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Space for Internet and Internet for space

Scott Burleigh [a,*], Vinton G. Cerf [b], Jon Crowcroft [c], Vassilis Tsaoussidis [d]

[a] Jet Propulsion Laboratory, California Institute of Technology, United States
[b] Google, United States
[c] Computer Lab, University of Cambridge, United Kingdom
[d] Space Internetworking Center, Democritus University, Greece

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ABSTRACT

Space flight and Internet service are technologies that are currently complementary but seem to be on the verge of integration into a new "space internetworking" discipline. The authors believe a comprehensive realization of space internetworking technology could dramatically enhance space exploration, augment terrestrial industry and commerce, benefit the economically disadvantaged, and nurture human and civil rights.

1. Introduction

People think of space flight and the Internet as distinct technologies, both exciting, both even central to the unfolding of our future as a species over the centuries ahead, but fundamentally independent. It is the thesis of this paper that this independence is ending. An infrastructure for universal interconnection among humans and their artifacts is emerging which will unify internetworking and space flight technologies, enhancing the impact of both on the way we enjoy and use our home in the solar system.

2. Space flight operations to support Internet

Internetworking is made possible by "links" that copy digital information between computers' memories. These links can take the form of copper telephone wires, television service cables, fiber optic lines, or, more recently, radio signals among cellular telephone towers. But all such terrestrial link technologies are innately limited by geography. Links that are formed by radiation to and from orbiting satellites, however, can transcend all geographic barriers with equal ease.

The potential value of such links has been recognized for decades. In the early 1980s an experimental satellite connection between ARPANET and European hosts was established, operating at 64 kbps and confirming that Van Jacobson's congestion control algorithm for TCP could tolerate .72 s of signal propagation latency [1,2].

By now, of course, satellite-based Internet service is a multi-billion-dollar industry, despite technological obstacles of its own. However, it can be argued that we have only begun to explore the ways in which spacecraft can enhance the capabilities of the Internet.

In particular, we continue to use satellites only as analogs for wired infrastructure, conducting continuous end-to-end TCP/IP dialogues. An alternative would be to exploit the enormous potential bandwidth of satellites in low-Earth orbit functioning as "data mules", acquiring data from possibly disconnected customers over high-frequency radio or free-space optical links, storing the data in local memory, and physically transporting the data over orbital tracks until they overfly gateways into wired local area networks – or the wired Internet – that can forward the data over high-speed terrestrial links.

* Corresponding author. Tel.: +1 818 393 3353; fax: +1 818 393 6871.
E-mail address: Scott.C.Burleigh@jpl.nasa.gov (S. Burleigh).

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This model is a variation on well-known "sneakernet" concepts that have bemused network designers for many years. For example, we have long been advised to "never underestimate the bandwidth of a 747 filled with DVDs." The theoretical capacity of a Boeing 747 filled with Blu-ray disks flying from New York to Los Angeles is 245.8 terabits per second [3]. The latency of this transmission channel – a round-trip time of around 12 h – would make it unsuitable for many Internet applications, but not all: remote system backups and the delivery of online journals, for example, do not depend on sub-second round trip times.

Less fancifully, we consider a constellation of hundreds of low-Earth orbiting (LEO) satellites with free-space optical links to the ground stations in their field of view, each operating at 1 Gbps. This constellation would constitute a geography-independent communication channel whose bandwidth would be on the order hundreds of gigabits per second. Again the round-trip latency would be high, but less so than for the network of 747s: LEO satellites travel at 25–30 times the speed of a commercial jet aircraft, so the theoretical round-trip time from New York to Los Angeles would be on the order of half an hour. At that rate, even Facebook posts and movie downloads might be suitable applications.

Here, then, we note that network technology to automate communications over unusual network topologies like those discussed above – where no end-to-end continuous connectivity is available at any time – already exists. Delay-Tolerant Networking (DTN [4]) protocols readily handle these kinds of topologies, simply because at the time the protocols were designed they needed to do so in order to enable generalized internetworking in space flight operations, as discussed in the next section.

