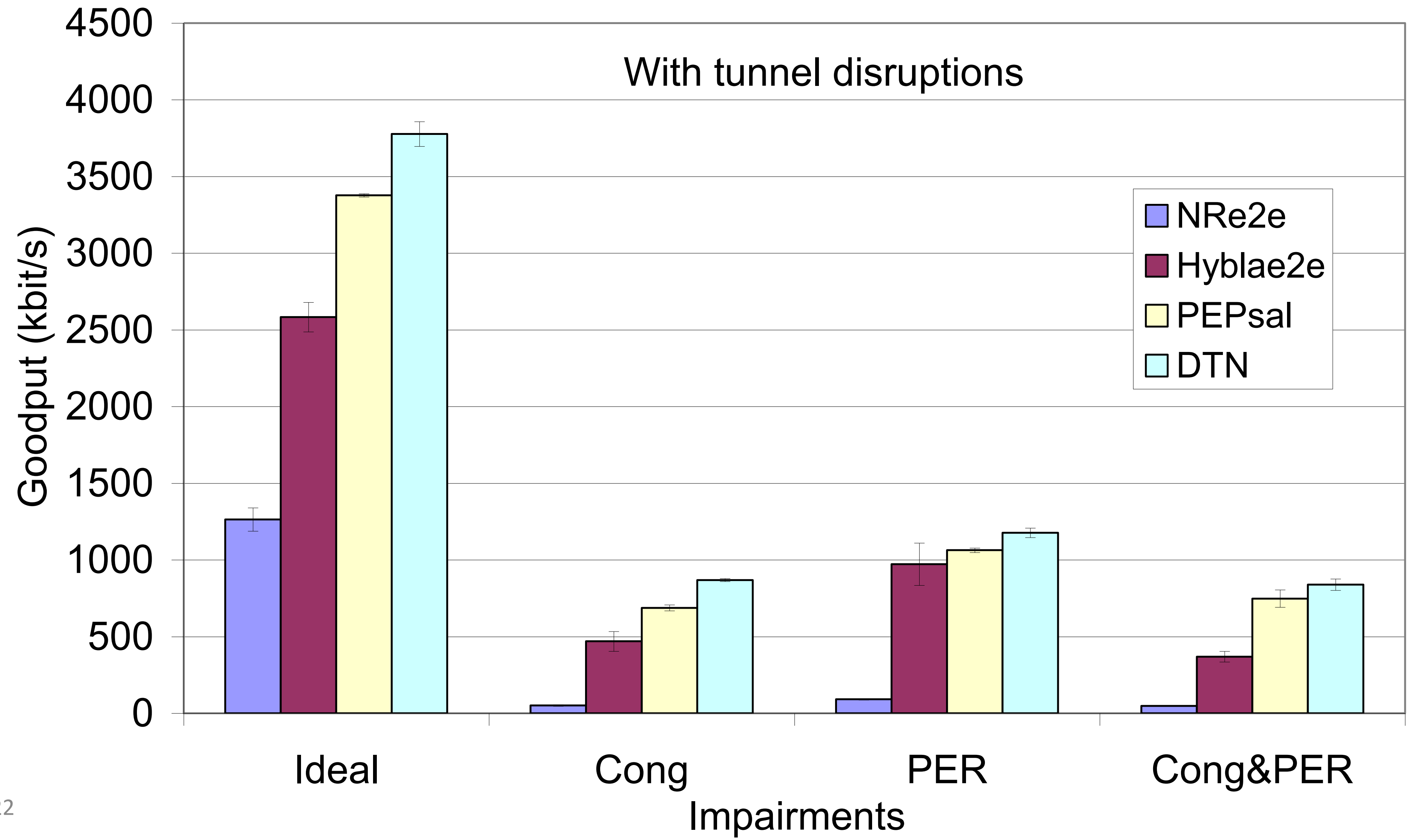
Disruption class	**Lenght**	**TCP (e-2-e or with PEP)**	**DTN Bundle protocol with TCP CLA**
“Short”	< 30s (DTN2 default)	Tackled by TCP	Tackled by TCP
“Long”	>30s (DTN2 def.) and < 1200 s (TCP Linux def.)	Tackled by TCP	Tackled by DTN.
“Very long”	> 1200 s (TCP Linux def.) < 24 h (DTN2 def.)	TCP failure	Tackled by DTN
“Extremely long”	> 24 h (DTN2 def.)	TCP failure	DTN failure

GEO satellites with mobile terminals: disruption lenghts (railway tunnels)

- Disruption lengths caused by tunnels in the Bologna-Florence "Direttissima" railway line, assuming a train speed of 120 km/h; the dotted line is the 30s threshold



GEO satellites with mobile terminals



GEO satellites with mobile terminals

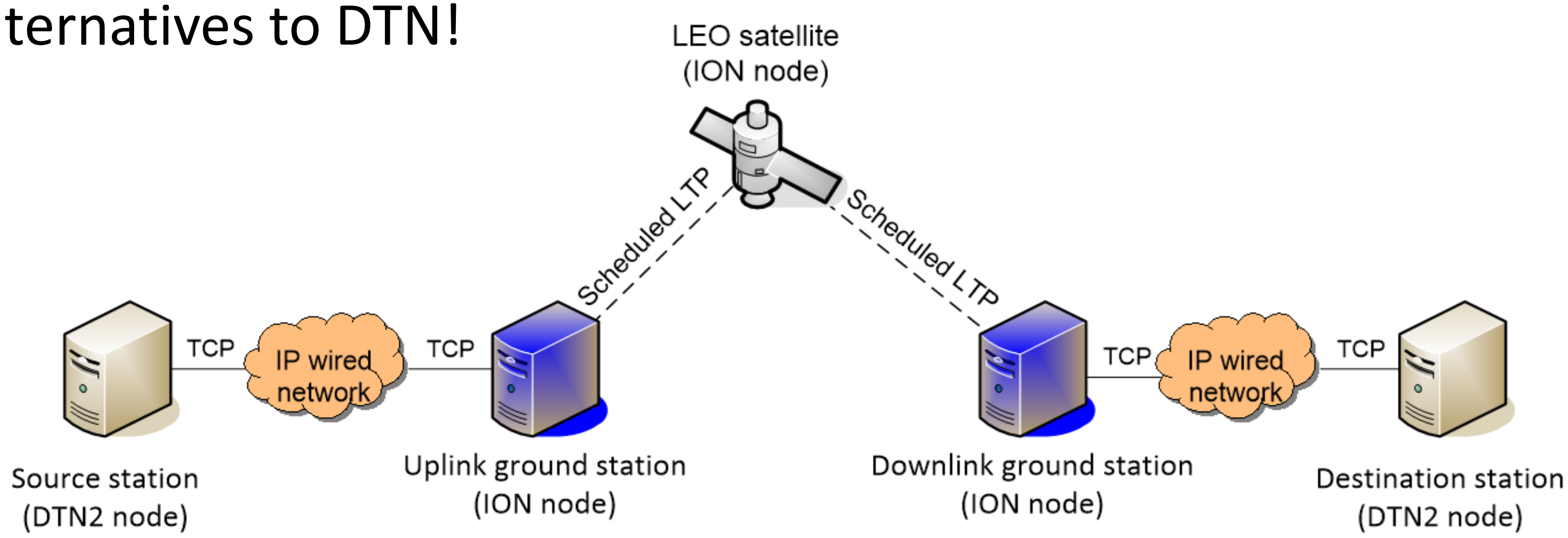
- First, performance is reduced in all cases due to:
  - the fact that the satellite channel is unavailable for 39% of the time because of tunnels;
  - the "restart delay" (time elapsed before transmission restart)
  - the time needed by TCP to reach a steady state (the longer the RTT, the worse this effect).
- The qualitative behaviour is the same as without disruptions
  - but best performance offered by DTN and not by PEPsal.
- With a mobile terminal, DTN can become advantageous also in terms of goodput
  - The advantage depends on the duration and frequency of disruptions.
- For very long disruptions, DTN is definitively better.
  - Had we considered a 60 km/h train speed, the longest disruption would have become greater than 1200 [s]
    - all techniques but DTN would have aborted the data transfer

LEO satellites

- LEO satellites are characterized by lower orbits with a reduced distance from Earth (160 - 2,000 km).
- Advantages
  - reduced propagation loss and delay
- Disadvantages
  - not fixed in the sky,
    - at 520 km altitude the orbital period is about ninety minutes.
    - a single satellite can only provide intermittent connectivity
  - continuous connectivity requires a constellation of satellites.
- We focus here on the case of single satellites, considering two experiments
  - Data mule (old basic experiment)
  - ESA Scenario A, Earth observation (a recent much more complex experiment).
- In all cases we will use
  - the „scheduled“ link connectivity of ION implementation
  - DTNperf (a tool for DTN performance evaluation and log collection)
  - No alternatives to DTN (except manual operation) !

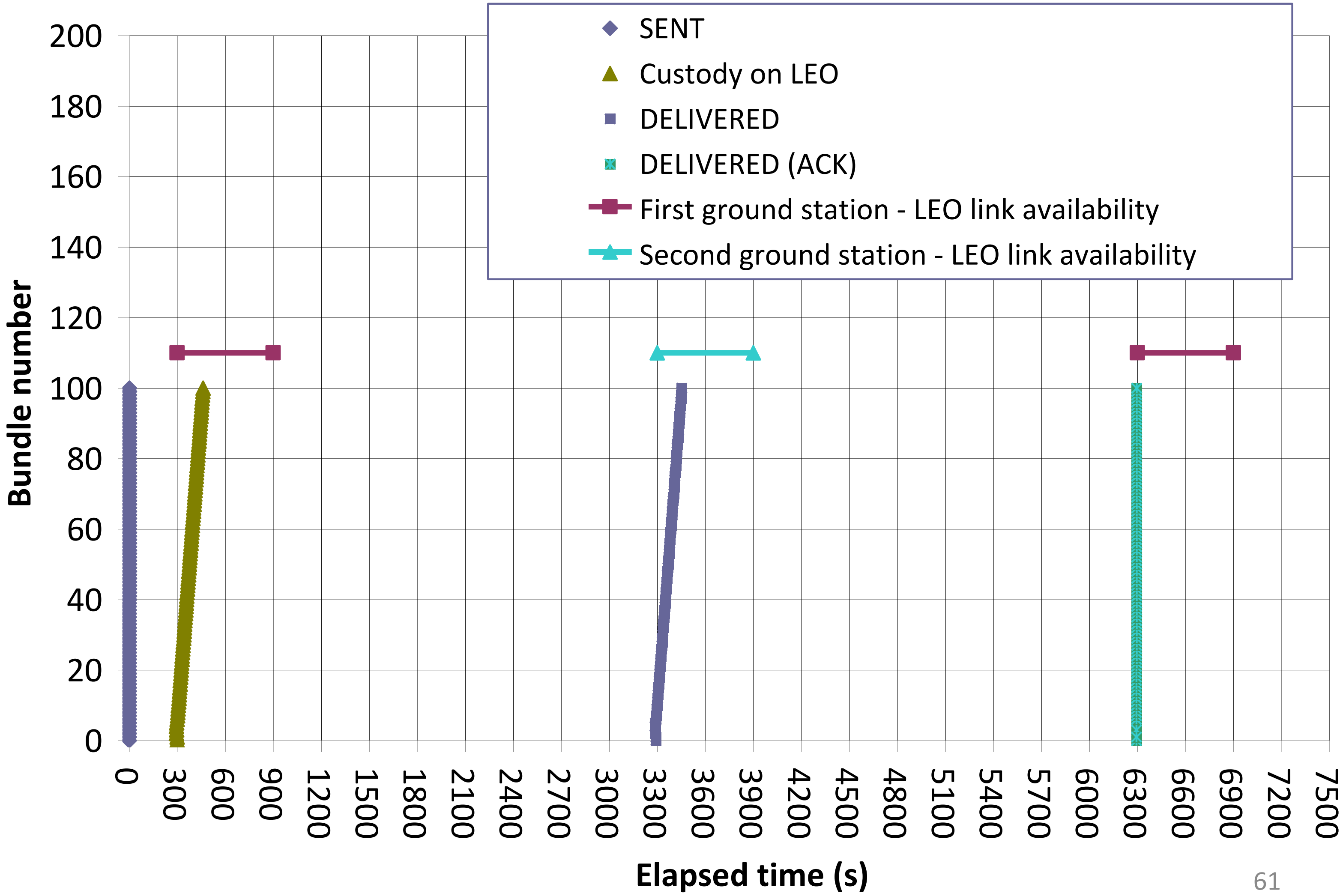
LEO satellites: data mule

- One LEO satellite forwards data from the first ground station to the second, located at great distance
  - The two ground stations are alternately in line of sight with the satellite
- No continuous path between end nodes
  - no alternatives to DTN!



