

# Enhanced Communication Network Solution for Positive Train Control Implementation

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## ABSTRACT

The commuter and freight railroad industry is required to implement Positive Train Control (PTC) by 2015 (2012 for Metrolink), a challenging network communications problem. This paper will discuss present technologies developed by the National Aeronautics and Space Administration (NASA) to overcome comparable communication challenges encountered in deep space mission operations.

PTC will be based on a new cellular wireless packet Internet Protocol (IP) network. However, ensuring reliability in such a network is difficult due to the “dead zones” and transient disruptions we commonly experience when we lose calls in commercial cellular networks. These disruptions make it difficult to meet PTC’s stringent reliability (99.999%) and safety requirements, deployment deadlines, and budget.

This paper proposes innovative solutions based on space-proven technologies that would help meet these challenges:

- Delay Tolerant Networking (DTN) technology, designed for use in resource-constrained, embedded systems and currently in use on the International Space Station, enables reliable communication over networks in which timely data acknowledgments might not be possible due to transient link outages.
- Policy-Based Management (PBM) provides dynamic management capabilities, allowing vital data to be exchanged selectively (with priority) by utilizing alternative communication resources.

The resulting network may help railroads implement PTC faster, cheaper, and more reliably.

## INTRODUCTION

### Background

The Rail Safety Improvement Act<sup>i</sup> of 2008 mandates all commuter rail agencies and freight railroads that transport hazardous material to implement a PTC system by the end of 2015. For Metrolink in Southern California, this deadline is the end of 2012. The passage of the bill by Congress and the House Transportation and Infrastructure Committee was largely motivated by the collision of a Metrolink passenger train and a Union Pacific freight train on September 12, 2008 in California. The crash was caused by human (operator) error. The Metrolink train engineer was allegedly text messaging and failed to obey the signals. Scenes of the crash were reported by media all over the world<sup>ii</sup>. Sadly, the accident resulted in 25 deaths and more than 135 injuries.

More recently, two Washington, DC Metro subway trains slammed into one another just outside the city during the afternoon rush hour on June 22, 2009, resulting in six deaths and at least 75 injuries. This crash was also allegedly due to human error by not adhering to speed restrictions.

Former President George W. Bush signed the Safety Improvement Act of 2008 into law on October 16, 2008. On January 12, 2010, the U.S. Transportation Secretary and Federal Railroad Administration (FRA) Administrator announced safety regulations requiring that PTC technology be installed on the nation’s major rail lines as well as commuter and intercity passenger rail routes by 2015<sup>iii</sup>.

### Current Plans for PTC and PTC Programs

PTC, as defined in the statute, will be a nationwide system intended to enhance the safety of conventional train control systems through continuous monitoring of train position and the ability to enforce a train to stop

before an obstacle. It is an ambitious program with the goal to prevent:

- Train-to-train collisions
- Over-speed derailments caused by human error, operator distractions, or lack of attention
- Incursions into established work zone limits that can cause harm to roadway workers
- Movement of a train through a switch left in the wrong position, including misaligned switches

The key intent of PTC is to provide safety, so the architecture must be highly reliable and available with built-in fault tolerance. The system must work perfectly across a vast network of rail lines of more than 140,000 miles, which are owned and operated by many different companies with their own equipment and procedures. It must provide situational awareness across many fixed and mobile network nodes (vehicles, stations, signals, etc.). Likewise, the system must enable the exchange of large amounts of data among various node components, including Vital Safety Data such as the exact position and time coordinates of each vehicle on each track segment, speed restrictions, signal aspects, etc.

PTC will be a nationwide predictive (positive) train control as opposed to the existing “reactive” train control systems. Thus, the PTC database must have the historical (past), current, and planned status information about all the trains on all US railways operated by all railroads. The system’s architecture (see Figure 1) encompasses not only the database, but trains’ onboard computers, wayside equipment and control points, railroads’ redundant Operations Control Centers, wireless roadway workers’ terminals, and the Back Office Systems (BOSs) of other (tenant) railroads. Therefore, the most critical component of PTC will be a communication network that provides robust and reliable connectivity among all PTC components; network reliability and availability of better than 99.999% will be required.