3. Internet to support space flight operations

The operations of spacecraft, whether crewed or robotic, have always been reliant on communication with mission teams on Earth. Early spacecraft had little or no on-board computing power, and mission communications were limited to relatively simple signaling; communications could be managed manually. But over the past 20 years the on-board computational capability of spacecraft has increased rapidly. With that increase has come rapid growth in the power and complexity of flight software, finally enabling collaborative operation among multiple spacecraft in situ. Moreover, observational instrument payloads on spacecraft are now able to generate science information at very high rates. Taken together, these advances have resulted in rapid growth in the volume and sophistication of mission communications and in the potential complexity of the mission configurations those communications support [5].

Just as in terrestrial research communications in the mid-20th century, the increasing demands on flight mission communication infrastructure are making earlier methods of communication management increasingly untenable. It is quickly becoming important to automate the operation of flight mission communication channels by deploying network technology.

However, the specific technology solutions that addressed the terrestrial research communication problem and developed into the Internet we know today are in some ways unsuitable for internetworking in space flight missions.

Interplanetary communication is characterized by long and variable signal propagation latencies (e.g., $1\frac{1}{4}$ s to the Moon; from 4 to 20 min to Mars) and by frequent lengthy lapses in connectivity, caused by the interposition of a planetary body between source and destination and/or by transient considerations of power or attitude management that make reception impossible. Consequently:

- Protocols must be connectionless. In the length of time required for all the round trips required to establish a connection, the communication opportunity might terminate.
- Timer expiration intervals are not predictable from statistics: at any time a lapse in connectivity might add minutes or hours to the round-trip time.
- Since lapses in connectivity are routine and nominal, they must not be interpreted as changes in network topology that need to be propagated to routing tables.
- In the worst case, there may never be contemporaneous connectivity among all nodes on the end-to-end path from source to destination. End-to-end forwarding and retransmission as performed by TCP/IP would never succeed.

In short, the operational assumptions on which the design of Internet transport, network, and routing protocols are based do not hold.

It is these considerations that led to development of the DTN architecture to which we alluded above. DTN protocols solve these problems by accepting different design assumptions:

- The DTN "Bundle Protocol" forwards data much as the Internet Protocol does, except that outbound bundles are held in local storage until forward links are available, destinations are expressed as names rather than addresses (because the topological location of the destination node might change while data are en route to it, so it may be necessary to delay the binding of the destination to a specific address), and routing decisions are based not on knowledge of current network topology – which is, in the general case, unavailable – but on expectations of future network topology.
- The retransmission of lost data is performed within the network rather than from end to end. Having survived the perilous transit from one node to the next, a DTN "bundle" need never repeat that ordeal: if it is lost on the next leg of its journey it is retransmitted from the last node at which it was successfully received.
- DTN security focuses on protecting bundles not only while they are in flight but also while they are at rest, because they may so often and so long be at rest. Security measures are integrated directly into the bundle structure rather than imposed only in ephemeral encapsulating structures.

Experience has shown that this foundation can be used to develop delay-tolerant mechanisms that provide functionality comparable to equivalent Internet mechanisms. For example, delay-tolerant protocols for file transfer [6], multicast [7], and even streaming media [8] have been published and demonstrated.

Importantly, though, DTN is not a wholly separate communication universe existing in isolation from the Internet. On the contrary, DTN nodes can be readily integrated into the terrestrial Internet in a number of ways:

- DTN communication paths can run "over" the Internet, in the same way that Internet communication paths run "over" existing local area networks (LANs) and wide area networks (WANs).
- DTN communication paths can in concept run over the same LANs and WANs that the Internet uses, sharing bandwidth.
- DTN communication paths can even run "under" the Internet (supporting any Internet applications that are themselves delay-tolerant), functioning as a WAN that provides greater resilience and latency tolerance than other WAN protocols that are currently in wide use.

This means that the ability to apply the power of Internet technology to communications in support of space flight operations – in Earth orbit, at the Moon, and even in deep space – is now at hand. The design of ever more complex and productive space flight missions in the future need no longer be inhibited by constraints on the configuration and management of flight communication channels.

