



From Sputnik to Interplanetary Networking:

a concise overview of Space Communications in the last 60 years.

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Outline

- First part: from Sputnik to Internet
 - A historical retrospective
 - A few experiments
- Second part: DTN overview
- Third part: DTN application to space networks
 - Satellite communications in a nutshell
 - Satellite Networks
 - Interplanetary Networking (IPN)

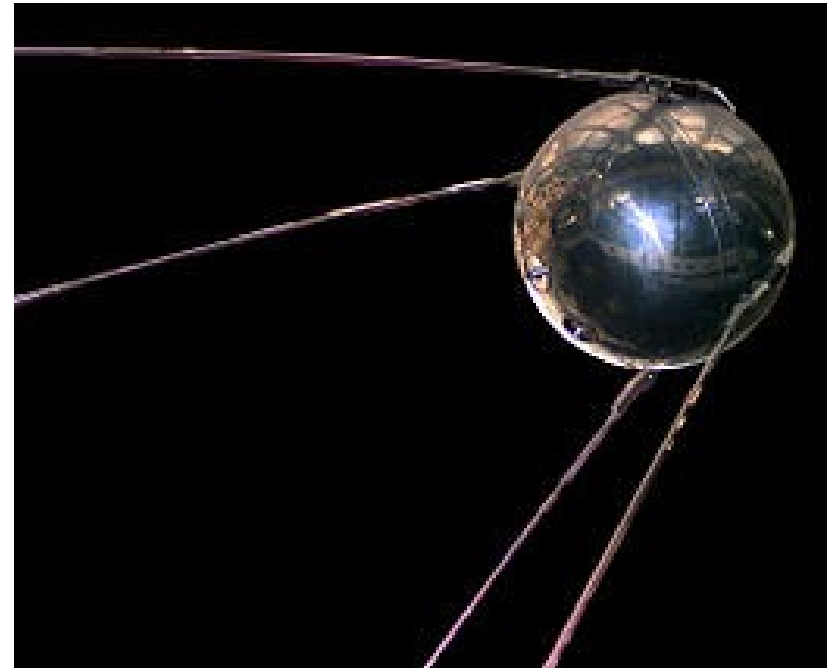


From Sputnik to Internet

A historical retrospective

1957: Sputnik

- 4 October 1957 Sputnik, the first artificial satellite, is launched by Russians
 - It is not a geostationary satellite and in fact it is NOT a telecommunication satellite.
 - It has a radio on board, which emits “bips”, intended for world wide radio amateurs.
 - It is glossy to facilitate its vision by astrophiles
 - It is a product of the cold war, and in particular of the research on Inter Continental Ballistic Missiles (ICMB)
- The propagandistic impact is enormous. US public opinion is shocked.
- The space race starts.

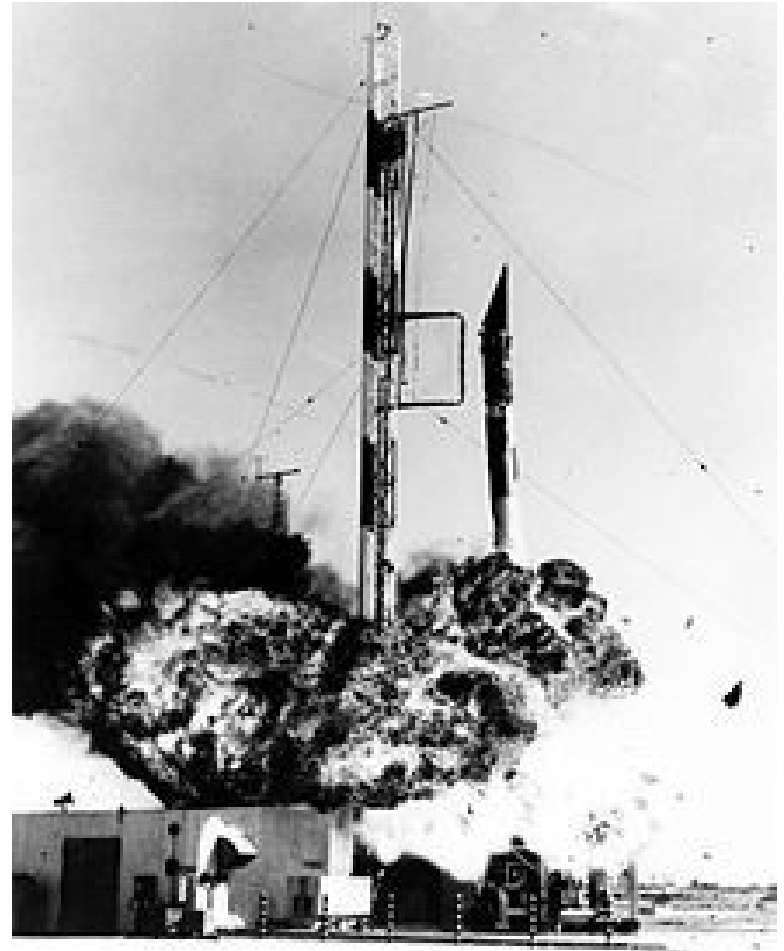


A challenging question...

- In the first edition of this summer school a student asked me if LEO satellites, i.e. satellites that move on the sky and pass over different nations as Sputnik, must be authorized by these nations.
 - I enjoyed the question but... I was not able to answer!
 - I am pleased to answer now
 - Russians did not ask anybody for the Sputnik. That was the sole consolation of Americans, which thought nobody could blame them in the future if they did the same!
 - In fact, both Americans and Russians were extremely interested in developing spy-satellites to take photograph of other country from space
 - US used special planes to take photographs of Russia; they had to deliberately violate the Russian airspace, which led to an international crisis in 1960
 - https://en.wikipedia.org/wiki/1960_U-2_incident

1957: Kaputnik (Vanguard)

- Two months later, on 6th December 1957, the US Vanguard (US NAVY) missile, with the satellite VT3 on board explode on the launching pad, live on TV. Humiliation for the failure is added to the loss of technical supremacy.
 - US press becomes furious against the administration.
 - The ABMA (US ARMY) center, where the German scientist Werner Von Braun (the designer of V1 and V2) works, previously blocked for politic reasons, is asked to put a remedy as soon as possible.



1958: Explorer

- After other two months, on 31st January 1958, the US satellite Explorer 1, built in only 84 days by JPL Caltech, is put into orbit by a Jupiter-C missile (designed by Von Braun)
- In February 1958 [ARPA \(Advanced Research Projects Agency, poi DARPA\)](#) is founded. The aim is to assure the technological supremacy of the United States.
- On 29th July 1958 [NASA \(National Aeronautics and Space Administration\)](#) is founded.

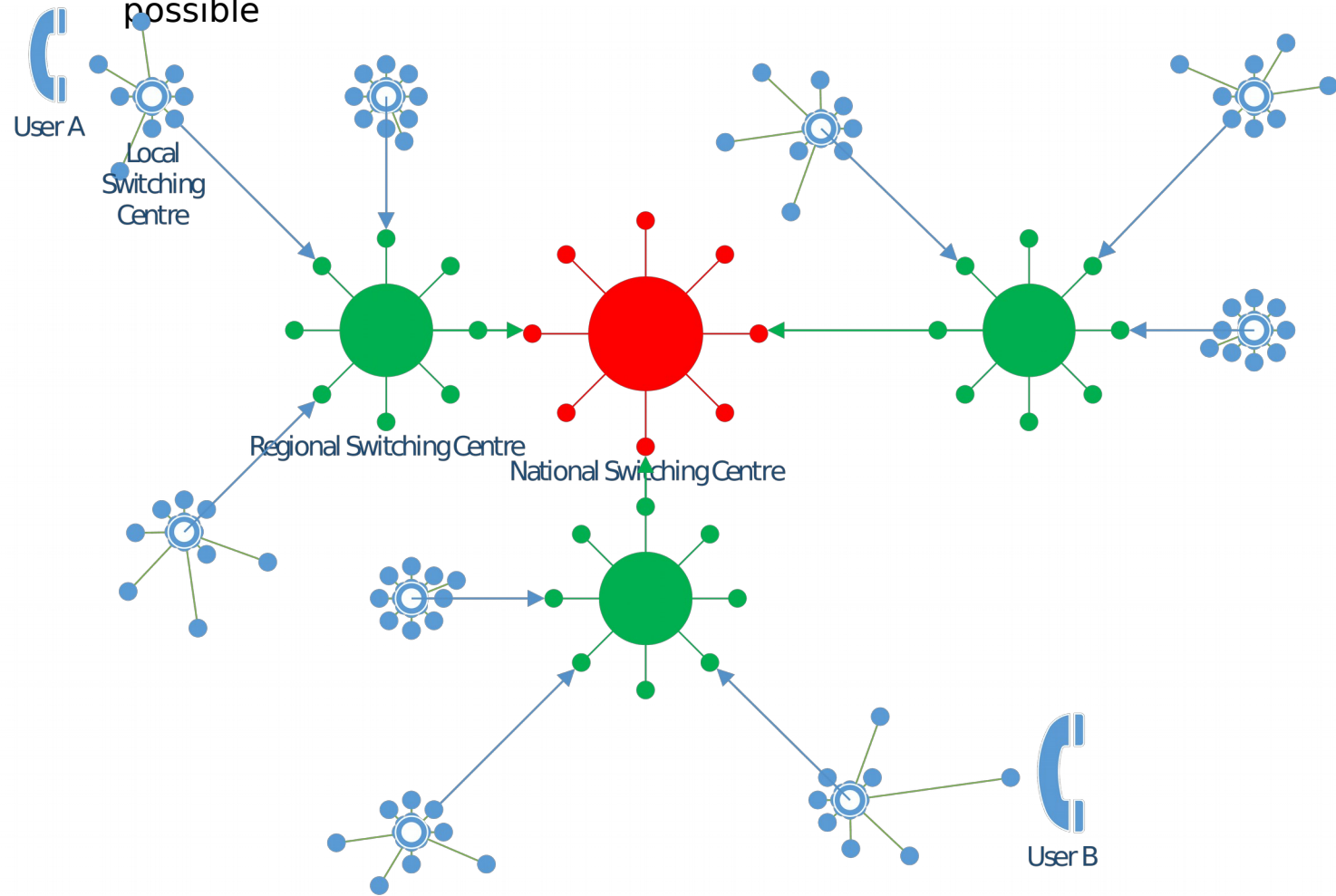


Internet origin

- Was Internet conceived for WWW, iTunes, Facebook, WhatsApp, Google...?
- In facts, it was work shaped by the Cold War
- Paul Baran 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."