The PTC communication network will consist of a fixed backhaul network and a mobile network for communication between the train and roadway employees. While the fiber optic backhaul network will readily meet the PTC reliability requirement, mobile networks have historically been less reliable. We believe the PTC mobile network can meet its reliability

requirement as well by leveraging advanced technologies that are used by NASA’s Jet Propulsion Laboratory (JPL) and the Department of Defense (DoD) to improve communication links. These technologies are discussed in Section 4. Section 5 will describe an enhanced PTC system solution that utilizes these technologies.

## **PTC Interoperability Standards and Requirements**

Interoperability is a critical component in safely implementing PTC technology across all rail systems nationwide. This is because, frequently, a railroad operates as a tenant on one another’s Right of Way (RoW). As a tenant vehicle moves on a railroad property, it must be able to communicate via the owner’s mobile network with the owner’s OCC (dispatch system) and possibly to the tenants’ dispatch systems through the owner’s BOS.

For the interoperable mobile communication network, ITC members have agreed to implement an IP-based digital radio system on a 220 MHz VHF band. Cellular architecture, with frequency reuse, will be deployed along railroads’ RoW. Both TDMA and FDMA multiplexing schemes will be used to increase the link capacity. Time slots and frequencies (slots) will be assigned for different operations, locations, and times based on negotiated agreements. In the stations, terminals, and yards, Wi-Fi (IEEE 802.11x) and WiMAX (IEEE 802.16e) Wireless Local Area Network (W-LAN) provide wireless connectivity to the trains to allow exchange of large amounts of data.

## **CURRENT PTC COMMUNICATION NETWORK ARCHITECTURE**

As depicted in Figure 1, the PTC communications network suite consists of the following sub components:

- Backbone fiber optic infrastructure network (shown by red lines in Figure 1)
- Wireless digital network elements (shown by black lines in Figure 1)
  - Wi-Fi/WiMAX W-LANs will be deployed in terminals and yards
  - The digital cellular network on the 220MHz VHF band will be used for connectivity with mobile components such as vehicles and EICs