LEO satellites: data mule

- 20 MB file transfer
  - 100 bundles, 50 kB each
- DTN BP Status report logs collected by DTNperf server

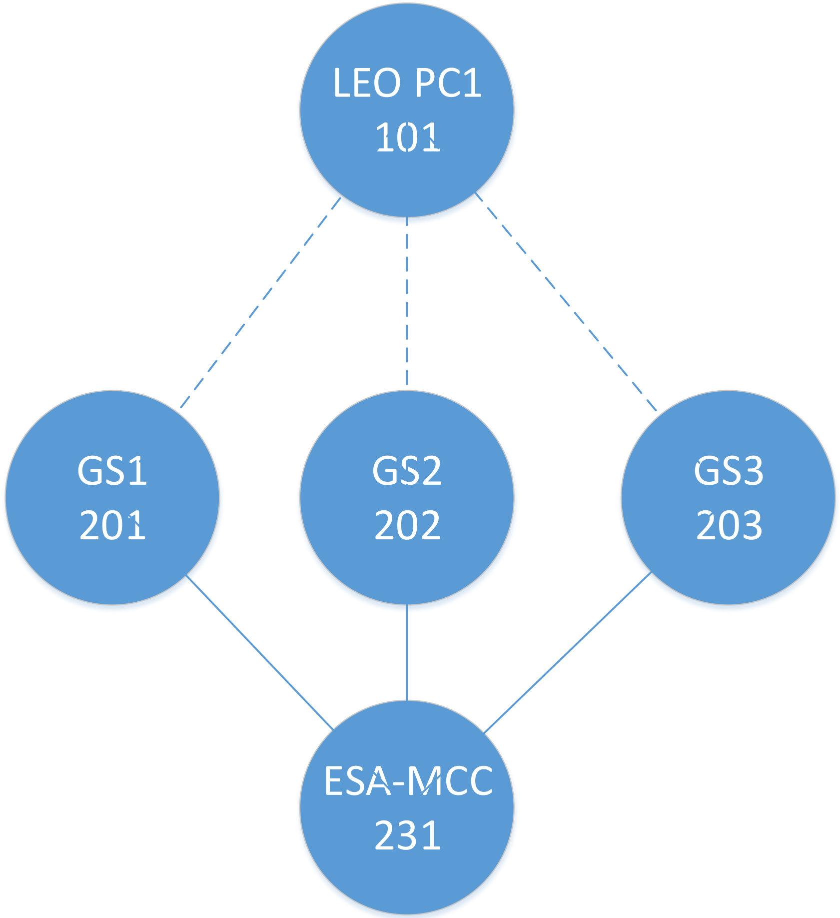


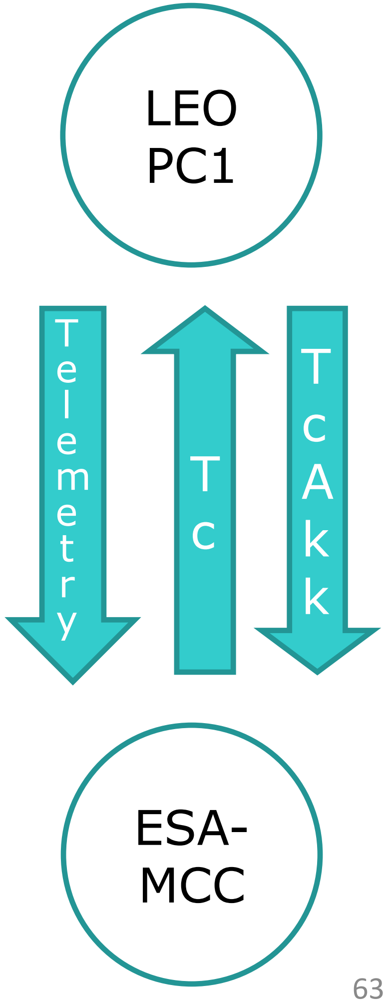
LEO satellites: earth observation

- Excerpt from Scenario A of ESA/ESOC project: “Delay tolerant network for flexible Communication with Earth Observation satellites”.
  - Only left hand layout considered

Scenario A: logical layout and data flows

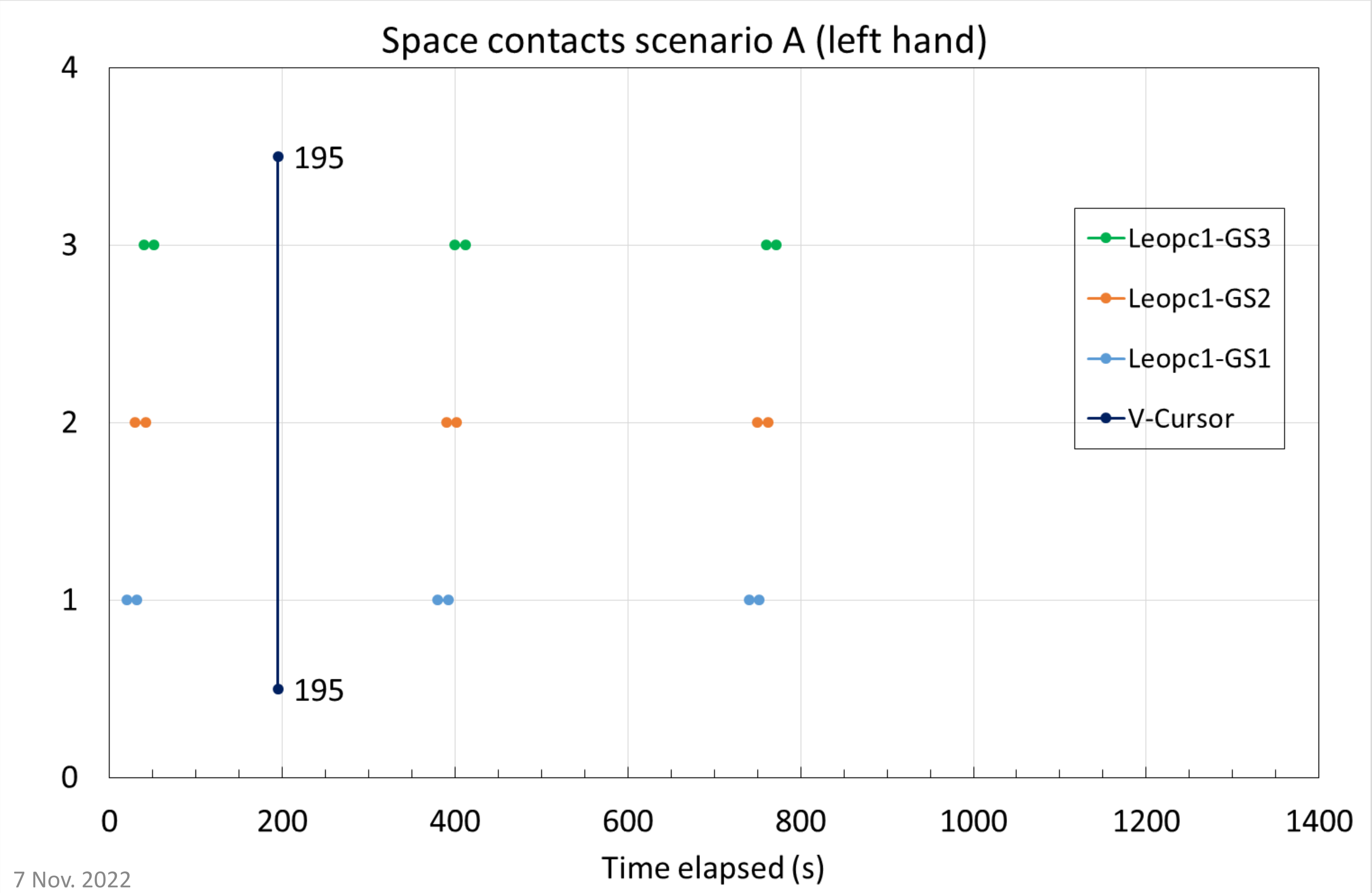
- Dotted lines=space intermittent links (intermittent contacts)
- Continuous lines=terrestrial continuous links





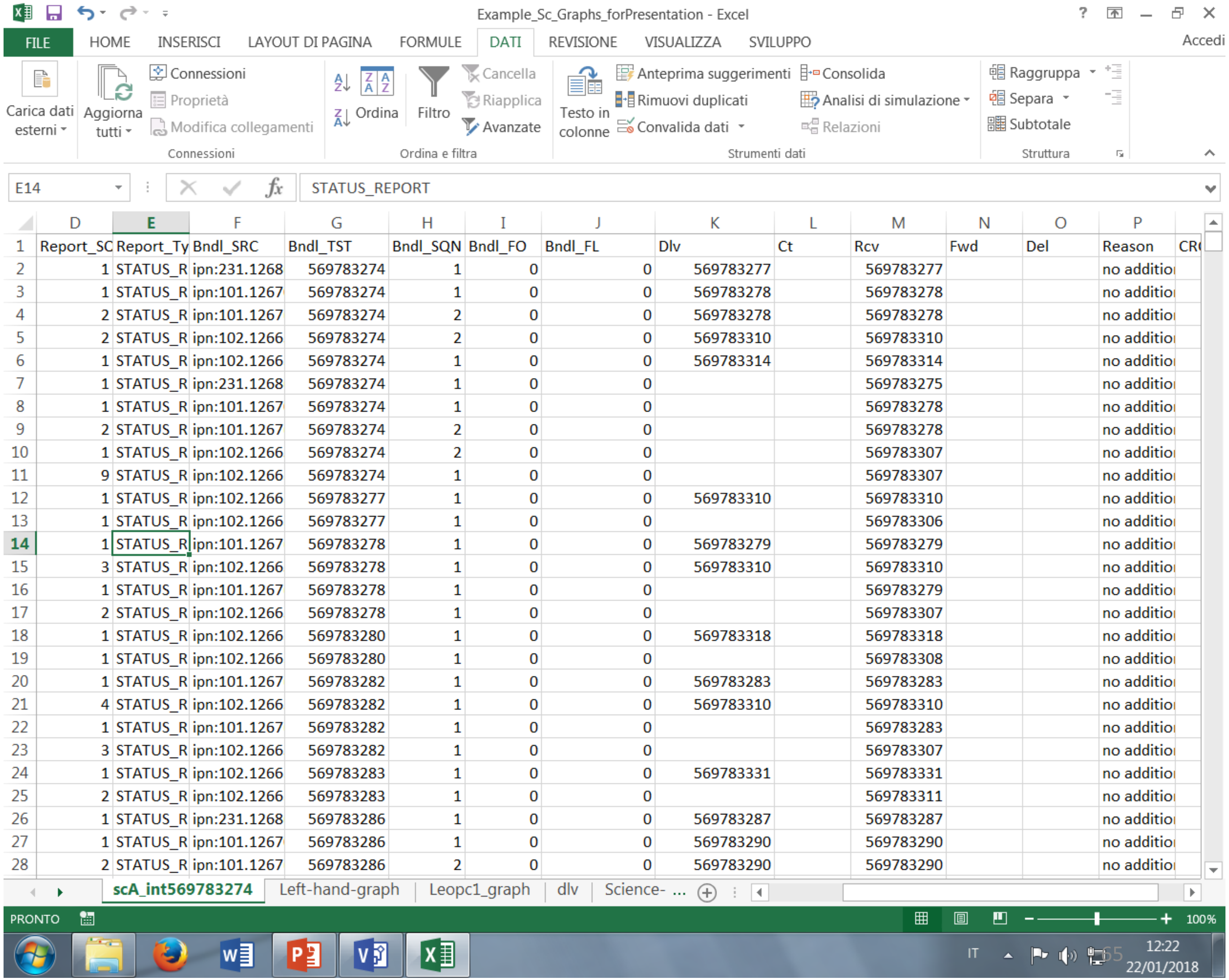
Scenario A: contacts

(time scaled: s instead of minutes)