Old Telephone Network Layout (simplified)

- Due to the hierarchical structure, from User A to User B only one path is possible



Internet basis

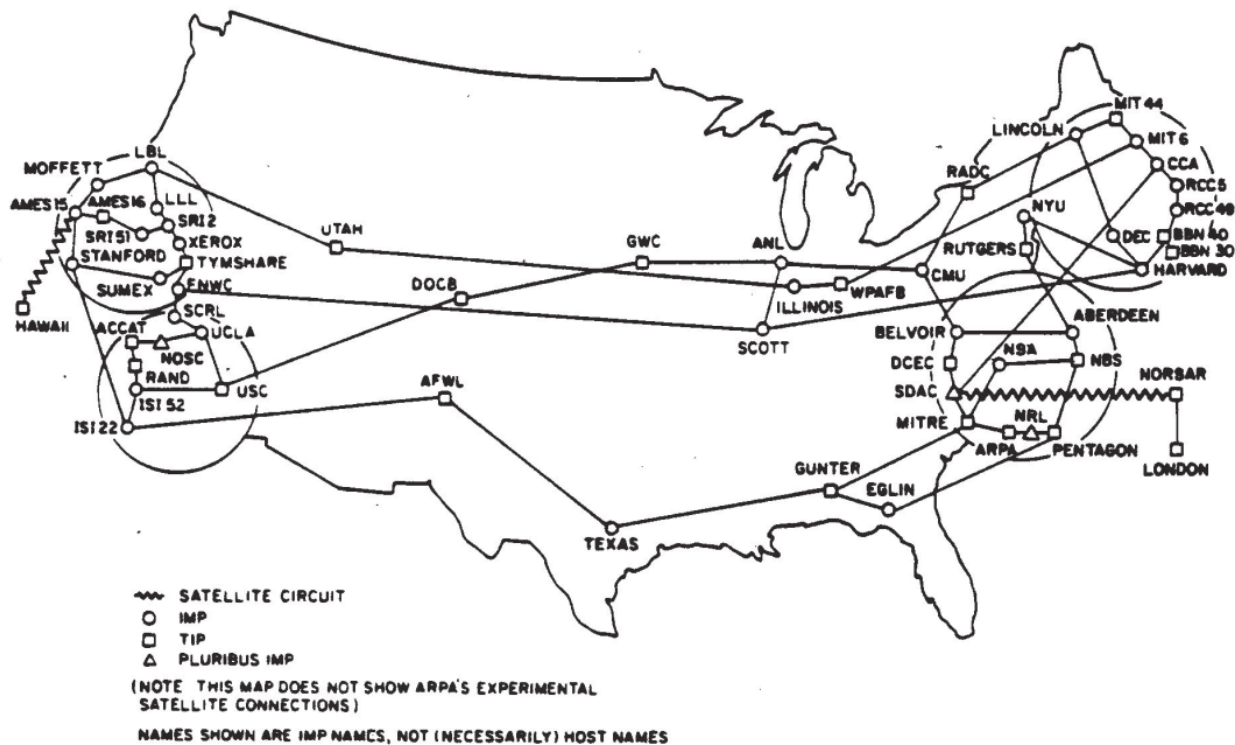
- Design pillars

- Packet switching (connectionless) instead of circuit switching
 - Packet switching divides messages into arbitrary packets, if connectionless routing decisions are made per-packet.
- Distributed & redundant architecture

- Aim

- Provided that there is a continuous path between A (source) and B (destination), communication must be possible.
 - The path among intermediate nodes is found in an automatic way
- We will see that DTN goes further and releases even this continuous path constraint!

ARPANET

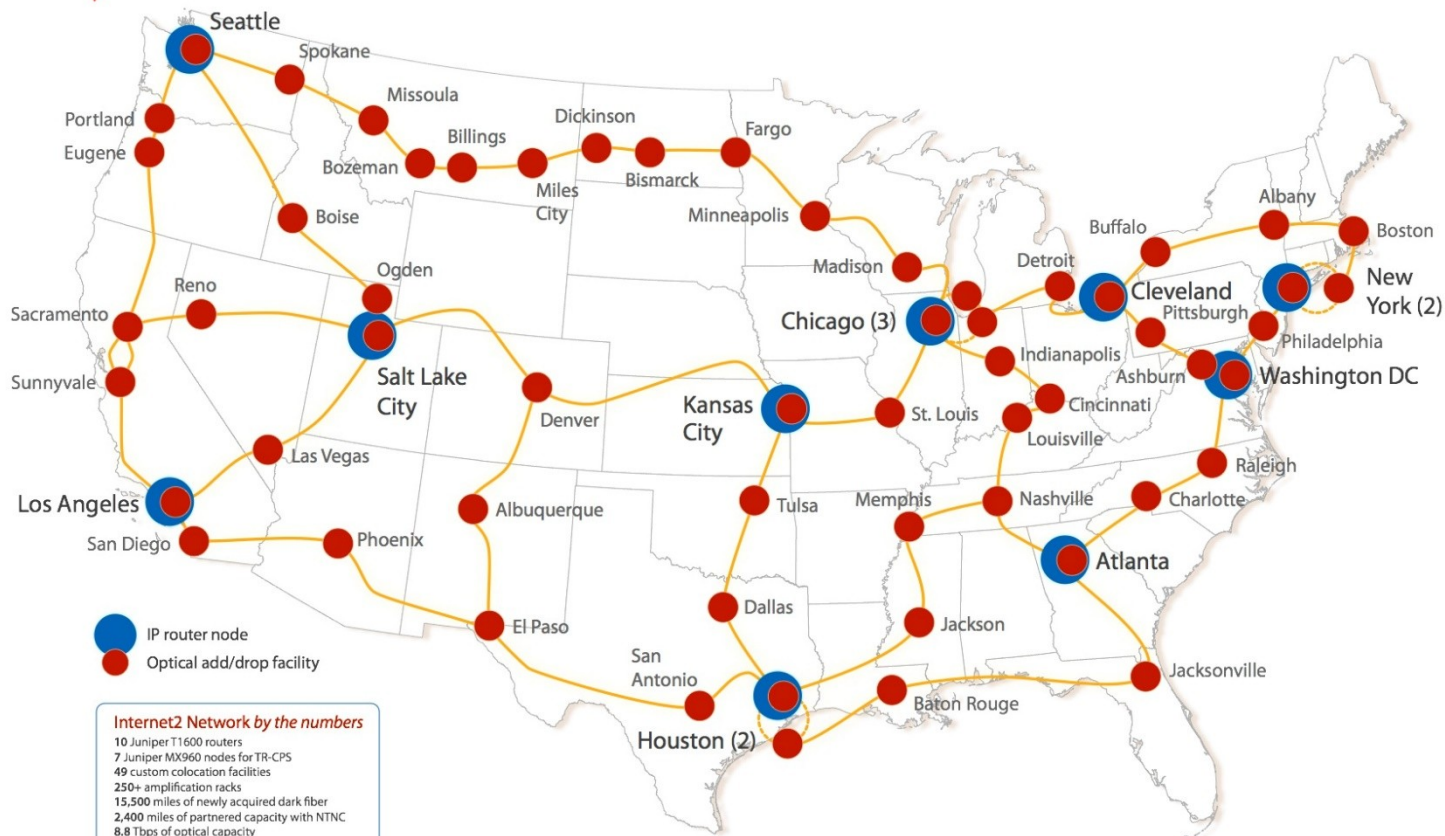


A planned high speed network (redundant topology)



Internet2 Planned 100 Gigabit Infrastructure Topology (DRAFT)

Draft – Last updated 04/10/11



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Internet evolution



- 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: First man on the Moon on 21 July
- **1969: First message on the ARPANET on October 29th**
 - (“lo” for “login”, but after 2 characters the host crashed)
- 1973: TCP/IP Protocols
 - by Vinton Cerf and Bob Kahn
- **1991: World Wide Web birth (first web site)**
 - by Berners-Lee and Robert Cailliau at CERN, HTML language, HTTP protocol
- 2001: Interplanetary (IPN) Architecture studies start (DARPA founded, by V. Cerf et alii)
- 2003: From IPN to DTN (Delay-/Disruption- Tolerant Networking)
- ? : 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...



From Sputnik to Internet

A few experiments

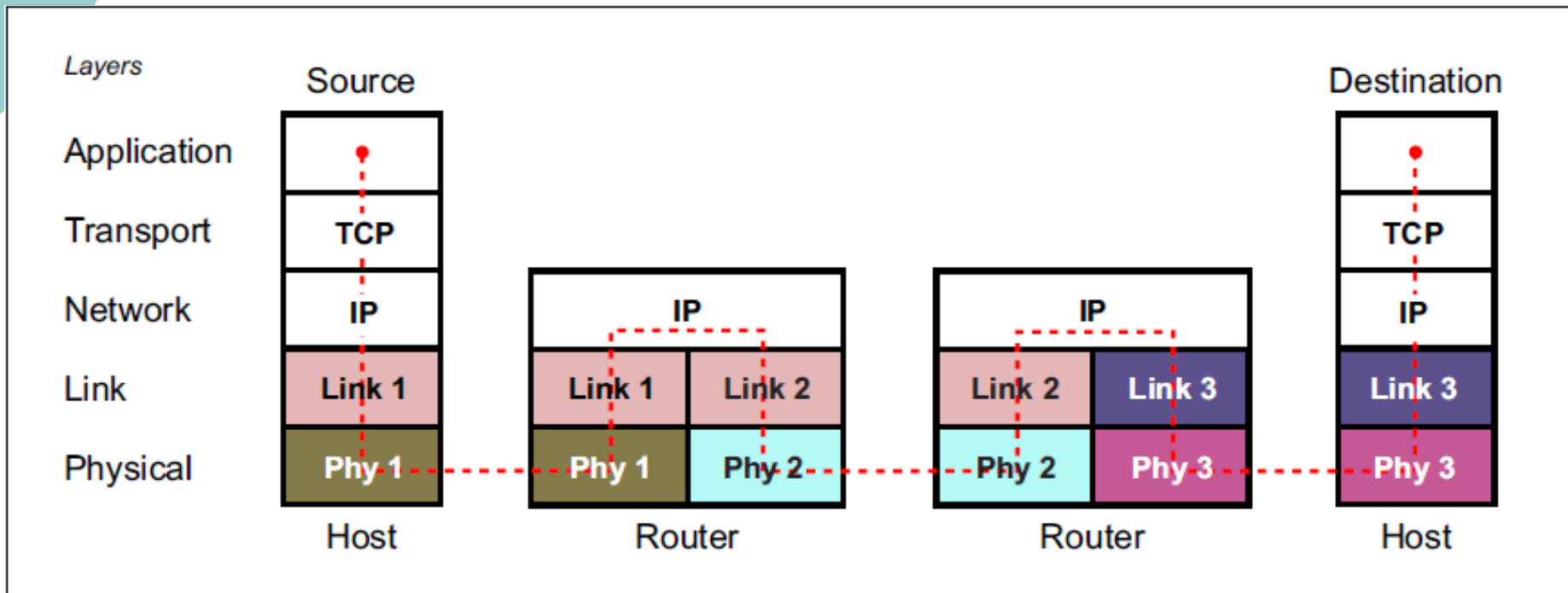
Everything started with a failed login!