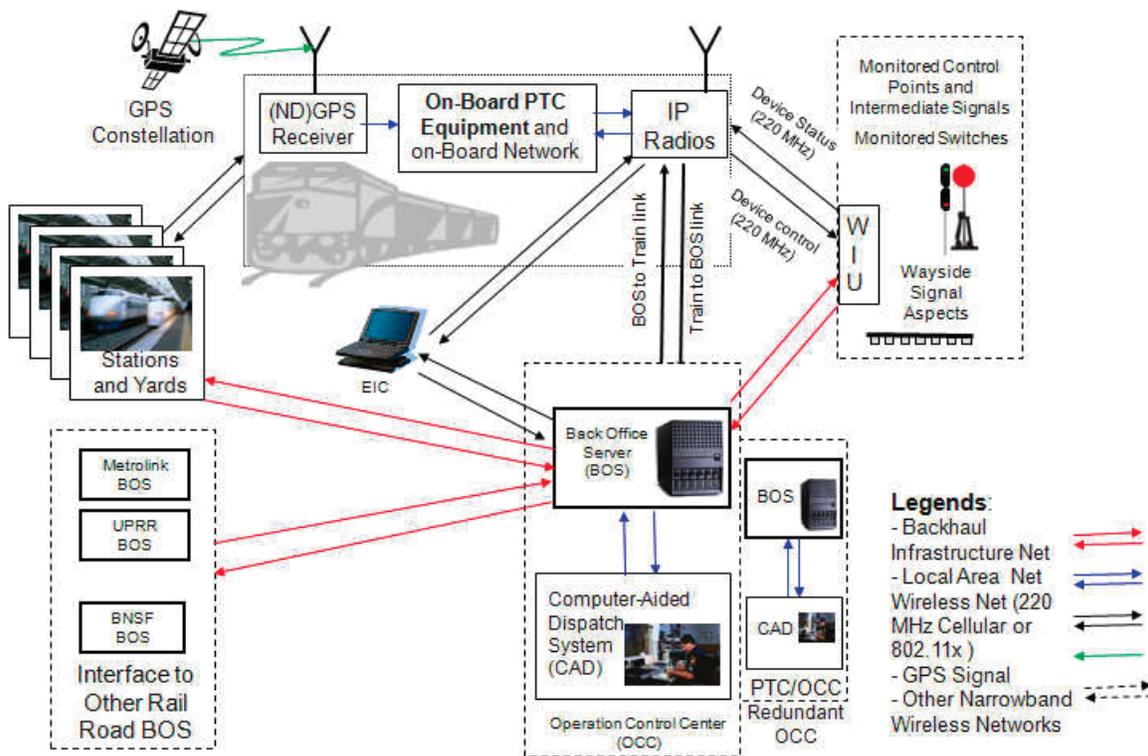


Figure 1. Architecture of a PTC Implementation in Southern California

- GPS signal (green line) receiver(s) receive accurate position and timing information from the GPS constellation on the two frequencies of 1.57542 GHz (L1 signal) and 1.2276 GHz (L2 signal)
- For local communications in OCC and other facilities, Giga Bit Ethernet (GbE) Local Area Networks (LANs) can be implemented (blue lines)

The railroads currently own or use other narrowband radio communication networking assets on the UHF and VHF bands that are not part of the PTC plan.

### PTC MOBILE COMMUNICATION NETWORK IMPLEMENTATION CHALLENGES

The implementation of PTC mobile communication networks faces three challenges:

1. Meeting the PTC implementation deadline of December 31, 2015 (December 31, 2012 for Metrolink)

2. Meeting the Fault-Tolerant Network (FTN) reliability and availability requirements
3. Meeting the implementation and operating cost targets allocated by the agencies

As currently planned, PTC communication networks are based upon existing cellular and radio system technologies and architecture, but on the new PTC 220 MHz spectrum. The reliability of the communication system depends on the coverage area and quality of the cellular service. Less than 100% cellular coverage can result in loss of data communications between trains and wayside equipment, dispatch facilities, BOS, and other PTC components.

To meet the intended safety requirements, the network must be highly-available, reliable, and fault-tolerant. Traditionally, this requirement would imply an oversized architecture in which:

- There can be no gaps (or dead zones) in the coverage area of the cellular network for all railroads in the entire nation, including within tunnels and other covered areas.

- At each point in the coverage area, there must be connectivity between the train/EIC and at least two base stations. This ensures that there will be no communication disruption in case of a single base station failure.

Such architecture would require a heavy investment in both time and funding, neither of which are available. We conclude that PTC can meet its reliability and availability requirements within the mandated time and at reasonable cost only by adopting enhanced communication network technologies.

The key issue is that it is not possible to guarantee such coverage at all locations, at all times, particularly in rough terrains and urban areas, before years of testing and tweaking. This is due to various types of coherent and incoherent interferences that mysteriously appear and cause unpredictable dead zones and time-depend fading. Such spatial and temporal dark zones are dictated by nature. In general, experience has proven that RF coverage and capacity design, especially in rough terrains and urban areas, is part science and part magic (as shown by experience). To eliminate coverage gaps and capacity degradation (as dictated by the PTC mandate), it would take years of testing and improvements.

Mathematical models have been developed that provide an aid in cellular radio network design for simple situations. The DoD's "Terrain Integrated Rough Earth Model (TIREM)<sup>iv</sup>" and the commercial model described in the ITU-R "RECOMMENDATION ITU-R P.1546-3"<sup>v</sup> document such mathematical models. Radio engineers/systems integrators can use such models as a starting point, but radio coverage must be experimentally determined and readjusted in complex environments.

The predictability of radio wave propagation and communication coverage modeling is even more complex in tunnels, covered stations, and subways. The secondary waves leaked from openings or waves reflected from walls and other structures can cause severe interference issues. The poor quality of radio communication systems implemented in the New York subway exemplifies this concern.

As reported in a New York Times article<sup>vi</sup>, the New York Police Department refuses to use a \$140 million radio system deployed in the New York subway system that was intended to allow transit officers underground to communicate with officers patrolling the streets above. As quoted by a Transit communications engineer, this is due to "widespread interference that garbles communication and creates areas where radios cannot receive properly." The Metropolitan Transportation Authority worked for more than ten years to correct this radio communication issue, but decided that it made more economical sense to redesign and implement an entirely new system.

Another challenge facing the timely implementation of the PTC mobile communication component is the reliance on IP for data communication on links that are subject to disruptions. The Internet Protocol Suite (IPS) is not suitable for communication networks that are subject to disruption or capacity deterioration. This is because the IPS assumes a data communications environment based on a robust communication infrastructure.