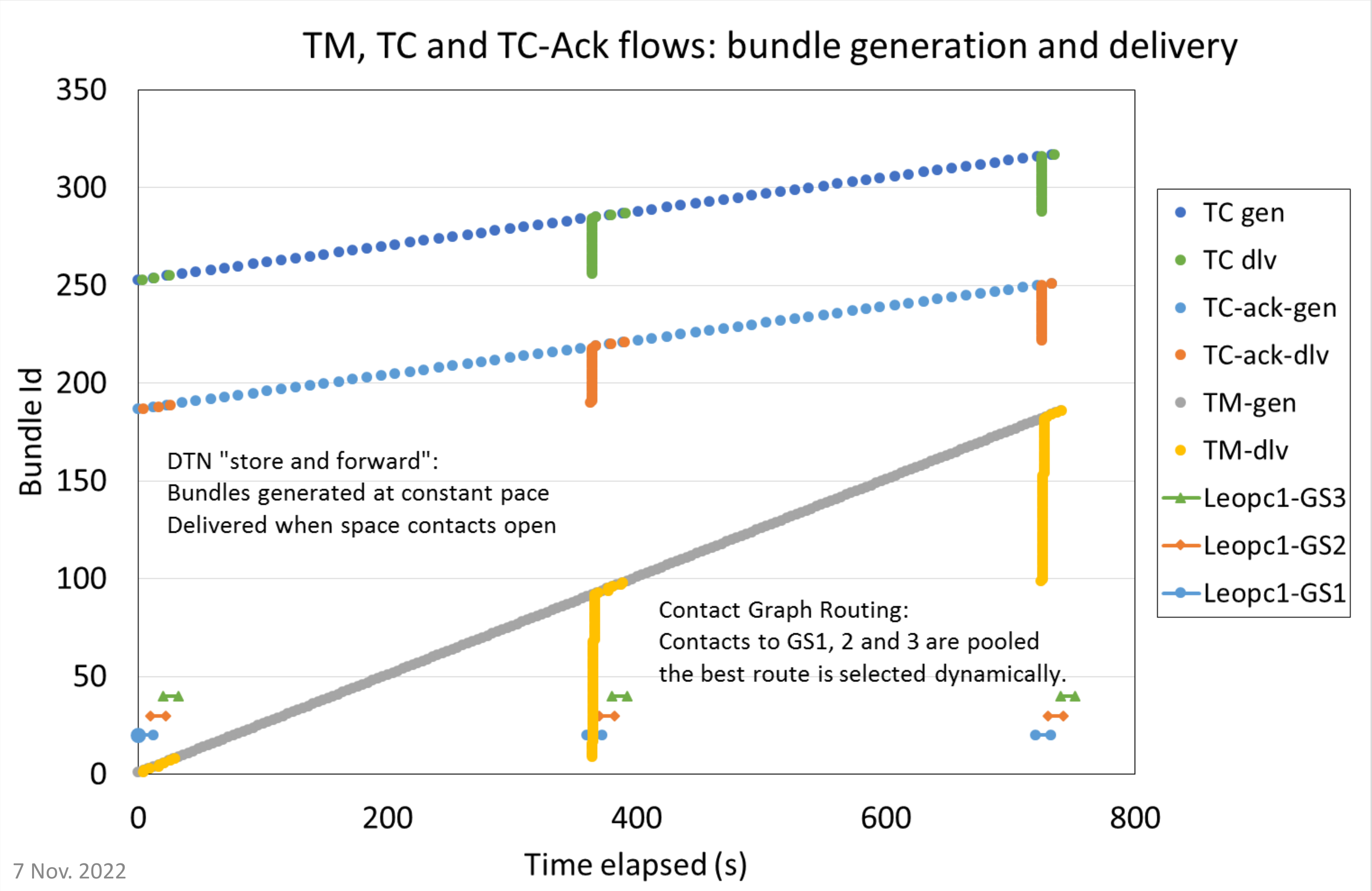
Scenario A: results

(status reports collected by DTNperf in a .csv file)



	Report_SC	Report_Ty	Bndl_SRC	Bndl_TST	Bndl_SQN	Bndl_FO	Bndl_FL	Dlv	Ct	Rcv	Fwd	Del	Reason	CR(
2	1	STATUS_R	ipn:231.1268	569783274	1	0	0	569783277		569783277			no additio	
3	1	STATUS_R	ipn:101.1267	569783274	1	0	0	569783278		569783278			no additio	
4	2	STATUS_R	ipn:101.1267	569783274	2	0	0	569783278		569783278			no additio	
5	2	STATUS_R	ipn:102.1266	569783274	2	0	0	569783310		569783310			no additio	
6	1	STATUS_R	ipn:102.1266	569783274	1	0	0	569783314		569783314			no additio	
7	1	STATUS_R	ipn:231.1268	569783274	1	0	0			569783275			no additio	
8	1	STATUS_R	ipn:101.1267	569783274	1	0	0			569783278			no additio	
9	2	STATUS_R	ipn:101.1267	569783274	2	0	0			569783278			no additio	
10	1	STATUS_R	ipn:102.1266	569783274	2	0	0			569783307			no additio	
11	9	STATUS_R	ipn:102.1266	569783274	1	0	0			569783307			no additio	
12	1	STATUS_R	ipn:102.1266	569783277	1	0	0	569783310		569783310			no additio	
13	1	STATUS_R	ipn:102.1266	569783277	1	0	0			569783306			no additio	
14	1	STATUS_R	ipn:101.1267	569783278	1	0	0	569783279		569783279			no additio	
15	3	STATUS_R	ipn:102.1266	569783278	1	0	0	569783310		569783310			no additio	
16	1	STATUS_R	ipn:101.1267	569783278	1	0	0			569783279			no additio	
17	2	STATUS_R	ipn:102.1266	569783278	1	0	0			569783307			no additio	
18	1	STATUS_R	ipn:102.1266	569783280	1	0	0	569783318		569783318			no additio	
19	1	STATUS_R	ipn:102.1266	569783280	1	0	0			569783308			no additio	
20	1	STATUS_R	ipn:101.1267	569783282	1	0	0	569783283		569783283			no additio	
21	4	STATUS_R	ipn:102.1266	569783282	1	0	0	569783310		569783310			no additio	
22	1	STATUS_R	ipn:101.1267	569783282	1	0	0			569783283			no additio	
23	3	STATUS_R	ipn:102.1266	569783282	1	0	0			569783307			no additio	
24	1	STATUS_R	ipn:102.1266	569783283	1	0	0	569783331		569783331			no additio	
25	2	STATUS_R	ipn:102.1266	569783283	1	0	0			569783311			no additio	
26	1	STATUS_R	ipn:231.1268	569783286	1	0	0	569783287		569783287			no additio	
27	1	STATUS_R	ipn:101.1267	569783286	1	0	0	569783290		569783290			no additio	
28	2	STATUS_R	ipn:101.1267	569783286	2	0	0	569783290		569783290			no additio	

Scenario A: analysis of «left hand» flows



DTN application to SATs (summary)

		DTN	PEP	e2e TCP (advanced)	E2e TCP (NewReno)
GEO scenarios	GEO fixed terminals	Yes	Yes	Yes with limits	No
	GEO mobile terminals	Yes	Yes	Yes with limits	No
LEO scenarios	LEO Earth observation	Yes	No	No	No
	LEO data mule	Yes	No	No	No

- The more challenging the scenario, the better for DTN!

References of the “DTN application to SATs” sections

- C. Caini, P. Cornice, R. Firrincieli, and D. Lacamera, “A DTN Approach to Satellite Commun.”, IEEE J. Select. Areas in Commun., vol. 26, no. 5, pp. 820-827, Jun. 2008.
  - DOI: 10.1109/JSAC.2008.080608
- C. Caini, P. Cornice, R. Firrincieli, D. Lacamera, M. Livini, “TCP, PEP and DTN Performance on Disruptive Satellite Channels” in Proc. of IEEE IWSSC’09, Siena, Italy, 2009, pp. 371 – 375
  - DOI: 10.1109/IWSSC.2009.5286336
- C. Caini, R. Firrincieli, M. Livini, “DTN Bundle Layer over TCP: Retransmission Algorithms in the Presence of Channel Disruptions”, in J. of Commun. (JCM), Academy Publisher, vol. 5, no. 2, pp. 106-116, Feb. 2010.
  - DOI: [10.4304/jcm.5.2.106-116](10.4304/jcm.5.2.106-116)
- C. Caini, H.Cruickshank, S. Farrell, M. Marchese, "Delay- and Disruption-Tolerant Networking (DTN): An Alternative Solution for Future Satellite Networking Applications," Proceedings of the IEEE , vol.99, no.11, pp.1980,1997, Nov. 2011
  - DOI: 10.1109/JPROC.2011.2158378
- C. Caini, “Application of DTN Architecture and Protocols to Satellite Communications”, in “Advances In Delay-Tolerant Networks (DTNs), Architecture and Enhanced Performance (second edition)”, Ed. J.Rodrigues, pp.23-pp.46, Woodhead Publishing Ltd, 2021, Cambridge, UK, ISBN-13: 9780081027936
  - DOI: [10.1016/B978-0-08-102793-6.00002-3](10.1016/B978-0-08-102793-6.00002-3)
- N. Alessi, C. Caini, T. de Cola, S. Martin, J. Pierce Mayer, “DTN Performance Analysis of Multi-Asset Mars Earth Communications”, Wiley International Journal of Sat. Commun. and Networking, vol.40, no.1, pp.11-26, Jan-Feb-2022 (printed) , July 2019 (first published);
  - DOI: [10.1002/sat.1326](10.1002/sat.1326); Open access.

DTN Application to Interplanetary communications

Motivations for DTN

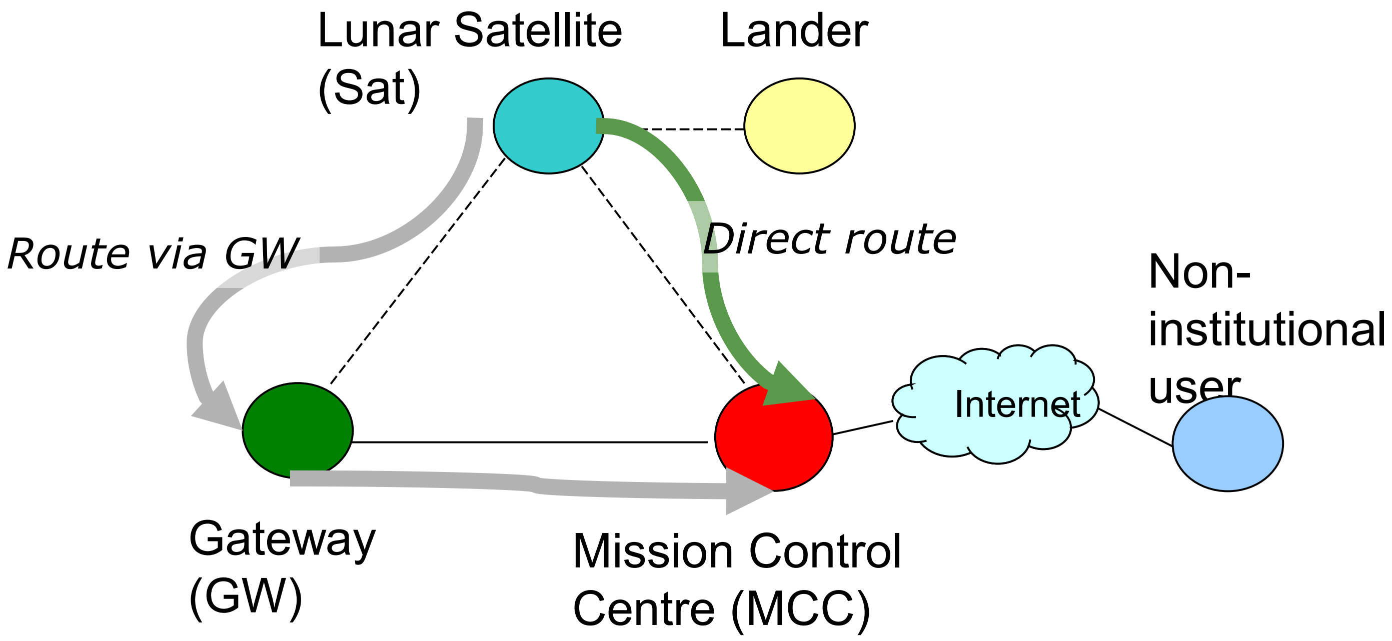
- Challenges
  - Very long propagation delays
    - LTP (Licklider Transmission Protocol) instead of TCP is mandatory on space links
  - Intermittent connectivity (scheduled)
    - due to the orbital motion of planets and spacecraft
  - Possible high losses
- Peculiarities
  - As in LEO sats, contacts are scheduled, i.e. known a priori
    - Routing can take advantage of this