- We can try to repeat the first experiment by logging in on a remote computer via SSH
 - Secure SHell is a network protocol to establish a cyphered connection with a remote host (computer)
- Never seen a character terminal? It is time to try it!
 - `ssh student@192.168.0.112 (pwd=student)`
 - If we do not succeed at the first attempt, we do not need to get discouraged...

Ping, local networks and Internet

- If the Access Point (AP, the WiFi router) is disconnected, we cannot go to Internet.
 - >ping www.google.com fails
- However, we can still reach the AP and all other nodes connected to the AP (i.e. the other nodes of our local network).
 - ping 198.162.0.1 (the router IP address)
 - ping 192.168.0.112 (the IP address of a node)
- If we connect the AP to Internet (e.g. via 3G), we can reach all Internet nodes worldwide
- The RTT (Round Trip Time) depends on the distance and the number of intermediate nodes. Compare:
 - >ping www.google.com (fast, few tenths of ms)
 - >ping www.ucla.edu (it takes longer, about 200ms)
 - We will see that the RTT has a strong impact on TCP performance
- We can also have an idea of the path to reach destination
 - >tracert www.ucla.edu

The TCP/IP architecture



Transport UDP & TCP

- Transport is the first end-to-end layer (only on source and destination)
 - UDP connectionless, unreliable (like ordinary mail)
 - TCP connection oriented, reliable (packets are ACKed by the destination; packet lost are retransmitted by the source)
 - Tx speed is based on ACKs received
 - the longer the RTT the worse the performance
- Example
 - Vm1>iperf -c vm2
 - Vm2>iperf -s



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 challenged networks
 - [DTN-DINET w/ Vint Cerf You Tube](#)

Background

- 1973 –Cerf’s and Kahn’s work on TCP
- Early ‘90 –Researchers at NASA Jet Propulsion Laboratory (JPL) try to adapt Internet protocols to space missions
- 1998 –Cerf at alii promoted the Interplanetary Internet (IPN)
- May 2001 –“Interplanetary Internet: Architectural Definition” Internet draft
 - Necessity of a new architecture
 - Whereas the Earth’s Internet was basically conceived as a “network of connected networks,” the IPN was thought of as a “network of disconnected Internets” connected through a system of gateways forming a stable backbone across interplanetary space.
- August 2002-updated version of the draft as “Delay-Tolerant Network Architecture: The Evolving Interplanetary Internet”
 - The new architecture can be applied to other environments (“challenged networks”)
- October 2002
 - IRTF DTNRG start
 - “It is an open research group, meaning that anyone interested can contribute simply by joining the mailing list and getting involved in the work”.
- 2015-from IRTF to IETF (from Research to Engineering)
 - IETF DTN WG start

IRTF-DTNRG & IETF-DTN

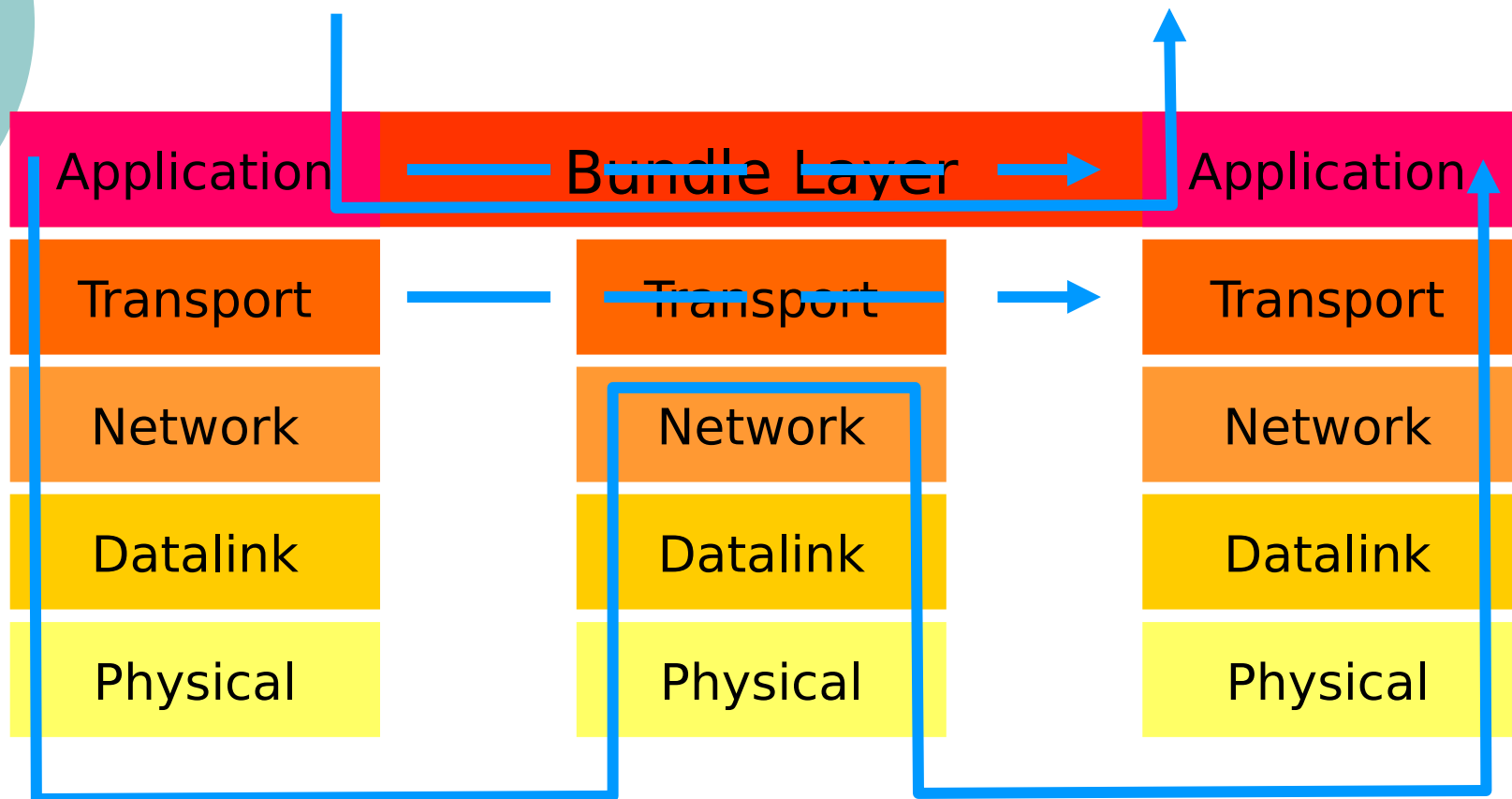
- Members of DTNRG first (now closed), and now of IETF DTN WG, are concerned with how to address the architectural and protocol design principles arising from the need to provide interoperable communications in performance-challenged environments.
- Examples of such environments include
 - Spacecraft
 - 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.
- Old Site of DTNRG: <https://sites.google.com/site/dtnresgroup/home>
- Site of IETF-DTN: <https://datatracker.ietf.org/wg/dtn/charter/>



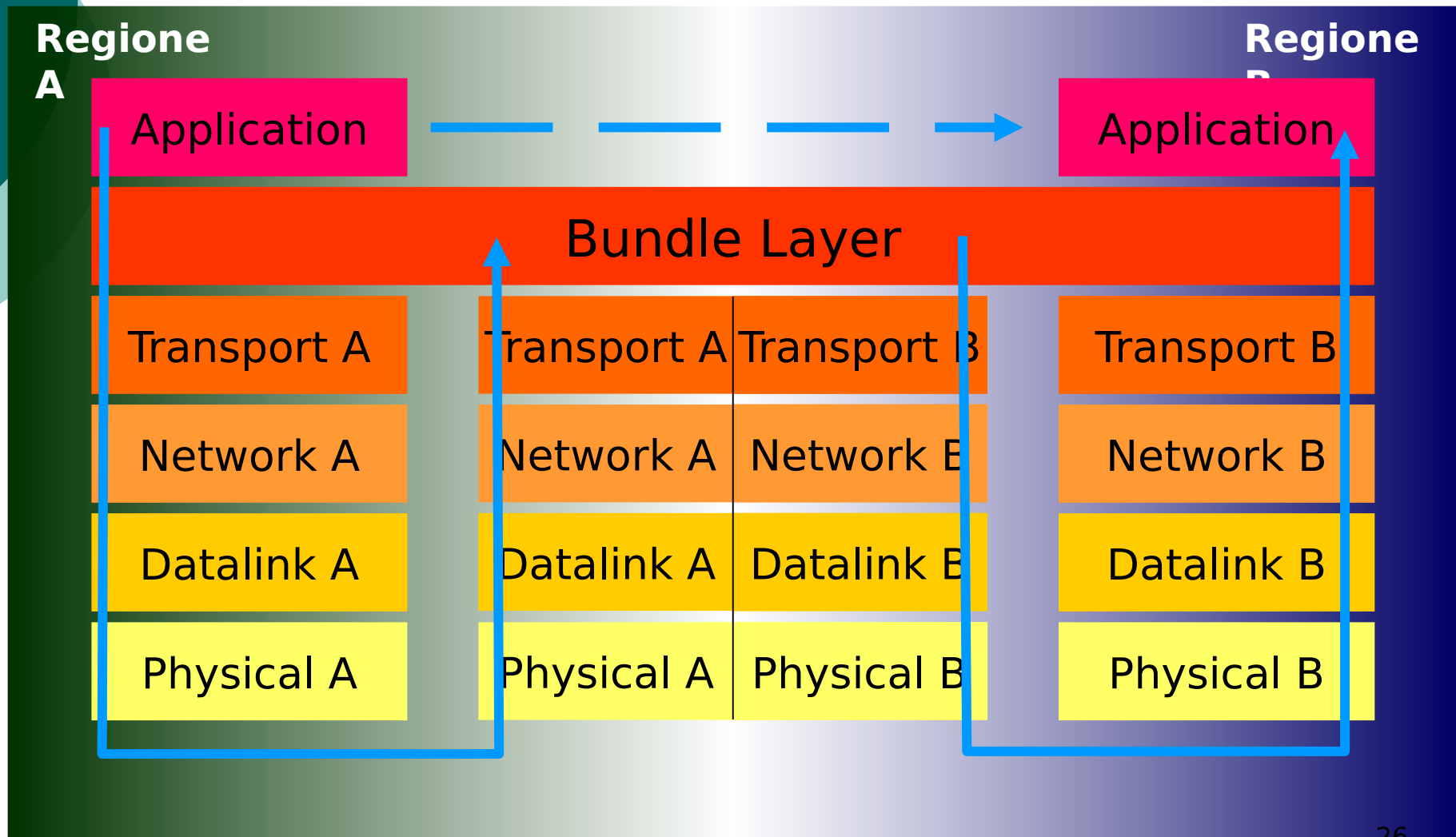
The Bundle Protocol DTN architecture

- 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 and forward
 - A bundle is first received, stored, and then transmitted (when possible)