## **PROPOSED PTC NETWORK ARCHITECTURE SOLUTION**

Booz Allen Hamilton, jointly with NASA/JPL, studied implementing a communication system technology used by NASA/JPL in space missions to compensate for the PTC-expected communication system shortcomings and impairments. The study concluded the following:

- DTN technology overlay prevents data loss during link disruptions due to 220 MHz cellular communication coverage gaps, signal fading, and impairments in rough terrains, urban areas, and tunnels
- PBM technology overlay takes advantage of the existing narrow band networks, including the VHF analog systems and UHF ATCS systems, to communicate high priority (vital) data (e.g., such as position, velocity, and signal aspects) during the 220 MHz link disruptions

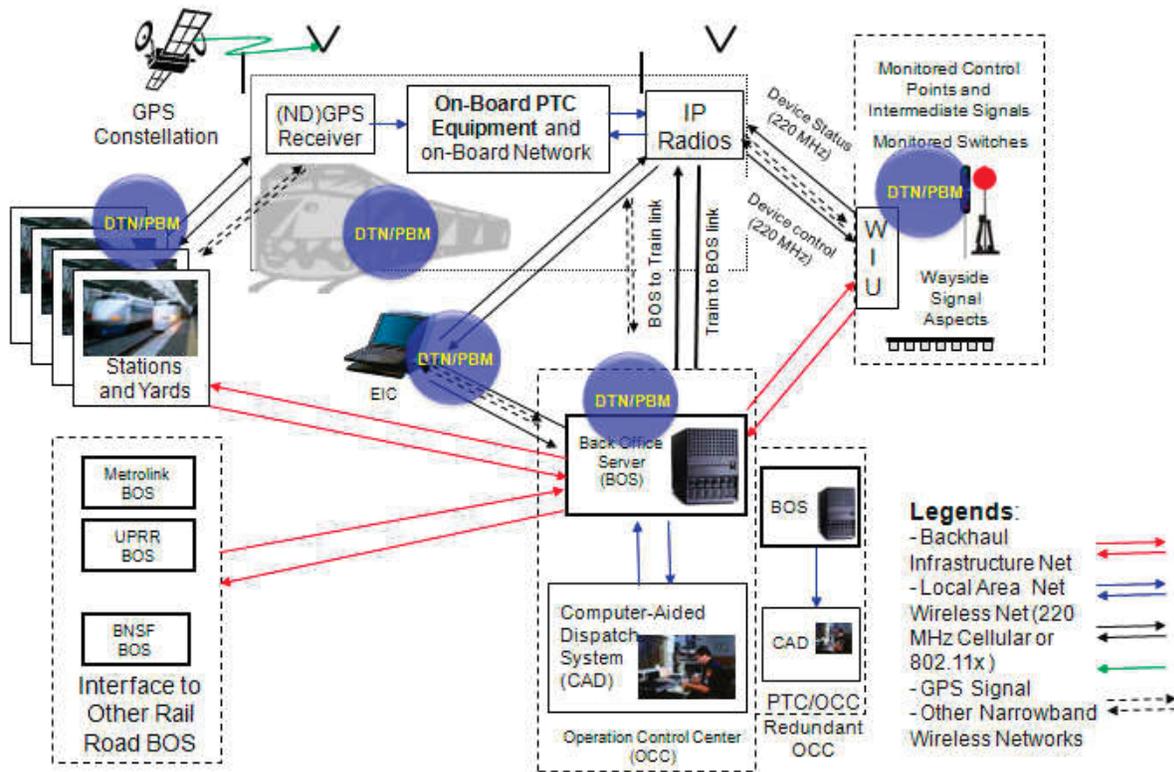


Figure 2. DTN/PBM-Enhanced PTC Communication Network Architecture

The preliminary study suggests that the augmented system will:

- Mitigate the risks of meeting the stringent PTC fault-tolerant network requirements
- Mitigate the risks of meeting the target deployment date of 2015 as mandated by Congress
- Reduce implementation costs by optimizing the re-use of existing VHF/UHF telecommunications assets in PTC

The improved network architecture and the changes to the onboard controls will be as follows.