4. Space internetworking

We are only now beginning to glimpse the wide variety of innovations that will benefit from the integration of Internet and space flight operations – *space internetworking*. Benefits will accrue:

- To vehicles and humans off Earth – high-volume data interchange with assets in deep space and humans at other planets can become routine.
- To scientists and (in time) space-based business enterprises on Earth – data interchange with network nodes in space can be readily extended beyond "ground stations".
- To the economically disadvantaged – the cost of data interchange service can be sharply reduced for everyone, no matter how geographically isolated.
- To the politically disadvantaged – suppression of free access to information can be made far more difficult.

4.1. Supporting space flight missions

The world's national space agencies have jointly endorsed an emerging Solar System Internetwork (SSI) architecture [9] based on the space internetworking technologies described above. Much as the terrestrial Internet enables communication among people and businesses without requiring a detailed understanding of network operations, the SSI will support communication among the engineers, scientists, and robotic devices operating in space ventures without requiring a detailed understanding of space communication operations.

The handover of satellite data flow from one Earth station to the next may be automated, ensuring continuous data flow between spacecraft and mission operations centers.

High-speed spikes in spacecraft data download may be automatically buffered for transmission over lower-speed (and less expensive) terrestrial network links.

Command and telemetry data that are lost or corrupted in transit may be automatically retransmitted, even over interplanetary distances and intermittent links. In particular, high-speed transmission disruptions due to severe weather will be automatically handled.

Multiple orbiters will be able to easily and automatically forward data to and from multiple landed vehicles, honoring prioritization decisions made at the data source.

Alternative data paths will be available in the event of the failure of a given communication resource, increasing vehicle safety and total mission data return.

Taking all of these together, the net effect of operating spacecraft within the SSI will be significant reductions in operating costs and mission risk, together with increased total data return value. These in turn will enable more flight missions performing ever more complex tasks.

4.2. Extending space flight mission information access worldwide

Dissemination of the data returned from space flight missions is managed by national space agencies in accord with established policies and treaties. Historically, space data dissemination has typically taken place on a distribution cycle ranging from a few minutes to a few years: mission-critical (mostly engineering) data is delivered through dedicated links to mission officers in near-real-time, while scientific data may be delivered only months after acquisition. At the extreme, science data collected by spacecraft may even become obsolete and be discarded before it is disseminated.

In large part, this latency in data dissemination can be attributed to cumbersome data distribution mechanisms implemented at the ground stations at which radio signals from spacecraft terminate, or at the data centers that operate these geographically distant ground stations. As the capacity of spacecraft communication devices (high-frequency radios, free-space optical links) grows, and the number of spacecraft exercising these devices grows, the problem of disseminating the information collected from flight missions will grow as well.

That is, data collected from flight missions currently cannot be fully exploited to the benefit of society due to the lack of adequate means to deliver non-proprietary mission data to end users. While strict agency policies, security concerns, and immaturity in end-user applications may explain this failure in part, a more profound obstacle is the lack of interoperability between space mission communications and the Internet: data must be extracted from space protocol data units, sometimes laboriously processed by skilled technicians, and then somehow securely inserted into the terrestrial TCP/IP framework. Moreover, data links from spacecraft have now become, ironically, faster than the Internet links connecting ground stations to control centers and investigators: data received at high rates from spacecraft must be stored in local media at ground stations while they are metered out over scheduled, load-balanced Internet services.

Now, however, DTN-based facilities have been demonstrated that solve these problems in a fashion that conforms to both Internet and CCSDS standards, as already recognized in [10]. Consider, for example, the scenario in Fig. 1.

Here the DTN Bundle Protocol operating at the network layer of the new Solar System Internetwork exploits all opportunities for contact between interconnected satellites and interconnected ground stations. The pilot implementation of this capability has been developed by the Space Data Routers project [10] as a tool that aggregates space mission data according to its content and distributes the aggregated data across a DTN overlay network to registered interested users. The tool acquires data from multiple missions, and the supporting registration service enables authorized users to access data delivered to multiple ground centers worldwide, ultimately directing space flight mission data directly into the mobile devices in users' pockets.