Vinton Cerf’s vision

- Vinton Gray Cerf (in brief Vint Cerf) is one of the fathers of Internet
  - He designed with Bob Kahn the TCP and the IP protocols.
  - He has started the IPN research, form which DTN derives
  - At present he is with Google as “Chief Internet Evangelist”
- Videoclip (Epoxy experiment)
  - http://www.youtube.com/watch?v=SniWy7C_shg

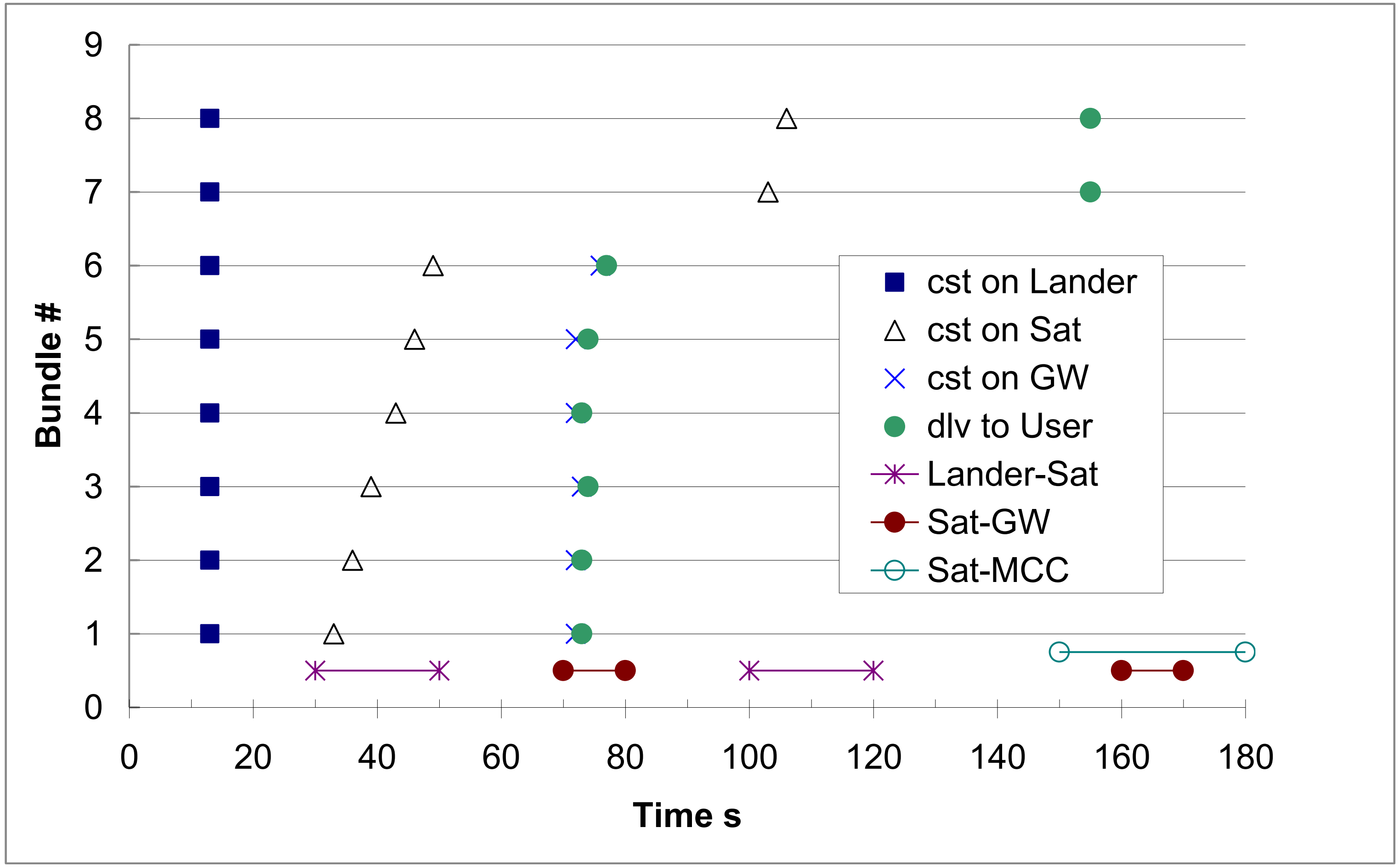
First example: images from the far side of the Moon…

- Two routes possible (via GW or direct); the choice is dynamic (as for trains or flights)
  - Dotted lines=space intermittent links (windows of visibility)
  - Continuous lines=terrestrial continuous links



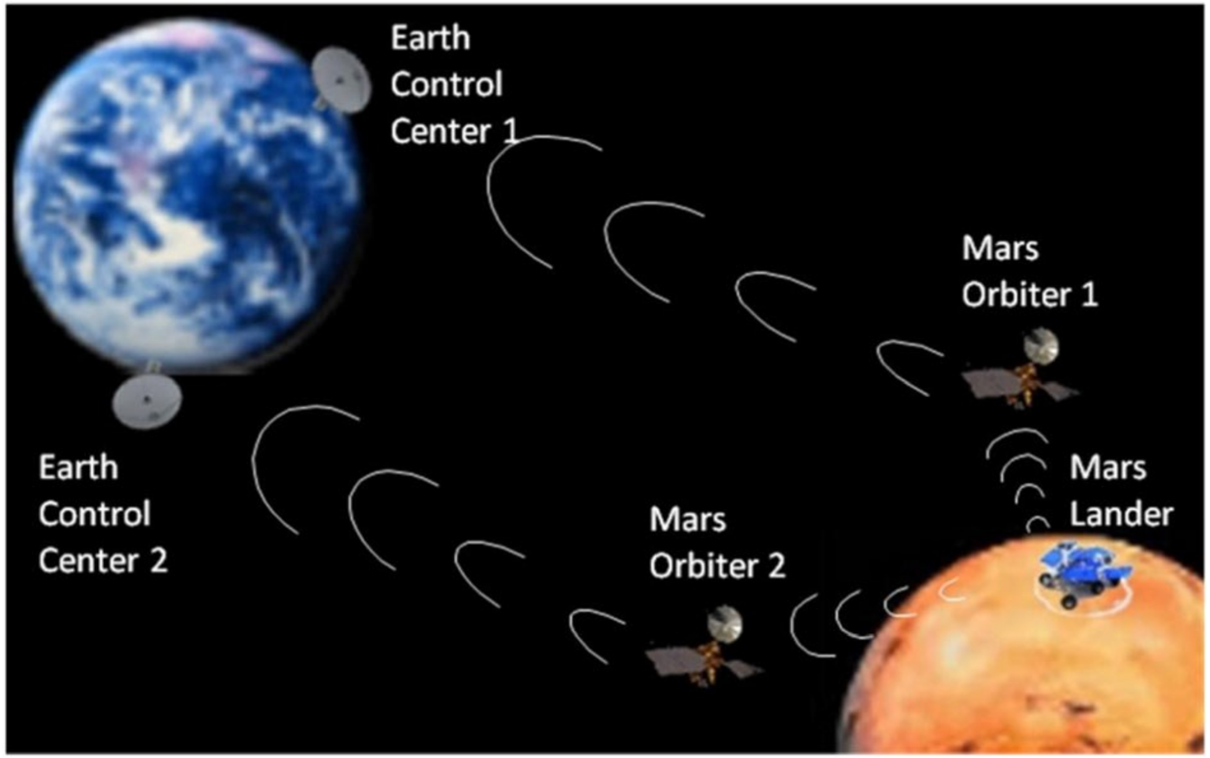
First example: images from the far side of the Moon…

- 8 bundles
  - First 6 transferred from Lander to Sat during the 1st Lander-Sat window
    - then routed via GW;
  - Last 2 transferred during the 2nd Lander-Sat window
    - then routed directly to MCC



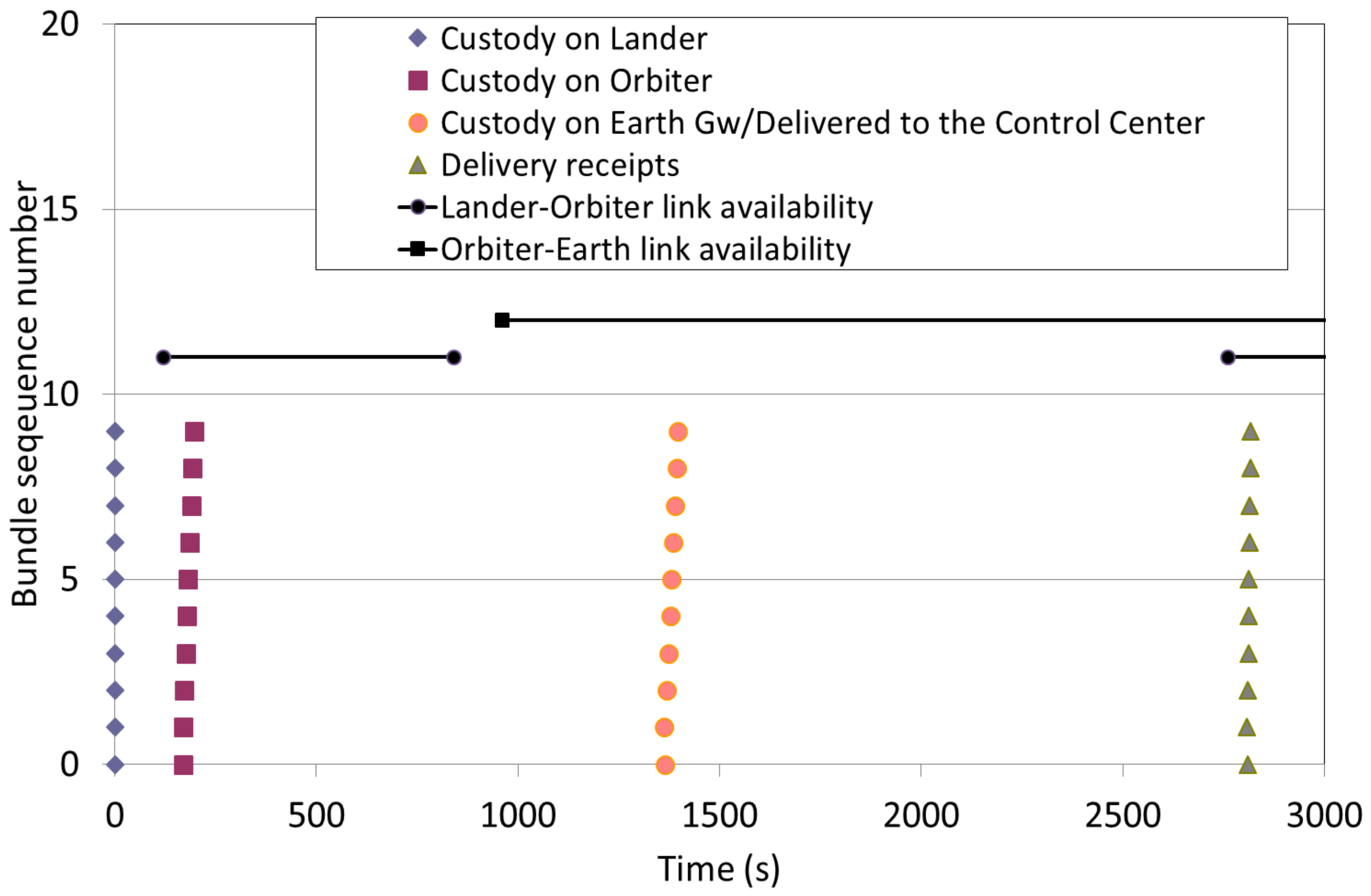
Second example: Mars to Earth DTN communications through orbiters…