### Enhanced Network System Architecture (Overlay)

The PTC communication network architecture, discussed in Figure 1, can be augmented for PBM technology by leveraging the existing narrowband links as backup links. The resulting network is shown in Figure 2. Comparing the two figures, the enhancements and changes are:

- DTN/PBM software/firmware modules are installed in wireless communication interface servers and clients, such as the Onboard computers BOS, EIC terminal, Wayside Interface Units, and stations. These enhancements are shown by blue circles in the figure.
- All existing communication assets such as VHF analog systems; UHF systems, including ATCS communication systems; and, optionally, commercial carriers' cellular networks, are adapted with appropriate physical interfaces to provide connectivity for high priority (vital data (e.g., such as position, velocity, and signal aspects) during the 220 MHz link disruptions. For security purposes, if desired, these links can be augmented with proper security protocols at the IP or higher layers. These links are shown by the dotted arrows in the figure.

### Enhanced On-board Computer Architecture

Based on the DTN/PBM-enhanced network architecture (Figure 2), the onboard components will be

equipped with additional radios and software modules as shown in Figure 3. The changes include:

- DTN/PBM software/firmware modules are installed on the onboard computers
- Existing (or additional if nonexistent onboard) radios are interfaced to the onboard local area networks
- Any existing analog radios are interfaced via appropriate MODEMs to provide backup narrowband links

The number of onboard radios may include: PTC 220MHz, 802.11 Wi-Fi, 802.16 WiMAX, VHF 160 MHz analog radio, UHF 900 MHz ATCS radios, etc. As a result, the Booz Allen/JPL team recommends that Software Defined Radios (SDR) be development for PTC as a secondary proposal. Such radios are currently being developed for use by the DoD.

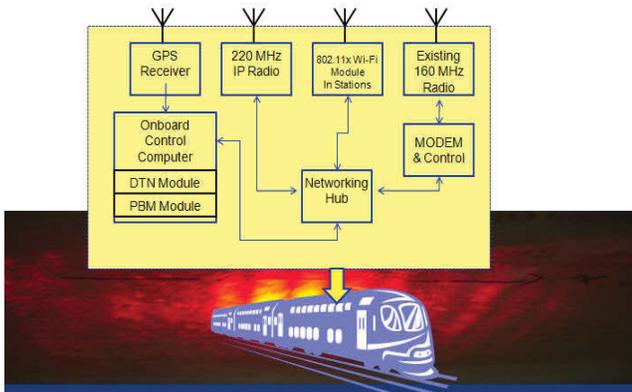


Figure 3. PTC Onboard Component Network Architecture

### Key Feature and Benefits

Specific enhancements to the PTC network provided by the DTN/PBM technologies are re-listed in Table 1:

Requirement/Feature	PTC enhanced with NASA/JPL technology
Gaps in mobile communication coverage	DTN/PBM overlay will mitigate communication disruptions. It enables reliable end-to-end communication over networks in which timely end-to-end data acknowledgment might not be possible.
Data communications	Data are not lost in dead zones, but are stored at custodians for delayed communication.
Vital Data communications	PBM prioritizes the Vital Data and allows high priority data to be communicated over alternate links (e.g., leaky coax cables in tunnels, VHF links, UHF ATCS links, etc.).

Table 1. DTN/PBM Enhancements

The general benefits of the enhanced communication component to PTC requirements are summarized in Table 2.

### Technology Introduction Strategy

Introduction of the DTN/PBM capability into the PTC system can be incremental and measured, as DTN/PBM can easily coexist with conventional Internet technology on the same cellular transmission channels. No dedicated radio frequency bands are needed, nor is any dedicated communication or computer hardware required. When DTN/PBM is installed on an ITC-compatible train, PBM will ensure that the sharing of cellular bandwidth between the DTN and non-DTN traffic is equitable and effective, so communication between trains that are equipped with DTN/PBM and those that are not can safely be sustained as long as necessary.