Bundle Layer



Bundle Layer

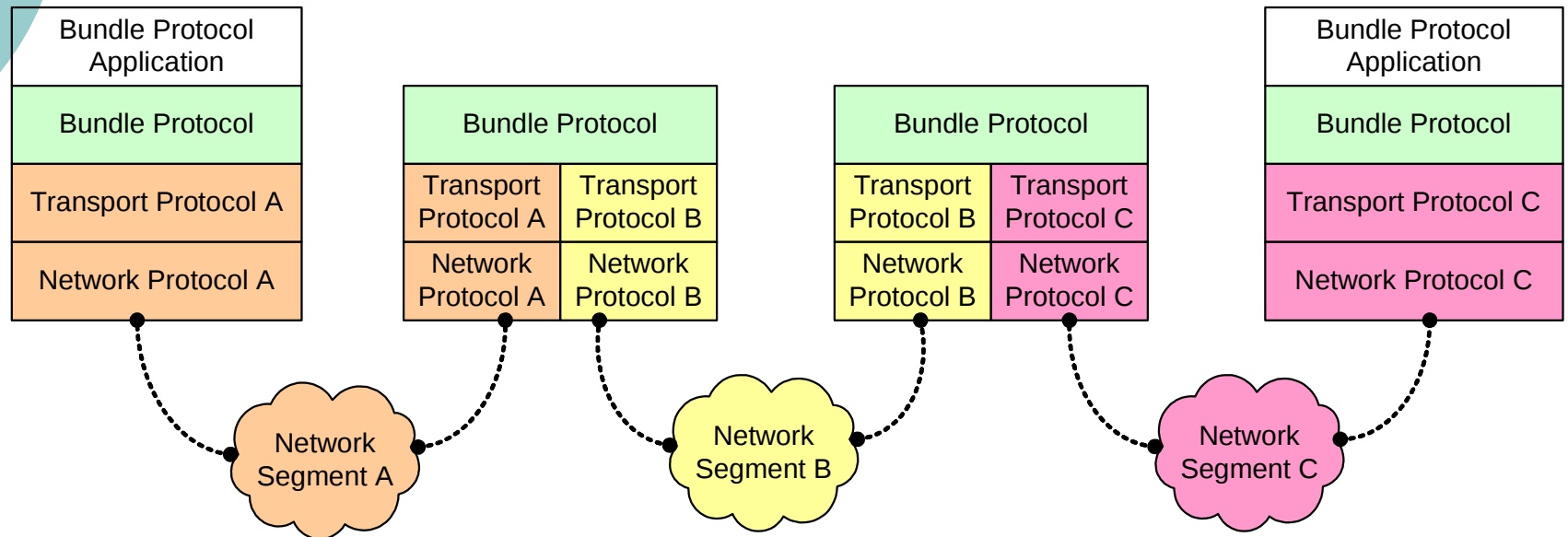




First basic concept: overlay network

- 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 for channel characteristics of each DTN hop
- Bundle layer is not truly end-to-end
 - It is present in some intermediate nodes too.

DTN overlay over a heterogeneous network

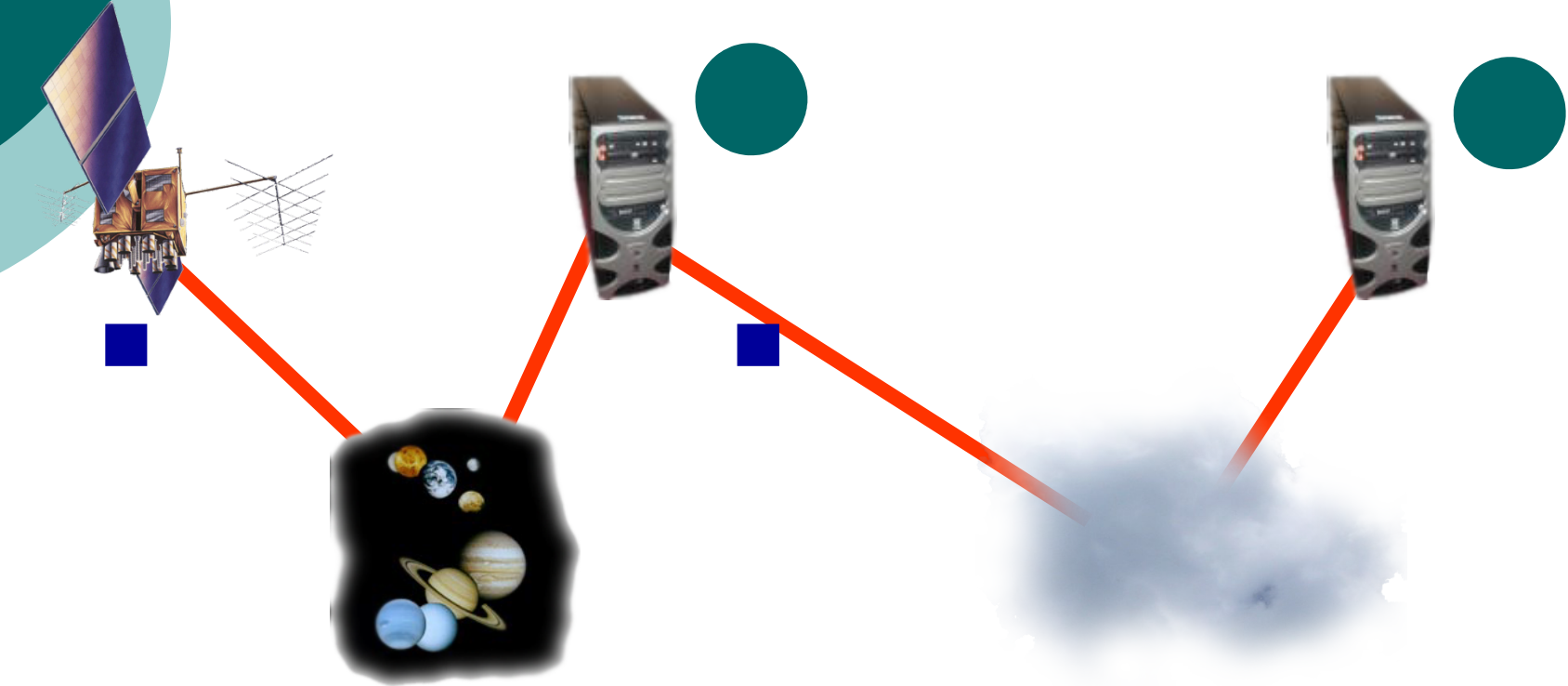




Second basic concept: information stored inside the network

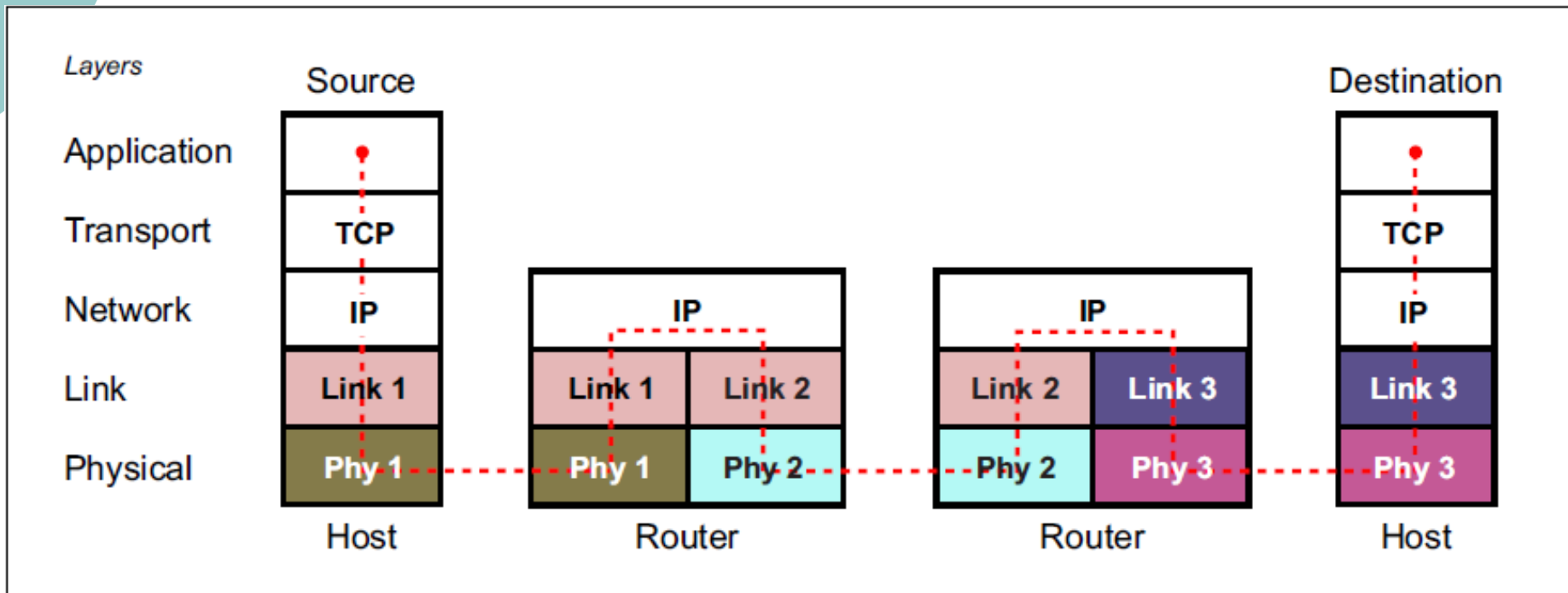
- Why necessary
 - To cope with the possible lack of a continuous end-to-end path (e.g. “data mule” applications)
 - More efficient loss recovery with long RTT
- Custody transfer option
 - The task of successful bundle delivery to destination is moved forward to the next DTN custodian
 - Bundles are deleted only when a following custodian has accepted the custody (or the bundle expires)
 - Bundles are retransmitted after a given interval, unless a custody acceptance signal has been received.