In addition to this generally familiar model, though, even bit-torrent-like architectures appear usable in space. A recent project [11] exploits the potential of a bit-torrent-like architecture for distributing large volumes of science data from spacecraft efficiently, similarly to the bit torrents that currently are utilized primarily in movie downloads. This architecture can be realized using both space assets and terrestrial nodes: a sequence of small windows of contact opportunity among orbiting assets and ground stations can be exploited and corresponding groups of globally distributed users can share data efficiently.

Nor is this advantage limited to future science investigations. As humanity's ability to operate in space matures, enterprising businesses will develop economic assets in space that will likewise benefit from seamless integration with Internet. This is vital, as it seems highly likely that the sectors of the world's economies that use space flight operations to produce goods and services will grow rapidly in the coming decades.

Space-based navigation services, notably the U.S. Global Positioning System (GPS), have already matured into a multi-billion-dollar industry. Clearly the market for the "downward-looking" observation services best provided by satellites – tracking weather systems, defending endangered species habitat, protecting coral reefs, monitoring fisheries, agriculture, forestry, etc. – is likewise poised for rapid growth. Less obvious, perhaps, are the potential economic effects of improved awareness of events on Earth's surface: consider, for example, the potential impact of accelerated disaster response on casualty insurance pricing.

Space-based solar power generation (SBSP [12]) has been shown to be entirely feasible: a satellite in Earth orbit deploys solar panels which generate electricity, which is used to transmit microwave energy to "rectenna" devices on Earth's surface, which convert the microwave energy to electricity for distribution through power grids. The principal obstacle to establishing an SBSP industry is the high cost of launching machinery into orbit, which makes the unit cost of the generated electricity too high to compete with other power sources. Eventually, however, launch costs will decrease to the point at which SBSP will become competitive and abundant low-cost electricity from orbit will be deliverable wherever it's needed. This in itself will have significant effect on world economies – for example, perhaps making sea water desalination more cost-effective.

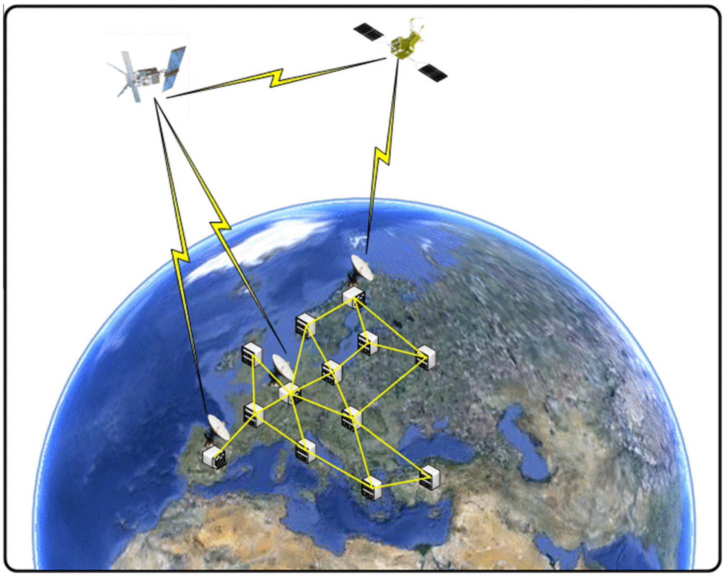

Fig. 1. Space Data Routers.

Further out in the future, the mining of asteroids may become practical and new industrial plants may grow up around interplanetary mining sites – perhaps at Lagrange points to which asteroids are towed for excavation. Continuous human occupancy of this infrastructure, potentially including tourism, would itself open a wide range of opportunities for commercial network services, including interplanetary social networking and shared virtual environments that could involve the public directly in planetary exploration.

4.3. Deeper access to information

Far-reaching as these innovations may be, the space flight and networking technologies that underlie them will ultimately have social significance that is even more profound.

Although space has initially served the Internet merely as an alternative data pathway, compensating for lack of wired infrastructure, its principal impact on the future of the Internet may lie in its potential for global reach and global empowerment. Given the astonishing ubiquity of smart mobile devices worldwide and the ability of satellites to offer network services unconstrained by geographic limits, space can enable proliferation of the most profound and continuous communication fabric – interconnecting people and devices – in human history.