	Current PTC Proposal	Enhanced with NASA/JPL Technology
Basic Requirements	Deliver specified functionalities	Compatible with PTC
Interoperability requirements	Expected to be interoperable	Compatible with PTC
Deployment Cost	Requires duplicated cellular coverage, without gaps, to support a fault-tolerant network	Fewer cell towers and potentially fewer 220 MHz spectral channels
Deployment Time (2015/2012)	Challenges to implement full coverage on time	Shorter implementation period due to the complementary nature of DTN/PBM
Enhancement to current Safety measures	Medium/High	High/Very High (Improved reliability)
Quality of Service (QoS) Architecture	Vital /Non-vital data communication	Multiple classes of services policy-driven channel rearrangement
Network Operations and Management	Current Communications Operations Model	Policy-driven approach, next generation control and command center, improved efficiency

Table 2. Benefits of DTN/PBM-Enhanced PTC Network Requirements

## IDENTIFIED TECHNOLOGIES

### Delay Tolerant Networking (DTN)

The Internet protocols currently proposed for PTC (e.g., TCP/IP) work well only if there is continuous connectivity between all pairs of adjacent nodes throughout the end-to-end data path for the duration of each individual transfer (Figure 4).

DTN technology offers an alternative. DTN is immune to transient lapses in connectivity; during intervals when there is no connectivity between adjacent nodes, it simply queues data for future transmission. As such, DTN enables data flow over communication links characterized by sustained or frequent lapses in connectivity and/or lengthy signal propagation latencies – conditions under which the protocols underlying Internet communications perform poorly or fail altogether.

The enhanced robustness of DTN communications makes the DTN architecture suitable for use in extremely dynamic or noisy wireless environments. DTN enables reliable, end-to-end communication over networks in which timely end-to-end data acknowledgments might not be possible due to transient link outages or latencies.

Such environments include not only interplanetary flight mission operations but also the highly mobile network topologies of Mobile Ad-hoc NETWORKing (MANET) and Vehicular Ad-hoc NETWORKing (VANET). The applicability of DTN to PTC is clear: DTN is an effective answer to transient episodes of

network disruption or bandwidth reduction as when, for example, trains traverse tunnels.

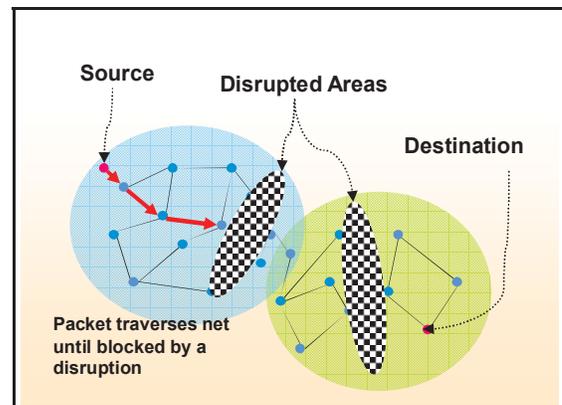


Figure 4. Network Disruption Prevents Message Flow

Moreover, DTN can provide a reliable and secure “overlay” network that would prevent loss of information transmitted over PTC wireless/cell channels even when there are relatively brief coverage gaps or lapses in connectivity to PTC base stations. As shown in Figure 5, the “router” nodes of the DTN Bundle Protocol function at the Application Layer of the standard IP stack. As soon as a data “bundle” passes from one DTN node to the next, that increment of progress through the network is protected: the bundle is retained in local storage, awaiting an opportunity to be forwarded to the next node. Thus, lapses in connectivity over individual cell transmission channels may retard delivery from one DTN node to the next, but they never cause messages to be lost.

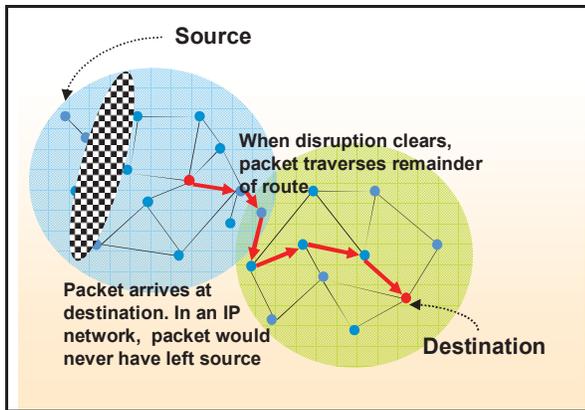


Figure 5. Delay Tolerance Enables Message to Reach its Destination

The result is that DTN can dramatically increase data throughput in networks where lapses in connectivity are commonplace. The Defense Advanced Research Projects Agency (DARPA) quantified this advantage in field trials conducted at Ft. A. P. Hill in 2007 (see Figure 6), confirming the effectiveness of DTN in highly dynamic network environments.