Bundle Transfer



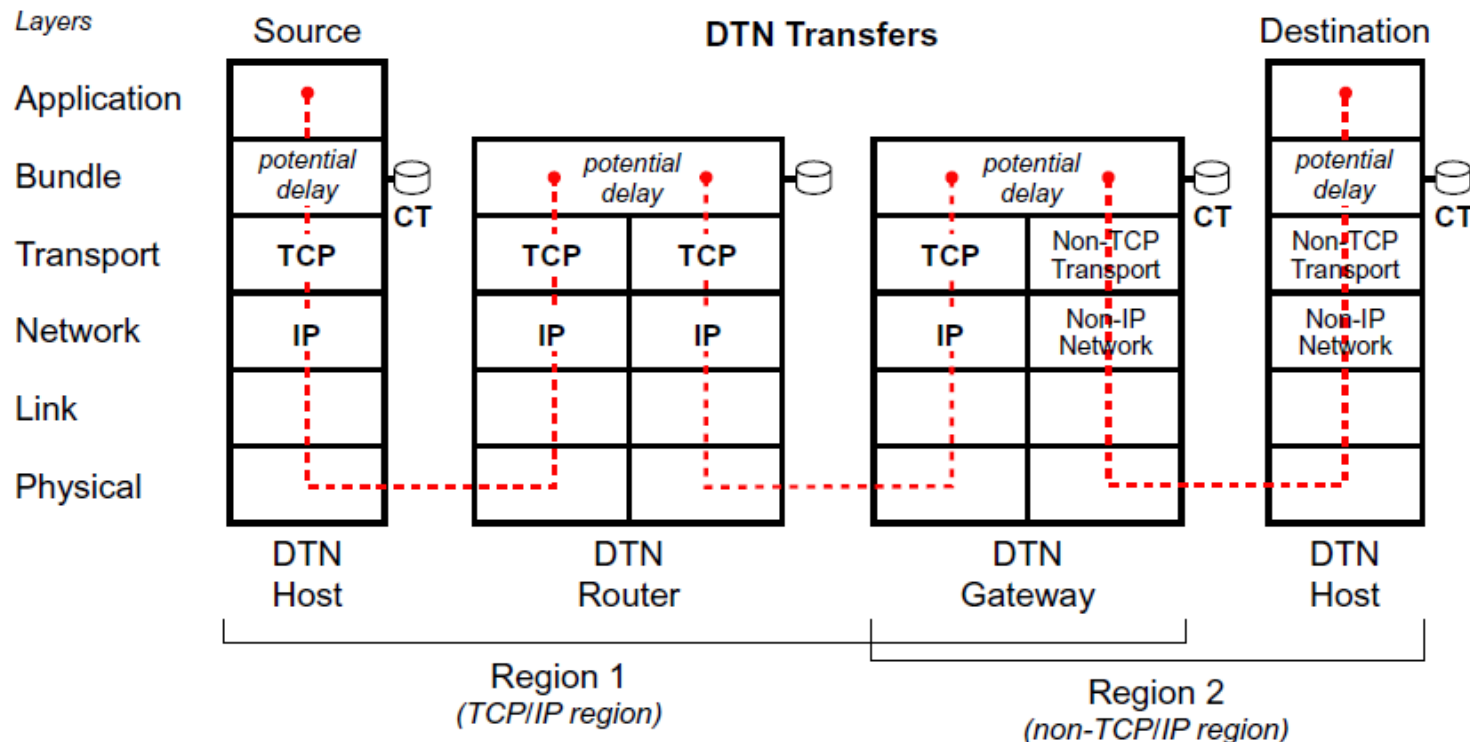
Bundle Layer

The TCP/IP architecture



The DTN architecture

- Note: between two DTN nodes, we can have many intermediate Layer 3 routers (not reported)

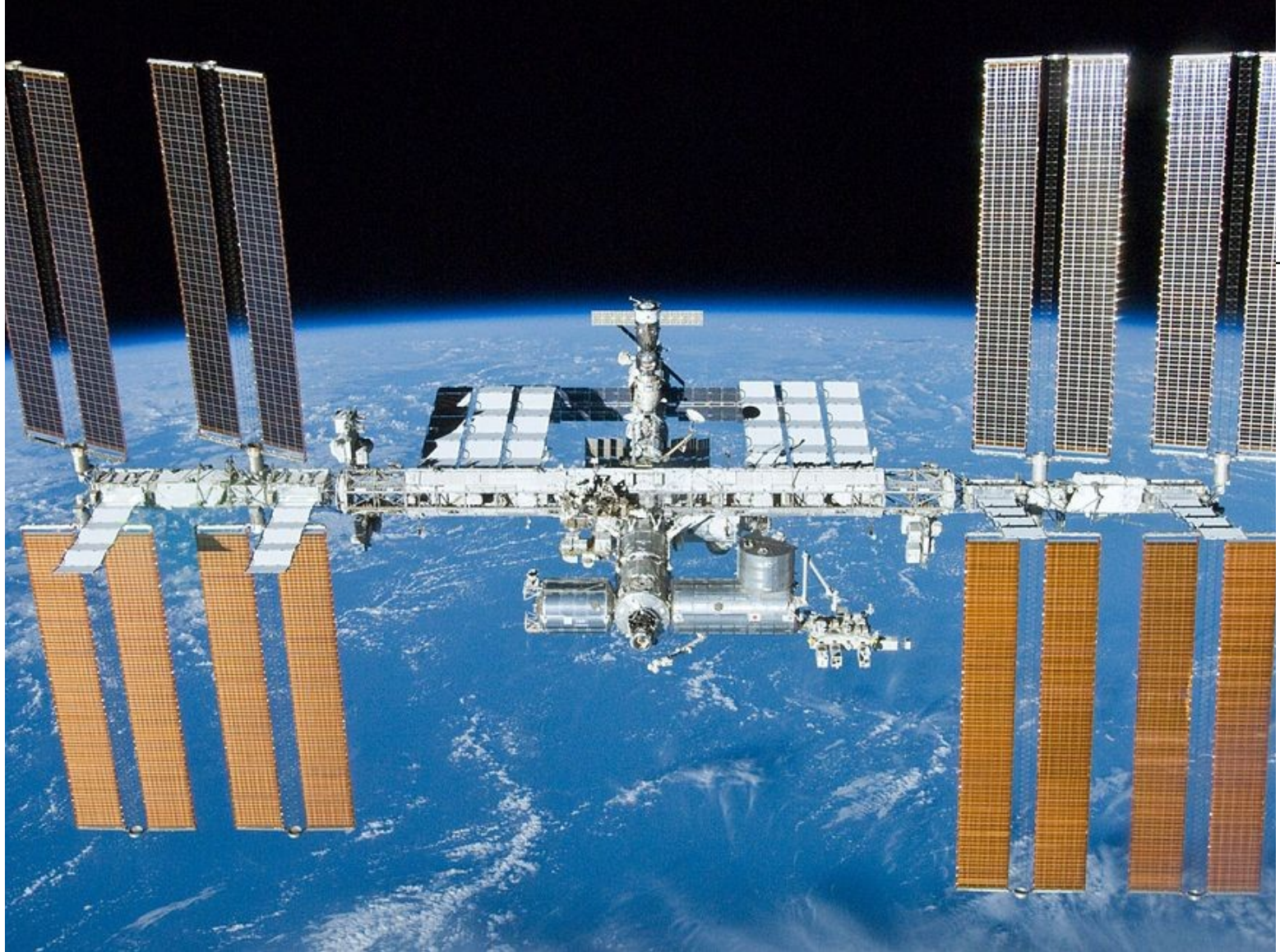


Routing

- Routing in DTN is a really challenging issue (and a hot research topic)
- DTN routing schemes have to deal with these major problems
 - 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 is impaired by delays and disruptions
- Possible objectives
 - delivery delay
 - probability of bundle delivery
 - storage management (new)
- Routing schemes must adapt to the peculiarities of the different DTN networks
 - CGR for scheduled intermittent connectivity (Interplanetary Networks)
 - Flooding, Spray-and-wait, Prophet, etc. (random intermittent connectivity)

DTN Experiments in space

- Epoxy experiment by NASA (one DTN node in deep space)
 - [NASA-DTN](#)
- Experiments from the International Space Station
 - http://www.nasa.gov/mission_pages/station/research/experiments/730.html
 - Multi-purpose End-To-End Robotic Operations Network (METERON, by ESA, NASA, DLR...)
- (Old) Experiments on satellites
 - UK part of the Disaster Monitoring Satellite (DMC)
 - MITRE (Tactical Networks)

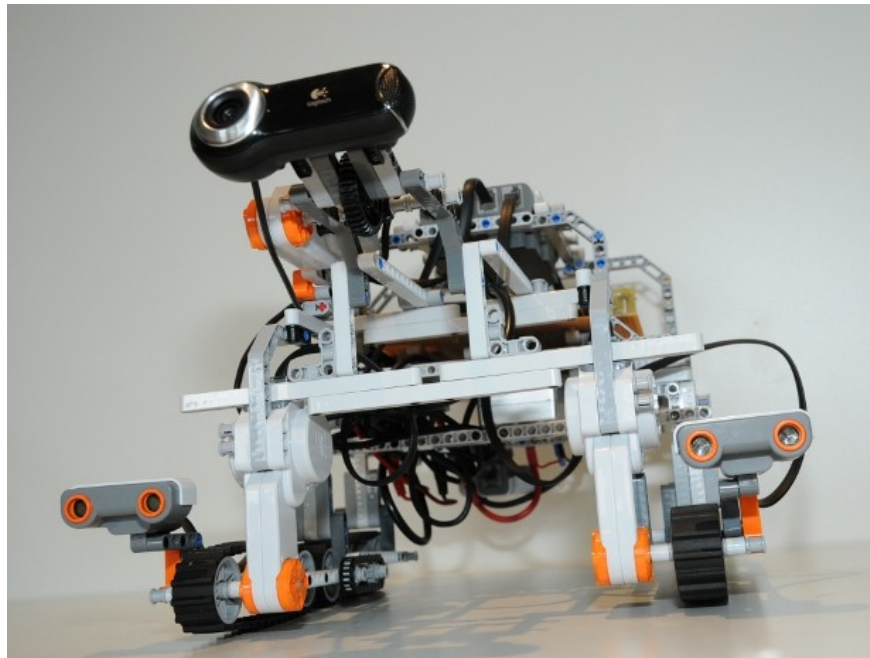


The ISS

By NASA/Crew of STS-132 [Public domain], via Wikimedia Commons

DTN & LEGO

- Lego robot on Earth controlled from the 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.”
 - <http://ipnsig.org/2012/11/14/dtn-in-the-news-nasaesa-collaborate-to-remotely-control-terrestrial-rover-from-iss/>