- DTN transfers from Mars Lander
  - Either via Mars Orbiter 1 or 2
  - Two DTN hops
  - LTP on all links
- The study focuses on the impact of LTP segments retransmissions on delivery delay



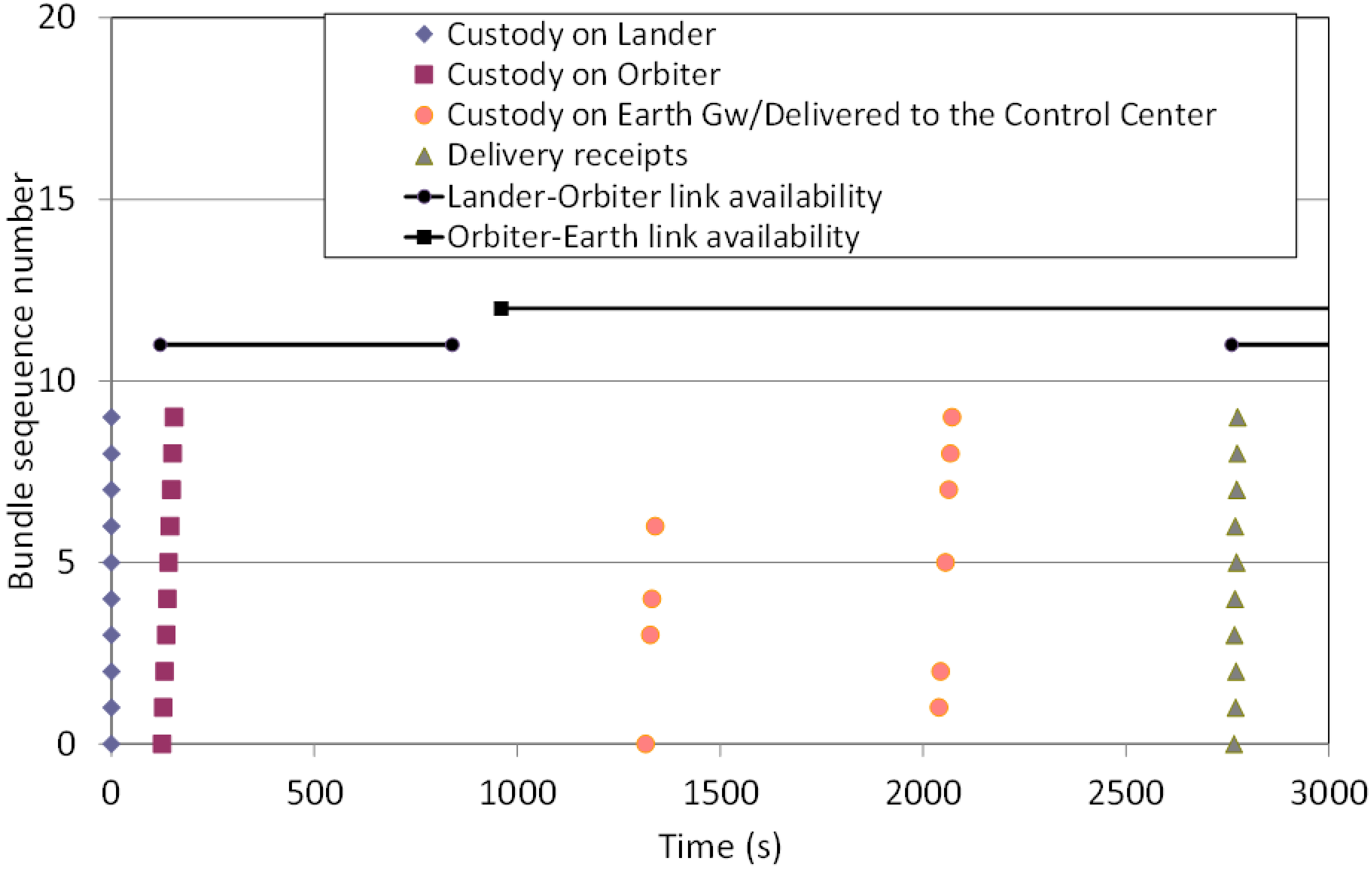
Second example: Mars to Earth DTN commun. through orbiters… (PER=0)

- 9 bundles of 50 kB are generated on Lander, to be delivered to Control Centre
  - All transferred to Orbiter1 (Odissey) during the 1st Lander-Orbiter contact;
  - all are delivered after only half RTT from the opening of Orbiter-GW contact (360s);
  - Delivery receipts sent to Orbiter and stored on board; they are transferred to Lander as soon as the 2nd Lander-Orbiter contact opens.



Second example: Mars to Earth DTN commun. through orbiters… (PER=3%)

- The experiment is the same as before but with LTP segment losses
- All bundles transferred to Orbiter during the 1st Lander-Orbiter contact, as before
  - 4 are delivered after a half RTT (360s) from the opening of Orbiter-GW contact, as before;
  - 6 after 1.5 RTTs (1080s) because of retransmissions of lost LTP segments
- The penalization of 1 retransmission cycle is equal to one RTT

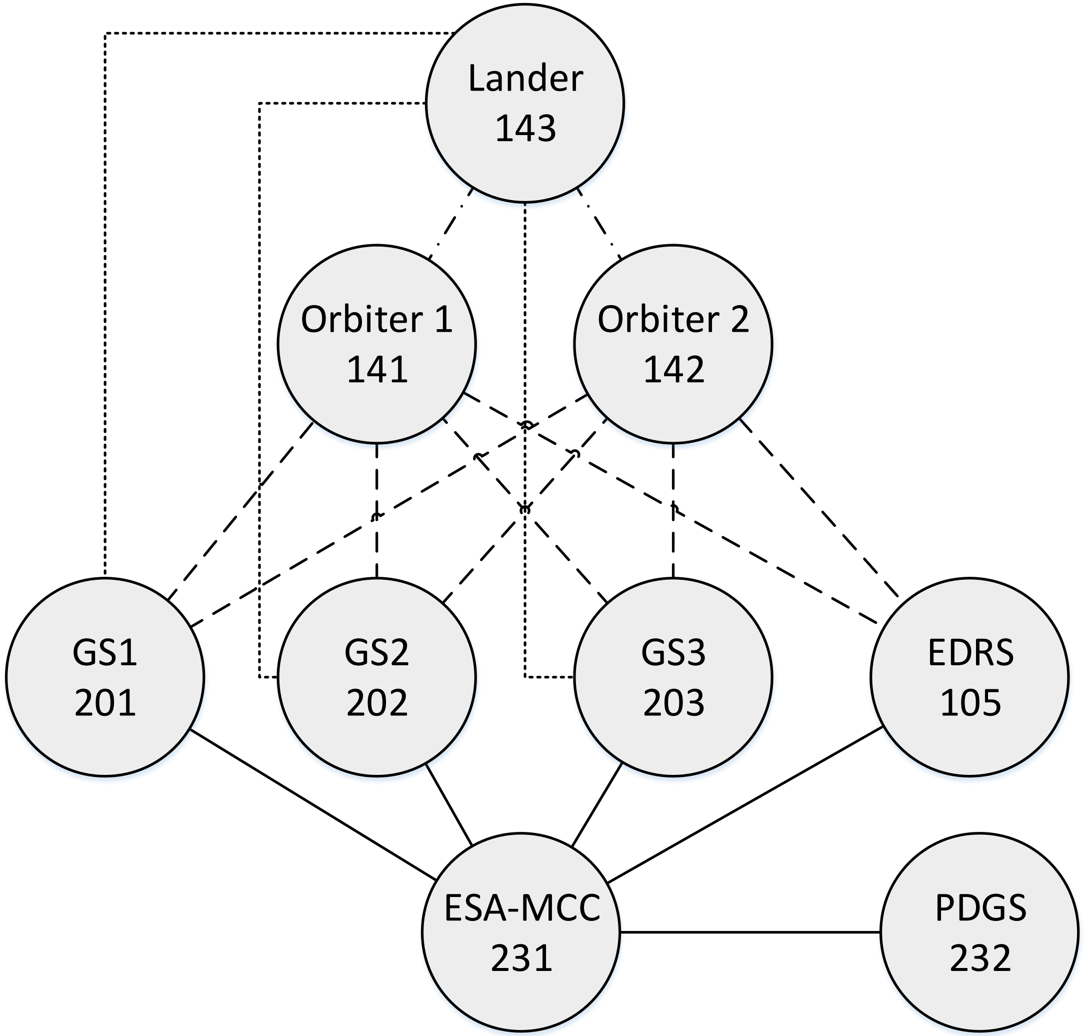


Third example: Multi-Asset Mars Earth Communications

- Excerpt form ESA/ESOC project: “Delay tolerant network for flexible Communication with Earth Observation satellites”, Scenario C
    - Fully described in Alessi et al., “DTN Performance Analysis of Multi-Asset Mars Earth Communications”, see references.

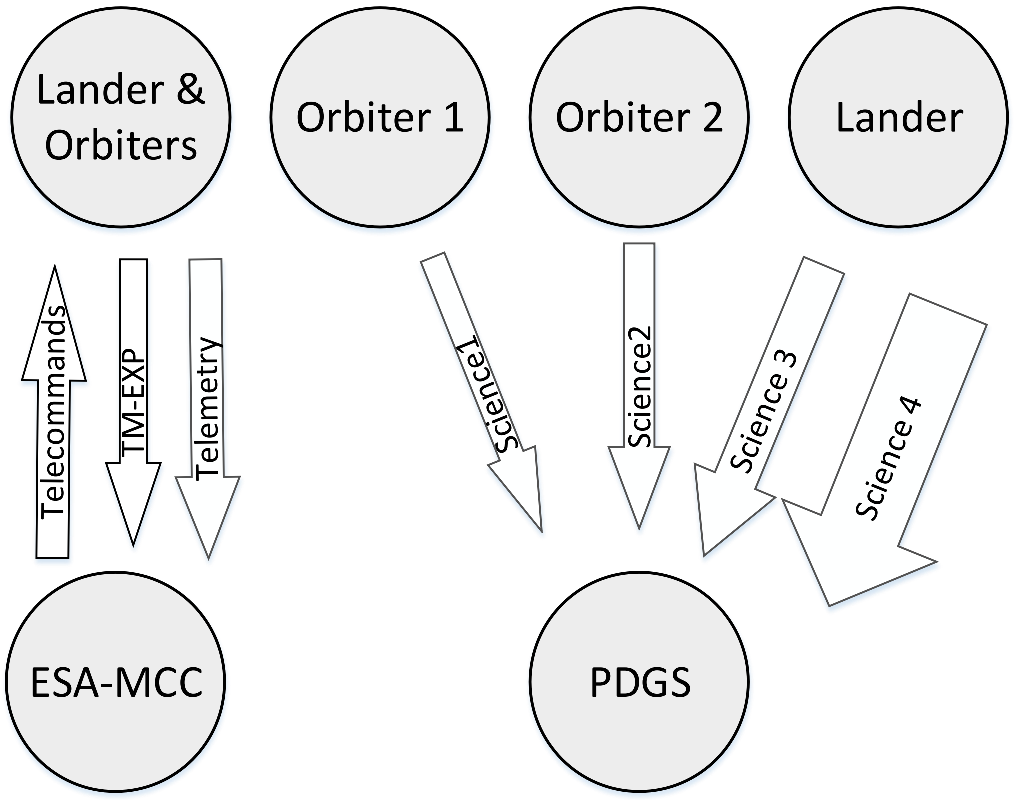
Scenario C: Logical Layout

- Spacecraft: 1 Lander on Mars and 2 Martian Orbiters
- Terrestrial intermediate nodes: 3 Ground Stations, 1 GEO satellite (EDRS)
- Terrestrial end nodes: ESA-MCC (for Telecommand and Telemetry) and PDGS (for science data)
- Lines:
  - Dotted=space intermittent links with very limited bandwidth (LTP)
  - Dashed= space intermittent links (LTP)
  - Continuous=terrestrial continuous links (TCP)
- No losses
- Very challenging for CGR routing
- ION 3.6.0b (with patches) on all nodes