Clearly the variations on space-based infrastructure with which we're already familiar will contribute to this fabric: cross-links among satellites, high-altitude balloons, and even unmanned aerial vehicles will continue to support end-to-end Internet connectivity where there is no substitute for immediate conversational data interchange [13–15].

In large part, though, the enormous potential for space-based global communications rests on the prospect of fielding the "sneakernet"-like satellite-enabled topologies discussed earlier. The bandwidth provided by such an infrastructure can be deployed and sustained at a tiny fraction of the cost of providing equivalent bandwidth over terrestrial surface infrastructure. Moreover, the service provided to users at every point on the surface of our planet, no matter how remote, would be identical in nature and capacity. Finally, because DTN protocols can be so readily integrated into the fabric of the Internet, this capability could easily be coupled with Internet access extension technologies such as unused bandwidth exploitation [16,17] that are similarly suitable for delay-tolerant applications.

In short, to the extent that an increase in latency can be accepted in applications, affordable network access to information worldwide would be continuously available to everyone on Earth.

The caveat regarding latency is an important one, but again its importance should not be exaggerated. In the relatively recent past, access to information by means of postal mail was equal to the task of sustaining the complex commercial, financial, governmental, and social institutions on which millions of people relied, and satellite-transit-based communication would be orders of magnitude faster than postal mail. Communication of inquiries and information for the purposes of public safety, public health, environmental protection or other socially significant activities does not typically require real time service. What is instead required is high assurance that information will be reliably conveyed, and DTN protocols readily provide that assurance.

4.4. Broader access to information

This emerging *Global Internet* service can change the way people think and react at every moment of the day, enabling their decisions to be informed by data continuously generated all over the world and delivered into their pockets.

Note that, in order to be fully realized, that service needs to exhibit three major properties:

(i) Global architecture, the integration of heterogeneous communication devices and protocols without limit. Barriers between the Internet and information sources that are currently alien to the Internet – resource-limited sensor systems, spacecraft, underwater information assets limited to acoustic communications [18] – are unnecessary and inhibiting.
(ii) Global reach, information access that is available everywhere information may be needed or produced.
(iii) Global empowerment, information access that is available to everyone who may need it to sustain enriched human life.

We have discussed above some of the ways in which space internetworking will help Global Internet acquire these properties, but global empowerment in particular merits further attention.

It is not solely a matter of economics. Even information access that is affordable to the poorest may be denied to them by political institutions. Network infrastructure that is built on Earth's surface is subject not only to geographic limits but also to political limits. Governments can constrain the information exchange that takes place within national borders, and it may sometimes seem to be in a government's interest to limit its citizens' access to information.

Network infrastructure in space, however, is subject to no such limits. Space assets operate beyond all national borders: radio frequency allocations are limited by international regulation, but broadcast content is not. While any given spacecraft may well be wholly under the control of a given government, nothing prevents other spacecraft under the control of other entities from taking their turn at the same point in the sky. A space-assisted, delay-tolerant network service would offer information access that can help oppressed peoples achieve civil rights and human rights globally [19].

5. Conclusions

Space flight technology and internetworking technology have already begun transforming humanity's tenure on this planet, but the advances we have seen to date will be dwarfed by those made possible by the integration of these technologies.

Global Internet is not yet realized. It will be, soon, when information without limit can be delivered into everyone's pocket. Space internetworking can help make this happen, and it will change the world.

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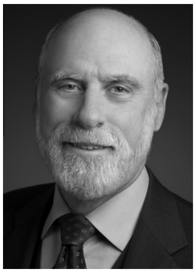
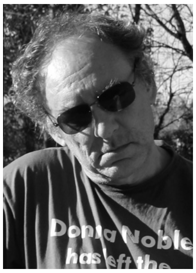
Scott Burleigh is a Principal Engineer at the Jet Propulsion Laboratory, California Institute of Technology, where he has been developing flight mission software since 1986. A member of the Delay-Tolerant Networking (DTN) Research Group of the Internet Research Task Force, Mr. Burleigh is a co-author of the DTN Architecture definition (Internet RFC 4838). He is also a co-author of the specification for the DTN Bundle Protocol (BP, Internet RFC 5050) supporting automated data forwarding through a network of intermittently connected nodes. In addition, he is a co-author of the specifications for the Licklider Transmission Protocol (LTP, Internet RFCs 5325 through 5327) supporting data block transmission reliability at the data link layer. Mr. Burleigh leads the development and maintenance of implementations of BP and LTP that are designed for integration into deep space mission flight software, with the long-term goal of enabling deployment of a delay-tolerant Solar System Internetwork. Mr. Burleigh has received the NASA Exceptional Engineering Achievement Medal and four NASA Space Act Board Awards for his work on the design and implementation of these communication protocols.