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- 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
- F. Warthmann [“Delay-and Disruption Tolerant Networks \(DTNs\), A tutorial” v3.2 2015](#)



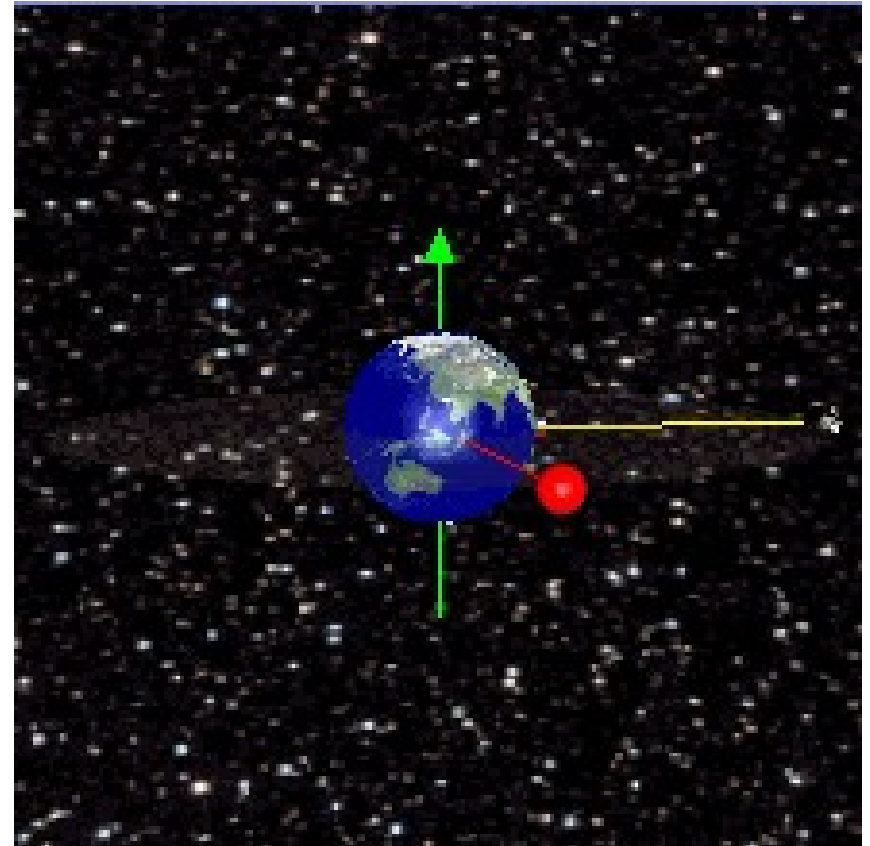
DTN Application to Space Networks

Satellite Communications in a nutshell

Geostationary Earth Orbit (GEO)

From Wikipedia: A circular orbit 35,786 kilometres (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 kilometres**
- 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.



GEO satellites

○ Advantages

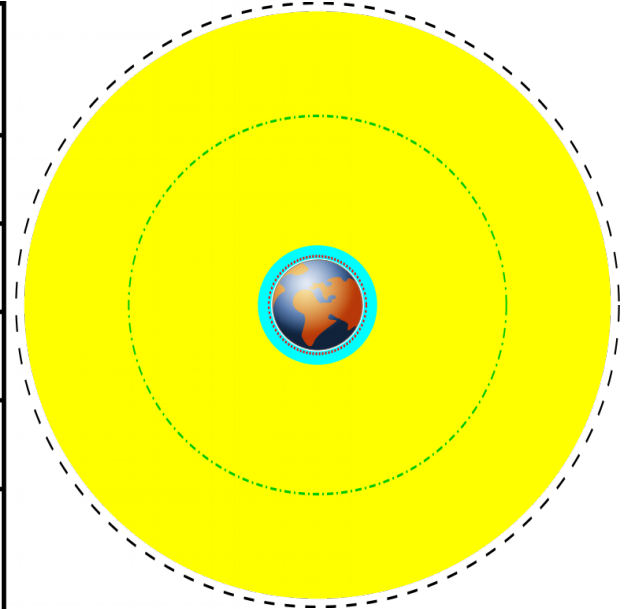
- To an observer on Earth they appear fixed in the Sky (no tracking necessary)
- 3 satellite at 120° on the GEO orbit can provide an almost full coverage of the Earth

○ Disadvantages

- High “free space” attenuation due to the long distance
- High propagation delay (about 125 ms from Earth to sat, i.e. $RTT > 500\text{ms}$)
- 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)
<u>Earth</u>	Blue/brown image	0	6370
<u>Low Earth Orbit (LEO)</u>	Cyan area	160 to 2,000	6,530 to 8,370
<u>Medium Earth Orbit (MEO)</u>	Yellow area	2,000 to 34,780	8,370 to 41,150
<u>International Space Station (ISS)</u>	Red dotted line	370	6,741
<u>Global Positioning System (GPS) satellites</u>	Green dash-dot line	20,230	26,600
<u>Geostationary Orbit (GEO)</u>	Black	35,794	42,164



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

Low Earth Orbit (LEO)

○ Advantages

- Low attenuation
- Short propagation delay (and RTT)
- The short distance allows 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 region of the Earth are covered (not simultaneously of course); good for Earth Observation
 - Typical orbit period=100m
 - LOS (Line of Sight) Window= few minutes (e.g. 8)

Some SatCom Providers

○ GEO

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

○ LEO

- Iridium (66LEOs, true global coverage, optical inter sat links)
 - <http://www.iridium.com/default.aspx>
 - http://en.wikipedia.org/wiki/Iridium_satellite_constellation
- Globalstar (coverage of continents, no Oceans...; no inter sat links)
 - <http://eu.globalstar.com/en/>
 - <http://en.wikipedia.org/wiki/Globalstar>

○ LEO-MEO planned mega constallations

- OneWeb (648 LEOs and about 2000 MEOs)
 - <http://oneweb.world/>
- SpaceX (4000 LEOs)
- «space debris» problem is still an open issue



DTN Application to Space Networks

Satellite networks

Motivations for DTN

- Challenges in GEO sats
 - Long propagation delay ($RTT=600ms$)
 - TCP performance severely impaired
 - Possible high losses
 - Disruption especially with mobile terminals (Tunnels, etc...)
- Challenges in LEO sats
 - Intermittent connectivity (contacts), due to the relative motion of satellites
 - Multiple gateway stations on Earth pose routing problems
- Peculiarities
 - The environment is mainly deterministic, but losses and disruptions.
 - LEO contacts are known a priori. Routing can take advantage of this

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!

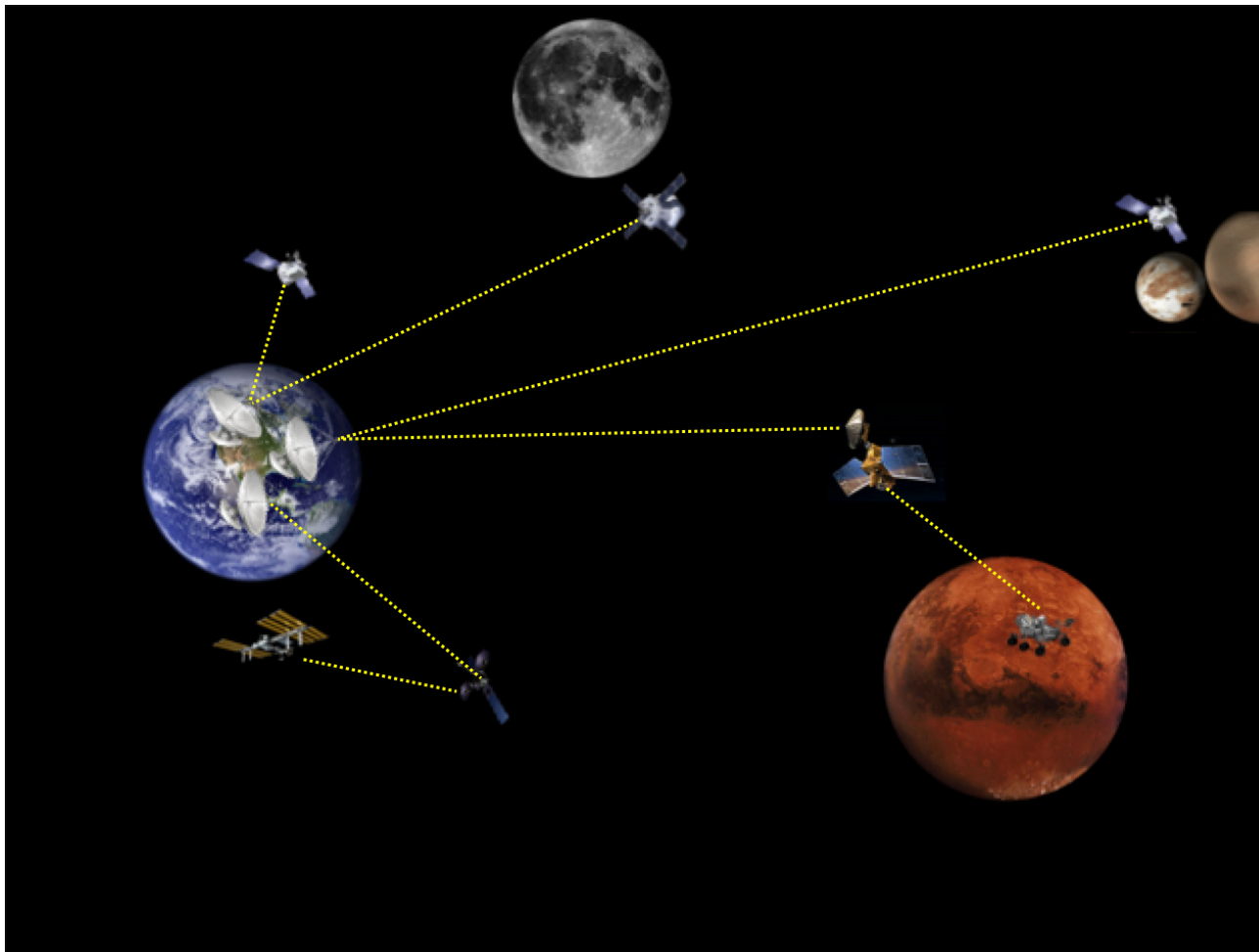
References of the “DTN application to SATs” sections