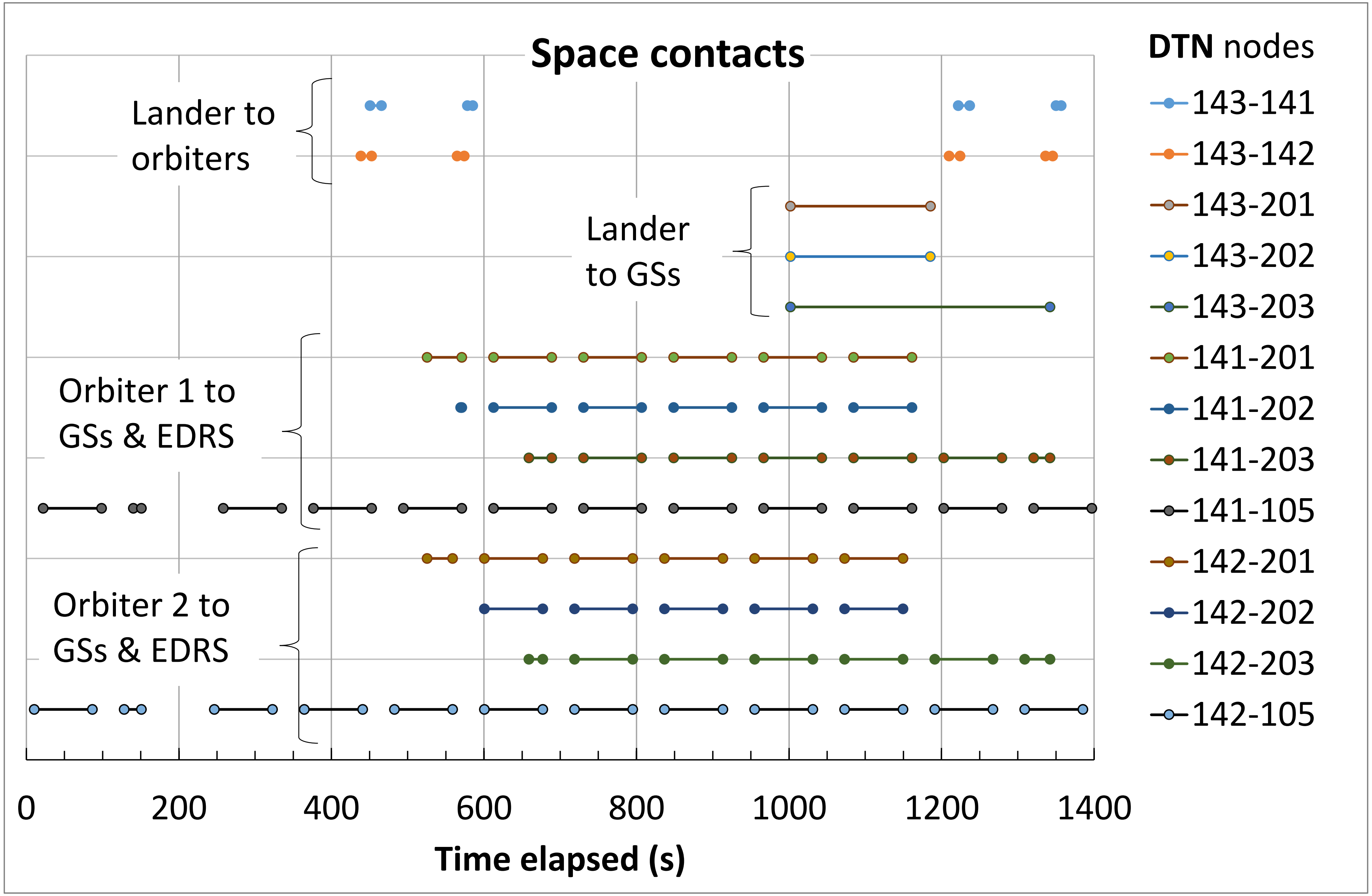
Scenario C: Data Flows

- Each spacecraft receives:
  - Telecommands from ESA-MCC (“expedited”)
- and sends back:
  - TM-EXP (Telemetry with expedited priority)
  - Telemetry (normal priority).
- Four different science flows (“bulk”) are sent by spacecraft to PDGS
- 13 Different flows
  - 13 instances of DTNperf client
  - 5 instances of DTNperf server
  - 1 instance of DTNperf monitor
  - 55000 status reports collected at each run!

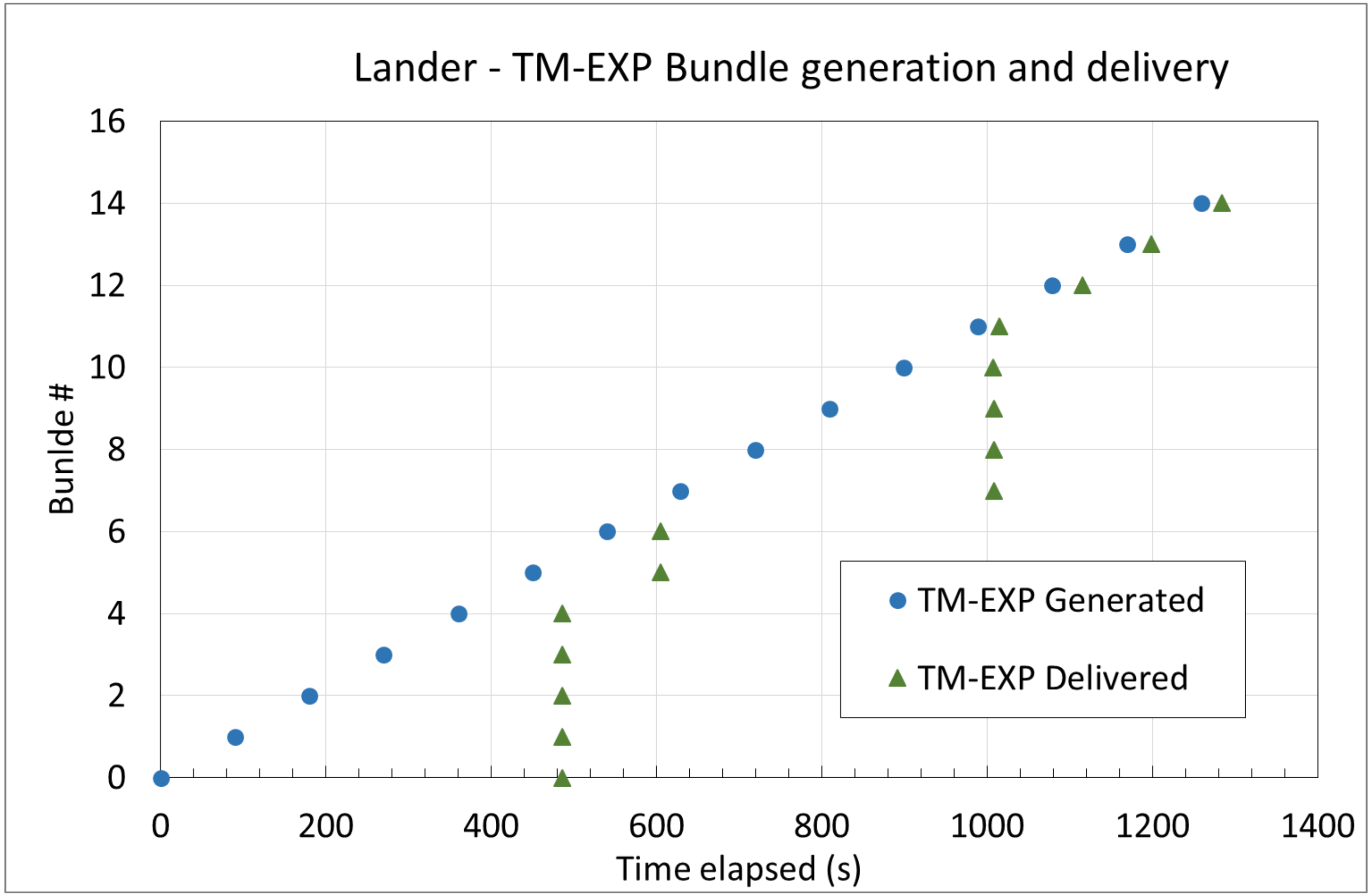


Scenario C: Contacts

(time-scaled, s instead of minutes)