Vinton G. Cerf is Vice President and Chief Internet Evangelist for Google. He contributes to global policy development and continued spread of the Internet. Widely known as one of the "Fathers of the Internet," Cerf is the co-designer of the TCP/IP protocols and the architecture of the Internet. He has served in executive positions at MCI, the Corporation for National Research Initiatives and the Defense Advanced Research Projects Agency. Vint Cerf served as chairman of the board of the Internet Corporation for Assigned Names and Numbers (ICANN) from 2000 to 2007 and has been a Visiting Scientist at the Jet Propulsion Laboratory since 1998. Cerf served as founding president of the Internet Society (ISOC) from 1992 to 1995. Cerf is a Fellow of the IEEE, ACM, the American Association for the Advancement of Science, the American Academy of Arts and Sciences, the International Engineering Consortium, the Computer History Museum, the British Computer Society, and the Worshipful Company of Information Technologists and he is a member of the National Academy of Engineering. He currently serves as President of the Association for Computing Machinery, chairman of the American Registry for Internet Numbers (ARIN), and chairman of StopBadWare, and he recently completed his term as Chairman of the Visiting Committee on Advanced Technology for the US National Institute of Standards and Technology. President Obama appointed him to the National Science Board in 2012. Cerf is a recipient of numerous awards and commendations in connection with his work on the Internet, including the US Presidential Medal of Freedom, US National Medal of Technology, the Queen Elizabeth Prize for Engineering, the Prince of Asturias Award, the Tunisian National Medal of Science, the Japan Prize, the Charles Stark Draper award, the ACM Turing Award and 21 honorary degrees. In December 1994, People magazine identified Cerf as one of that year's "25 Most Intriguing People." His personal interests include fine wine, gourmet cooking and science fiction. Cerf and his wife, Sigrid, were married in 1966 and have two sons, David and Bennett.



Jon Crowcroft has been the Marconi Professor of Communications Systems in the Computer Laboratory of the University of Cambridge since October 2001. He has worked in the area of Internet support for multimedia communications for over 30 years. Three main topics of interest have been scalable multicast routing, practical approaches to traffic management, and the design of deployable end-to-end protocols. Current active research areas are Opportunistic Communications, Social Networks, and techniques and algorithms to scale infrastructure-free mobile systems. He leans towards a "build and learn" paradigm for research. He graduated in Physics from Trinity College, University of Cambridge in 1979, gained an MSc in Computing in 1981 and Ph.D. in 1993, both from UCL. He is a Fellow of the Royal Society, a Fellow of the ACM, a Fellow of the British Computer Society, a Fellow of the IET and the Royal Academy of Engineering, and a Fellow of the IEEE. He likes teaching and has published a few books based on learning materials.

Vassilis Tsaoussidis (Professor, DUTH) holds degrees in Applied Mathematics (Aristotle University) and Computer Science (Ph.D. in Computer Science, Humboldt University, Berlin). After an obligatory break at the Greek army for 1.5 years Vassilis joined the research community of Rutgers and later the faculty communities of Stony Brook and Northeastern. He also joined MIT as visiting Professor in 2009. Vassilis returned home in 2003 to join the Faculty of the Department of Electrical and Computer Engineering of Democritus University. He introduced the first European "Space Internetworking Center – SPICE" in Xanthi, Greece, thanks to generous funding of FP7 Research Potential Program. Together with his bright team they developed numerous protocols for delay tolerant communications, congestion control and routing in the context of ESA and FP7 projects. Vassilis enjoys discussions about Greek and World politics, economic theories, social policies, psychology and history. He is elected member of the Board of University Council.