- C. Caini, 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
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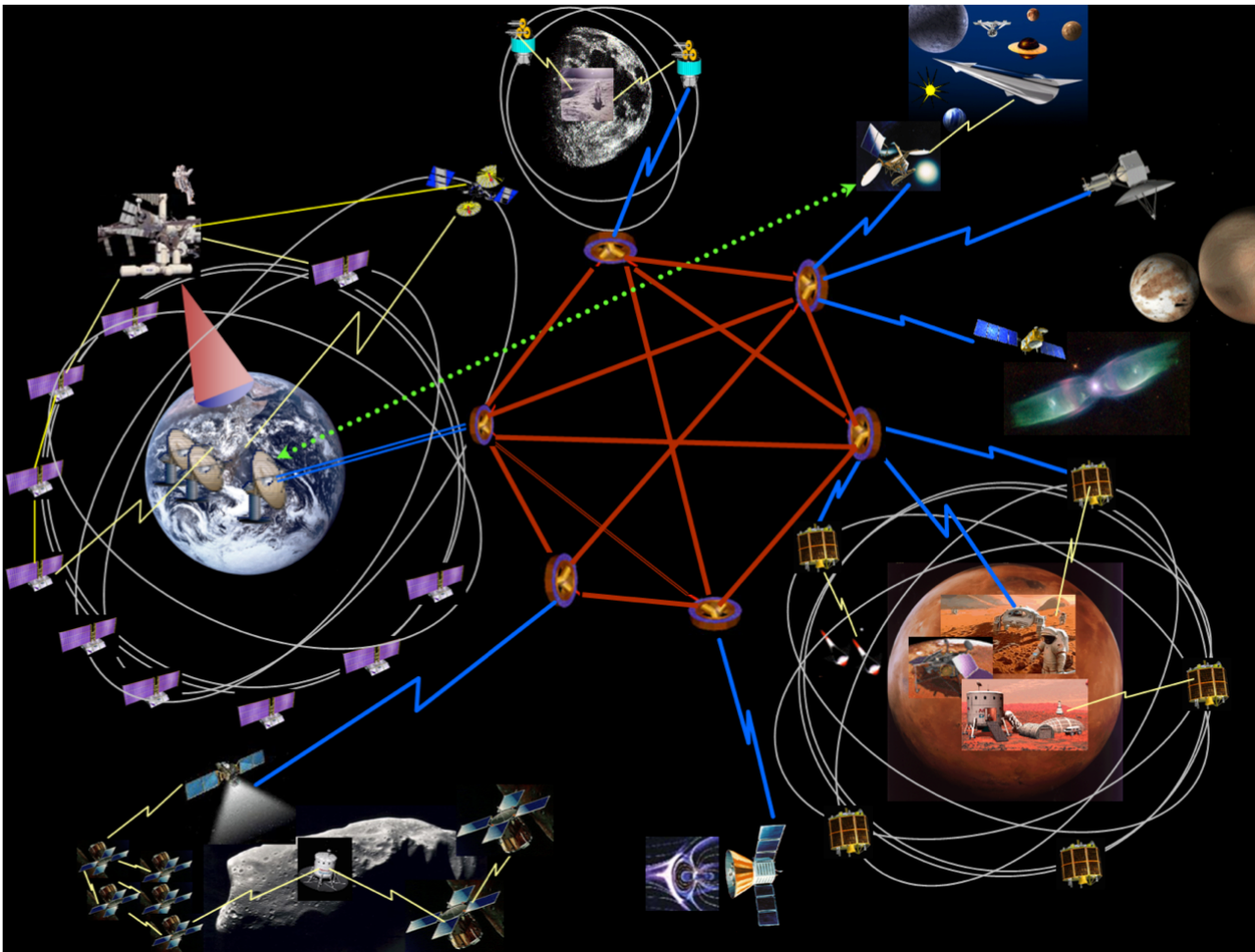
DTN Application to Space Networks

Interplanetary Networks



Interplanetary Networks

NASA missions have used direct or single relay communication, but future missions will require Internet-like communication. From [NASA-DTN](#)



Solar System Internet

The Disruption Tolerant Network protocols will enable the Solar System Internet, allowing data to be stored in nodes until transmission is successful. From [NASA-DTN](#)

Motivations for DTN

○ Challenges

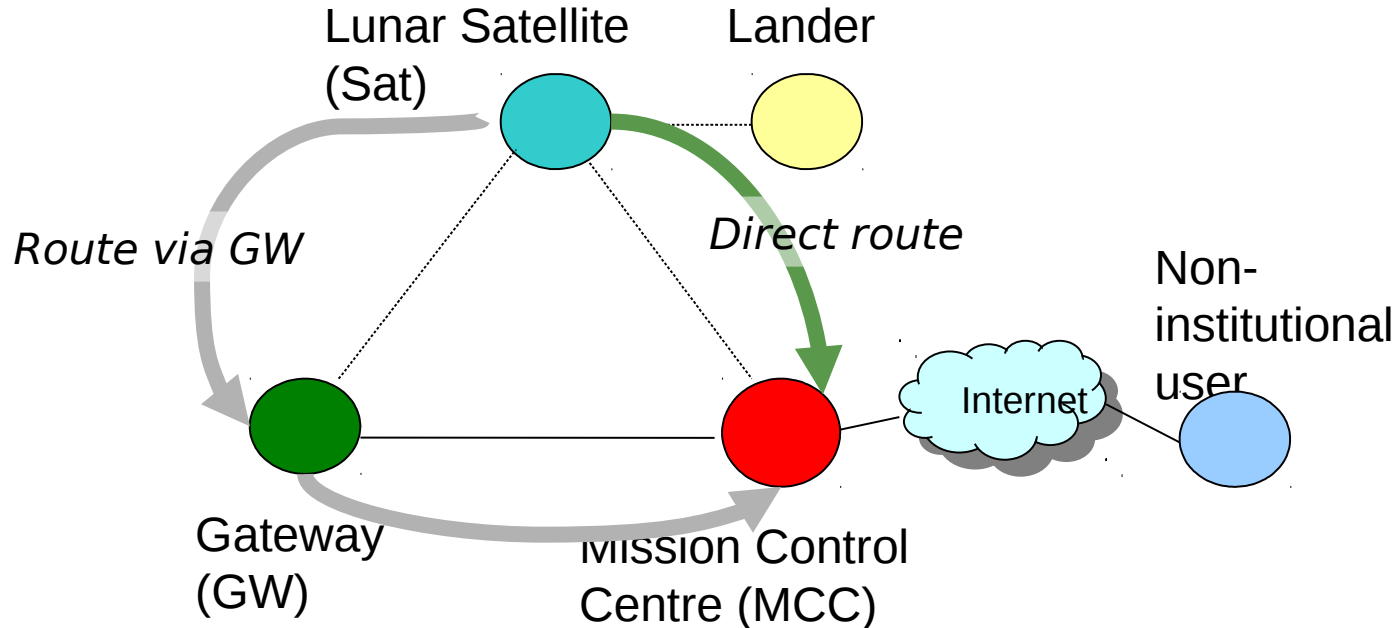
- Very long propagation delays
 - On Interplanetary DTN hops LTP (Licklider Transmission Protocol) instead of TCP is mandatory
- Intermittent connectivity (contacts), due to the orbital motion of planets and space assets
- Possible high losses

○ Peculiarities

- Contacts are essentially deterministic, i.e. known a priori
 - Routing can take advantage of this

An example: images from the far side of the Moon...

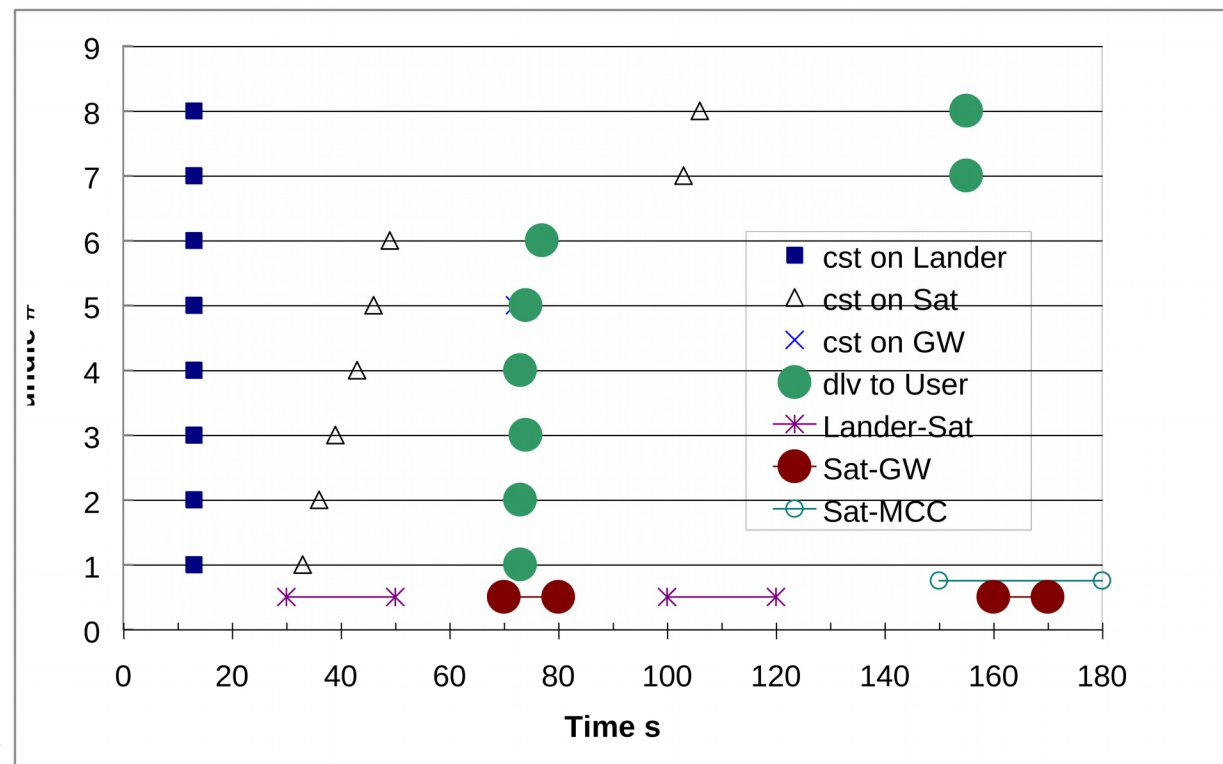
- Dotted lines=space intermittent links (windows of visibility)
- Continuous lines=terrestrial continuous links
- Two routes possible (via GW or direct); the choice is dynamic (as for trains or flights)



An example: images from the far side of the Moon...