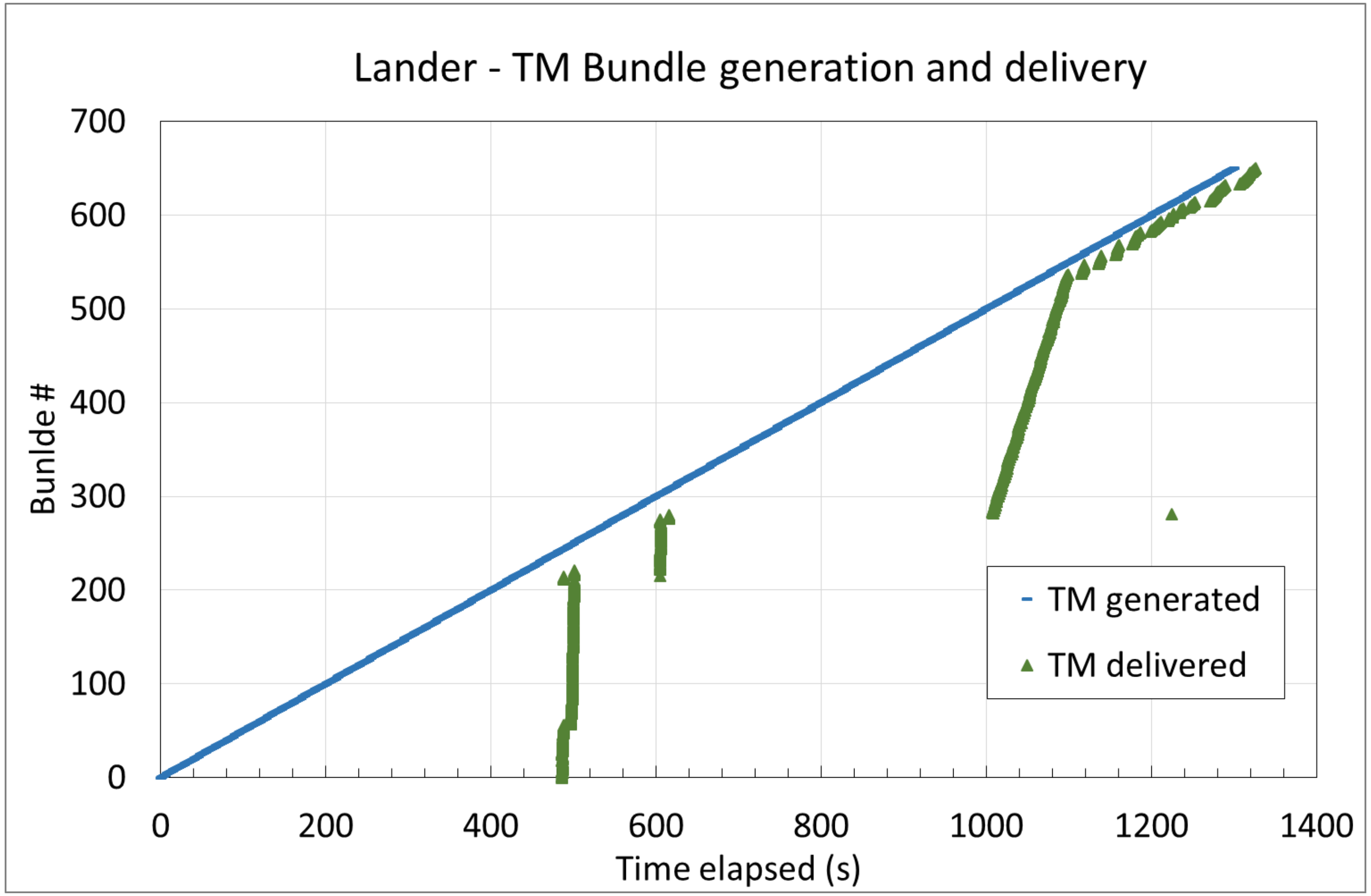


Scenario C: TM-EXP data flow (expedited) from Lander to ESA-MCC



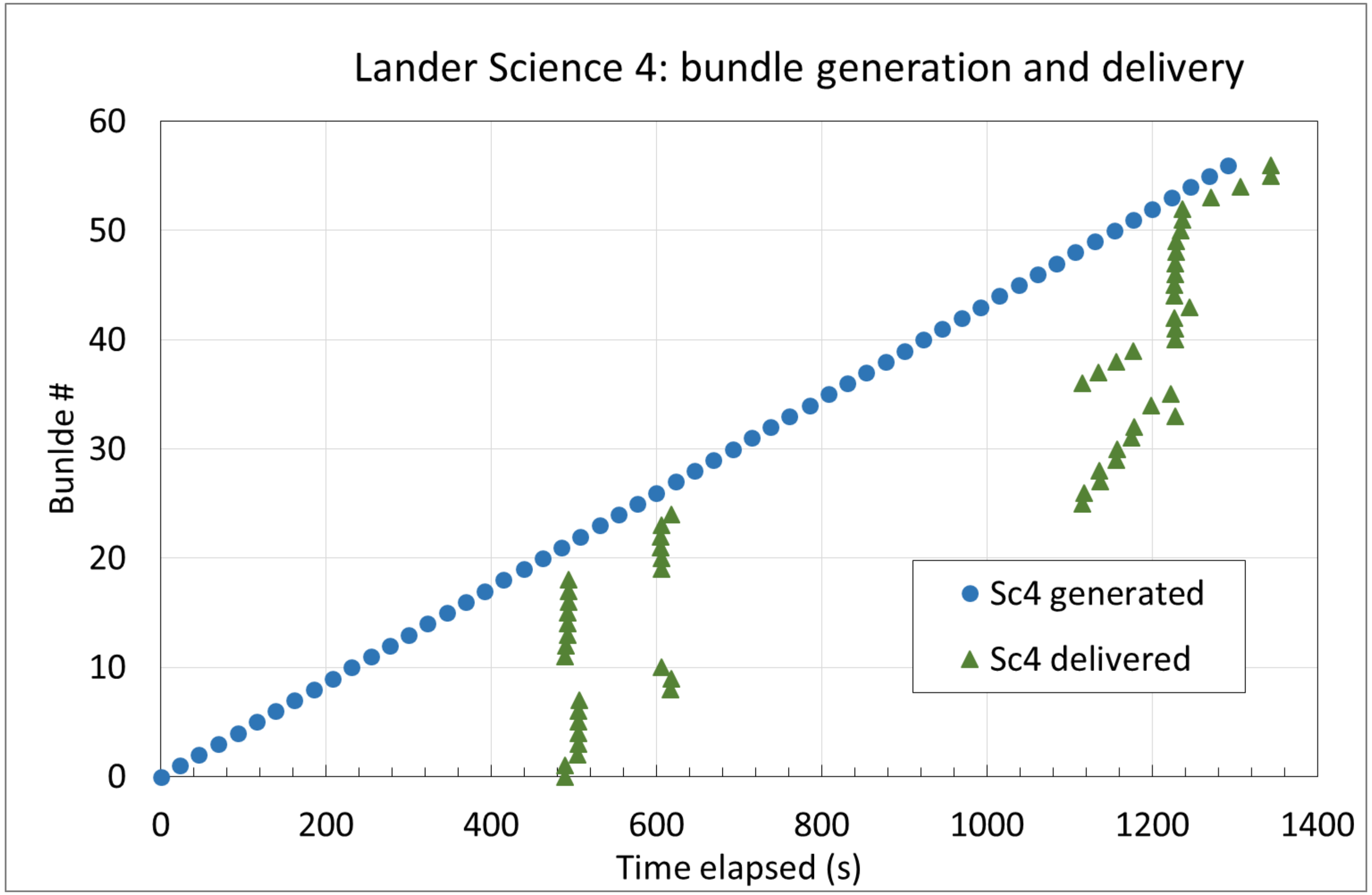
- TM-EXP have the highest priority and a low generation rate.
- Bundles delivered in order, but delivery bursts are evident, due to the frequent lack of connectivity.
- No bundles delivered before about 470s, because there are not opportunities to leave the Lander
  - (no contacts from Lander to orbiters or ground stations before 440s)

Scenario C: TM data flow (normal) from Lander to ESA-MCC



- Tm data have "normal" priority and a high generation rate
- Gaps in connectivity evident as before; first cases of disordered delivery
  - Allowed, but a symptom of performance degradation
- For one bundle, the delivery delay is huge

Scenario C: Science 4 data flow (bulk) from Lander to ESA-MCC



- Science 4 data flow is the most challenging
  - fast generation rate, large bundles, and only "bulk" priority
- Disordered delivery is evident
  - caused by the scarce bandwidth between the Lander and other nodes
- The sum of all contact volumes available, i.e. the total amount of data that can be transferred during the experiment, is only marginally larger than the traffic injected.
  - This is more challenging for bulk flows, as their bundles are sent last.
- Thanks to our fixes on ION 3.6.0b, all bundles are delivered before the end of the experiment (1440s).

References of the “DTN application to Interplanetary communications” section

- Rationale, Scenarios, and Requirements for DTN in Space. CCSDS 734.0-G-1. Green Book. Issue 1. Aug. 2010.
  - https://public.ccsds.org/Pubs/734x0g1e1.pdf
- Licklider Transmission Protocol (LTP) for CCSDS. CCSDS 734.1-B-1. Blue Book, May 2015.
  - https://public.ccsds.org/Pubs/734x1b1.pdf
- P. Apollonio, C. Caini, V. Fiore “From the Far Side of the Moon: DTN Communications via Lunar Satellites”, China Communications, Vol.10, No.10, pp.12-25, Oct.2013.
  - DOI: 10.1109/CC.2013.6650316
- C. Caini, R. Firrincieli, T. de Cola, I. Bisio, M. Cello, G. Acar, “Mars to Earth Communications through Orbiters: DTN Performance Analysis”, Wiley, Int. J. Satell. Commun. Network, pp.127-140 March 2014.
  - DOI: 10.1002/sat.1043
- N. Alessi, C. Caini, T. de Cola, S. Martin, J. Pierce Mayer, “DTN Performance Analysis of Multi-Asset Mars Earth Communications”, Wiley International Journal of Satellite Communications and Networking, vol.40, no.1, pp.11-26, Jan-Feb-2022 (printed) , July 2019 (first published);
  - DOI: 10.1002/sat.1326; Open access.

Part 3: Other topics

DTN Security

DTN Security

- IRTF RFC 6257 Bundle Security Protocol (BSP) (2011)
  - defines a set of BP extensions to support:
    - hop-by-hop authentication
    - end-to-end integrity and authentication
    - end-to-end confidentiality.
    - Different treatment for bundle payload and other data (e.g. metadata)
  - Security requires the insertion of security blocks in the bundle structure
- Some problems emerged soon
  - Too complex (KISS rule largely violated)
  - Scarce compatibility with bundle fragmentation
  - Scarce compatibility with routing
    - Security Destination(s) different from Destination makes impossible to route bundles on the basis of the destination EID only.
- DTN security standardization continued in IETF DTN Working Group (DTNWG), leading to RFC 9172 Bundle Protocol Security (BPSec), for BPv7
  - https://datatracker.ietf.org/doc/rfc9172/

Security sources, destinations and nodes

- Security-aware nodes
  - DTN nodes able to process security blocks
  - Other nodes are “transparent” as far as security is concerned
- “Security source”
  - “a bundle node that adds a security block to a bundle”
  - Usually coincides with the bundle source, but not necessarily
- “Security destination”
  - “a bundle node that processes a security block of a bundle” (ambiguous definition)
  - In BPSec it is said that must coincide with the bundle destination (thus it is unique) to solve some of the original BSP problems; however, also intermediate nodes can process security blocks.

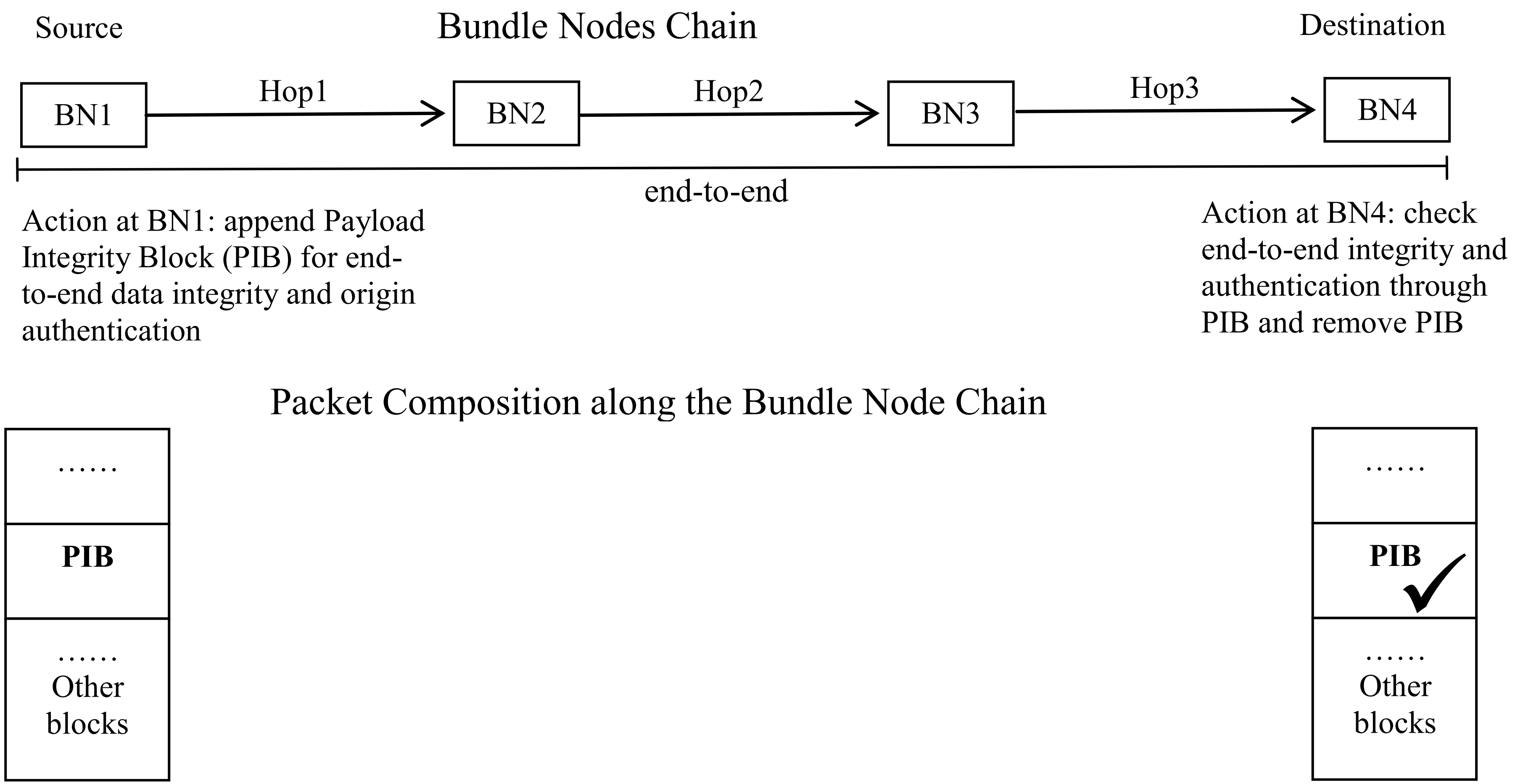
Block-Level Granularity in BPSec

- In BPSec each bundle block can have its own security block.
  - Security services in BPSec MUST allow different blocks within a bundle to have different security services applied to them.
    - The primary block contains identification and routing information.
    - The payload block carries application data.
    - Extension blocks carry a variety of data that may augment or annotate the payload, or otherwise provide information necessary for the proper processing of a bundle along a path.
  - Therefore, applying a single level and type of security across an entire bundle fails to recognize that blocks in a bundle may represent different types of information with different security needs.