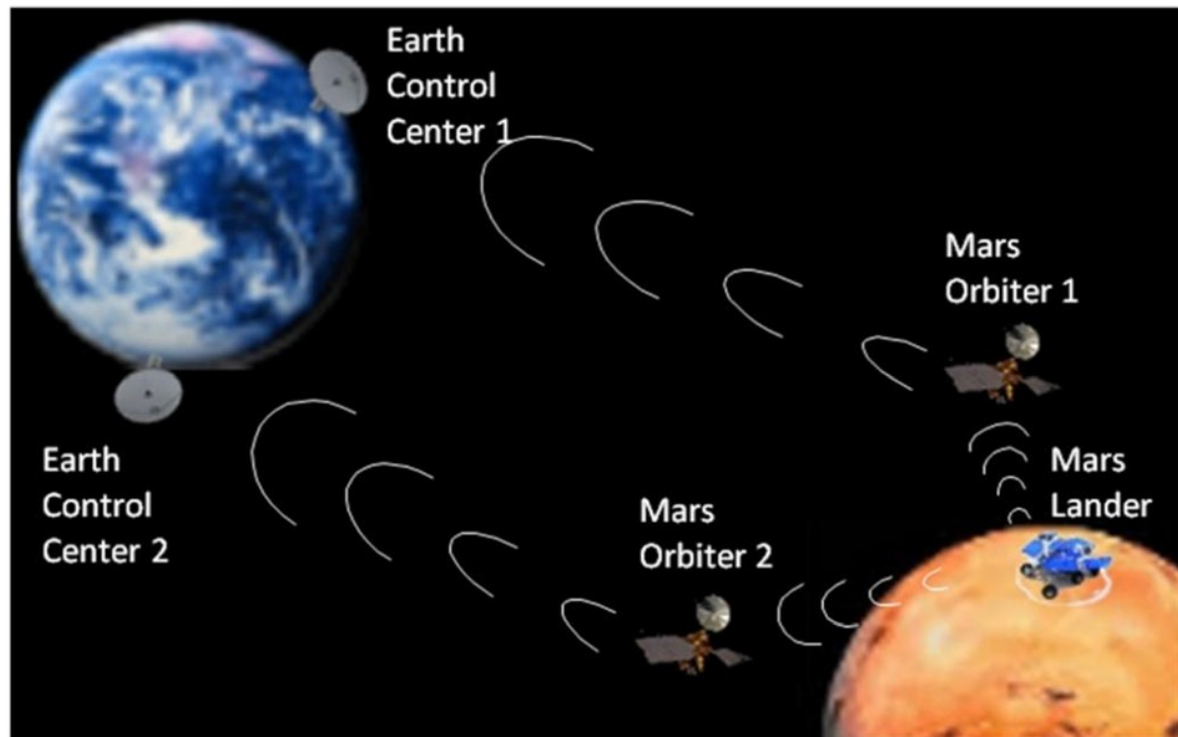
The 8 bundles generated on Lander have to be delivered to User

- First 6 transferred 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



An example: Mars to Earth DTN communications through Orbiters...

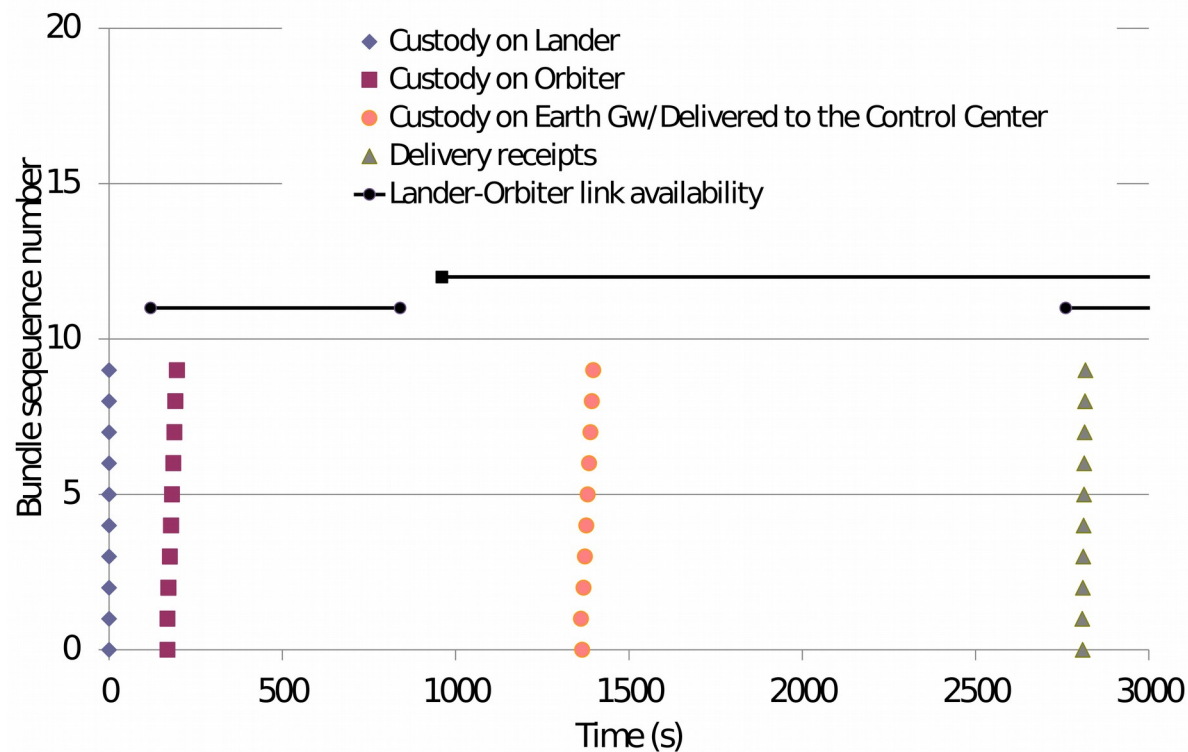
- The Mars Lander is not always in visibility with Earth Control Centre
- DTN transfer via Mars Orbiter 1 or 2 (a DTN node);
 - Two DTN hops
 - LTP on all links



An example: Mars to Earth DTN communications through Orbiters...

9 bundles of 50 kB are generated on Lander; they have to be delivered to Control Centre

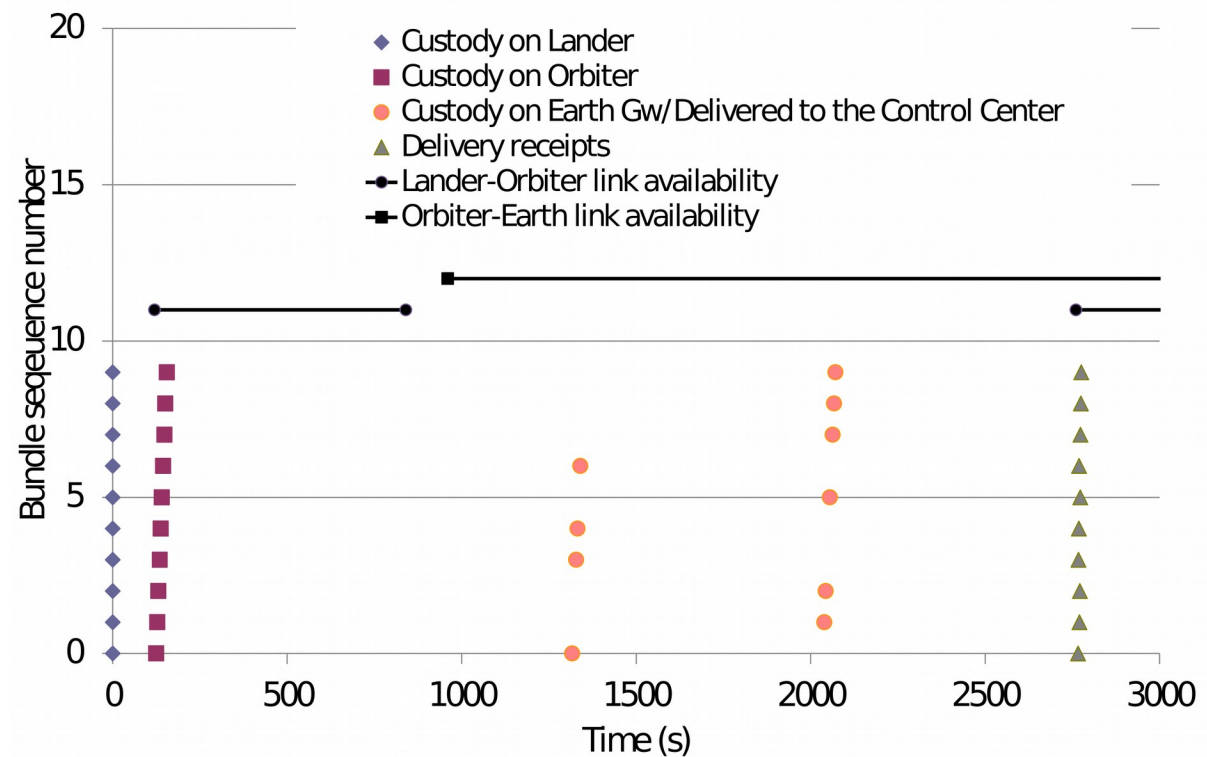
- All transferred to Orbiter1 (Odyssey) during the 1st Lander-Orbiter contact;
- all are delivered after only a half RTT from the opening of Orbiter-GW contact (PER=0);
- Delivery receipts are immediately sent to Orbiter and then transferred to Lander as soon as the 2nd Lander-Orbiter contact opens.



An example: Mars to Earth DTN comm. through Orbiters...(with PER=3%)

9 bundles of 50 kB are generated on Lander; they have to be delivered to Control Centre

- All transferred to Orbiter during the 1st Lander-Orbiter contact;
- 4 are delivered after a half RTT (360s) from the opening of Orbiter-GW contact;
- 5 after 1.5 RTTs (1080s) because of retransmissions of lost LTP segments (PER=1.5%)



References of the “DTN application to Interplanetary communications” section

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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?