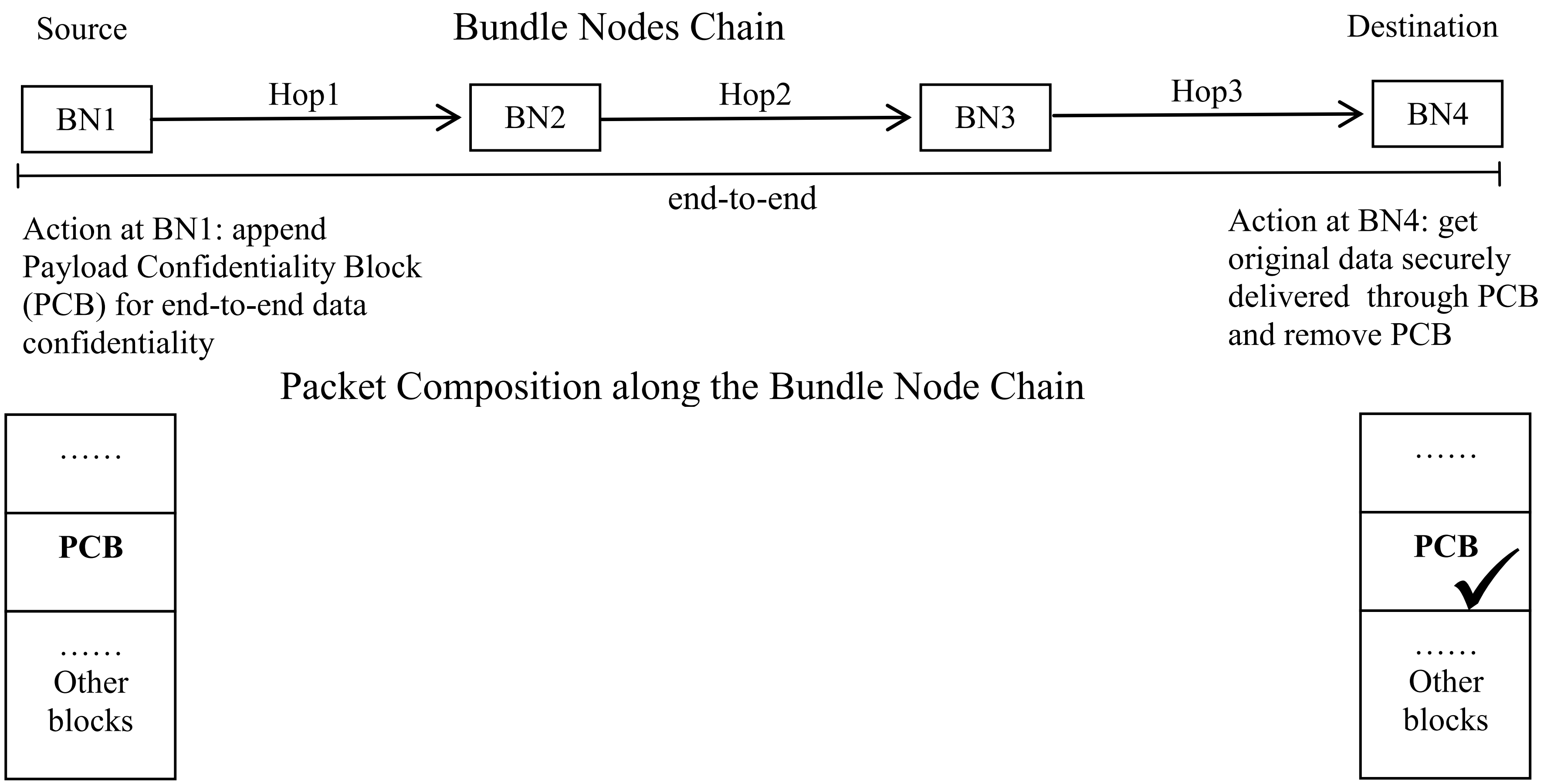
BPSec security blocks

- Block Integrity Block (BIB, ex PIB in BSP)
  - It is used to ensure the integrity of its security target(s). The integrity information in the BIB MAY be verified by any node in between the BIB security source and the bundle destination. Security-aware waypoints may add or remove BIBs from bundles in accordance with their security policy.
- Block Confidentiality Block (BCB, ex PCB in BSP).
  - The BCB indicates that the security target(s) have been encrypted at the BCB security source in order to protect its content while in transit. The BCB may be decrypted by security-aware nodes in the network, up to and including the bundle destination, as a matter of security policy.

BIBs (when used for end-to-end integrity and authentication, as ex PIBs)



BCBs (when used for end-to-end confidentiality, as ex PCBs)



DTN Security References

- RFC 6257 Bundle Security Protocol Specification S. Symington et al. May 2011
  - http://tools.ietf.org/html/rfc6257
- ETSI Report TR 102 676: Technical Report on Performance Enhancing Proxies (PEPs) for the European ETSI Broadband Satellite Multimedia (BSM) working group. (Sept. 2009).
  - https://www.etsi.org/deliver/etsi_tr/102600_102699/102676/01.01.01_60/tr_102676v010101p.pdf
- W. Ivancic, " Security Analysis of DTN Architecture and Bundle Protocol specification for Space-Based Networks", in Proc. of IEEE Aerospace Conf., Big Sky Montana, 2010, pp. 1-12.
  - DOI: 10.1109/AERO.2010.5446946
- C. Caini, H. Cruickshank, S. Farrell, M. Marchese, "Delay- and Disruption-Tolerant Networking (DTN): An Alternative Solution for Future Satellite Networking Applications", Proceedings of IEEE, Vol. 99, N. 11, pp.1980-1997, Nov. 2011.
  - DOI: 10.1109/JPROC.2011.2158378
- RFC 9172 Bundle Protocol Security (BPSec), E. Birrane K. McKeever, Jan. 2022
  - https://datatracker.ietf.org/doc/rfc9172/

DTN QoS

Priority classes

- RFC 5050 defines three (“cardinal”) priority classes
  - Bulk, normal, expedited
  - they imply some form of priority-based scheduling within DTN routers
  - Only partially supported by DTN2
    - Priority flags can be set, but DTN routers do not care of them…
- NASA has recommended the introduction of a much finer granularity to match complex deep space requirements
  - “Ordinal” priorities added to differentiate expedited bundles
  - “Critical” (i.e. emergency) bundles routed by CGR in a different way (controlled flooding)

Delivery options and status reports

- The DTN architecture (RFC4838) offers a set of delivery options based on the following “Bundle Status Reports”
  - Bundle Received
    - sent when a bundle is received by a DTN node.
  - Custody Accepted
    - sent when a node has accepted custody of a bundle.
  - Bundle Forwarded
    - sent when a bundle is forwarded to next DTN node.
  - Bundle Deleted
    - sent when a bundle is discarded.
  - Bundle Delivered
    - sent from the destination node when a bundle is delivered to the DTN application
  - Acknowledged by application
    - sent by the application at a destination node
- Delivery options may help manage QoS related to scheduling, flow and congestion control, and routing.

Routing classification

- Static
  - Through tables
- Dynamic
  - Forwarding schemes
    - send one bundle copy
  - Replication schemes
    - send multiple copies
      - Pro: high delivery ratio and short delivery time
      - Con: higher traffic due to redundant copies
    - suitable for opportunistic networks

Forwarding schemes: CGR/SABR

- Contact Graph Routing
    - Developed by NASA JPL and implemented in ION
        - well suited to deterministic networks with intermittent scheduled connectivity (deterministic «contacts»)
            - Good for deep space but also excellent for LEO sats
        - Each node has full knowledge of network topology and «contact plans»
        - Nodes are not aware of traffic generated by other nodes
            - Congestion may be an issue
    - Latest version standardized by CCSDS as SABR (Schedule-Aware Bundle Routing)
    - Examples of use shown in previous sections (e.g. ESA Scenarios A and C)

Routing (replication schemes)

- For opportunistic environments (random connectivity) there is a huge number of proposals. The most important ones are:
  - Epidemic routing
    - It is highly reliable but heavily resource demanding
    - nodes continuously replicate and transmit bundles to all new contacts that do not possess a copy yet, without any attempt to avoid replication;
  - ProPHET
    - It uses the non-complete randomness of contacts, as often happens in real scenarios, to replicate and pass bundles only if the encountered node has enough chances to deliver it;
  - Spray-and-Wait
    - It “sprays” a limited number of copies into the network, and then “waits” till one of these nodes meets (“contacts”) the destination.
  - MaxProp
    - It is based on prioritizing the schedule of both bundles transmitted to DTN nodes and of bundles to be dropped. Priorities are based on path likelihoods calculated according to historical data and on complementary mechanisms. It was evaluated on a real DTN bus network,
  - RAPID
    - Another variant on the theme, also evaluated on a bus network.

DTN QoS References

- A. Balasubramanian, B. Levine, and A. Venkataramani, "Replication routing in dtns: A resource allocation approach," IEEE/ACM Trans. on Netw., vol. 18, no. 2, pp. 596 –609, Apr. 2010
  - DOI: 10.1109/TNET.2009.2036365
- C. Caini, H. Cruickshank, S. Farrell, M. Marchese, "Delay- and Disruption-Tolerant Networking (DTN): An Alternative Solution for Future Satellite Networking Applications", Proceedings of IEEE, Vol. 99, N. 11, pp.1980-1997, Nov. 2011.
  - DOI: 10.1109/JPROC.2011.2158378
- G. Araniti, N. Bezirgiannidis, E. Birrane, I. Bisio, S. Burleigh, C. Caini, M. Feldmann, M. Marchese, J. Segui, K. Suzuki. "Contact Graph Routing in DTN Space Networks: Overview, Enhancements and Performance", IEEE Commun. Mag., Vol.53, No.3, pp.38-46, March 2015.
  - DOI: 10.1109/MCOM.2015.7060480
- N. Bezirgiannidis C. Caini,V. Tsaoussidis, "Analysis of contact graph routing enhancements for DTN in space", International Journal of Satellite Communications and Networking, No.34, pp.695-709, Sept./Oct. 2016,
  - DOI: 10.1002/sat.1138.
- CCSDS 734.3-B-1: Schedule-Aware Bundle Routing
  - https://public.ccsds.org/Pubs/734x3b1.pdf
- C. Caini, G. M. De Cola, L. Persampieri, "Schedule-Aware Bundle Routing: Analysis and Enhancements", International Journal of Sat. Commun. and Networking, vol. 39, no.3, pp. 237-243, May/June 2021.
  - DOI: 10.1002/sat.1384

Conclusions

- DTN can play a key role in space communications
- No longer need specific solutions
  - Through DTN, space networks might become just a component of a larger Internet.
- Space technology has often proved to be very useful also on earth.
  - Why this should not hold true for DTN?