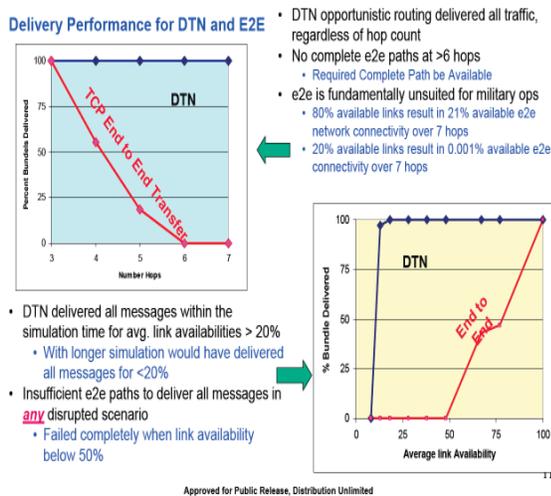


Figure 6. Insert Title

JPL’s implementation of the DTN protocols, named “ION,” was designed specifically for use in resource-constrained mobile systems, such as interplanetary robotic spacecraft – or locomotives.

ION is being adopted NASA-wide as standard software for “Solar System Internet” communications. The software was first demonstrated in space flight on-board the EPOXI spacecraft in 2008. In the course of this experiment, the EPOXI spacecraft functioned as a DTN router in space for four weeks at a distance of up to 81 light seconds from Earth. The ION software on-board the

spacecraft and in other network nodes at JPL operated continuously and automatically through eight tracking passes of NASA’s Deep Space Network (DSN), forwarding 300 images through the spacecraft without loss or corruption and automatically compensating for multiple DSN contact outages caused by tracking station hardware resets.

ION has been operating continuously on the International Space Station since May 2009. ION is currently installed on two Commercial Generic Bioprocessing Apparatus (CGBA) machines on the ISS experiment LAN, where it is used to convey science data from biology experiments to an operations center at UC Boulder via the Huntsville Operations Service Center at Marshall Space Flight Center. Immediately after deployment on ISS, ION was found to provide a four-fold increase in effective data rate from instruments.

ION was also deployed on the EO-1 Earth-orbiting spacecraft for experimental purposes in December 2010.

### Policy-Based Network Management

The core store-and-forward capability of DTN observes Quality of Service (QoS) parameters established by the user application at data origination time. As a result, DTN not only will increase the robustness of data flow in the network – that is, minimize data loss – but will also try to maximize the value-weighted rate of data value delivery.

However, traffic prioritization can only be effective when traffic flow is possible, i.e., when data links are available and the availability of those links is exposed to DTN route computation. The structure of ION enables DTN routing to be tuned for awareness of transmission opportunities as asserted in any number of ways, provided some system component is asserting those opportunities.

JPL’s PBM system complements DTN in two ways:

- Asserting the DTN QoS parameters applicable to various applications and revising those parameters dynamically in response to changes in the operational state of the system. PBM provides a customizable QoS architecture to ensure preferential delivery of critical data at different situations.
- Detecting and asserting transmission opportunities that DTN can utilize in order to individually honor the QoS requested for each bundle originated by each application. During network disruptions, PBM can take advantage of

whatever narrow-band network is available (e.g., “leaky” coaxial cable, backup analog radio, etc.) and instruct DTN to communicate high priority data – position, velocity, and signal aspects – over that network, while less critical information is retained in the transmission queues of DTN nodes pending re-establishment of connectivity.

As such, PBM gives users and network engineers the ability to tune system behavior to changes in system state automatically and dynamically, on the basis of user-defined policies, without programmer involvement. JPL’s PBM Software System is mature technology that is currently used by multiple DoD agencies.

### CASE STUDY: NORTH COUNTY TRANSIT DISTRICT’S PTC IMPLEMENTATION

As a sample case study, we evaluated the North County Transit District (NCTD) Coaster line for evaluation of the enhanced PTC system. The Coaster is a relatively short line with major sources of communication interference and can encounter both classes of interference issues.

#### Coaster Line Coherent Interference

For the Coaster line, the 220 MHz cellular network planning is expected to be challenged by coherent interference issues. From the satellite imaging of the Coaster line, one can easily identify three segments that influence the behavior of RF propagation on the 220 MHz band quite differently. These details are identified in Figure 7.

- A. In the northern portion of the line (Segment A in Figure 7), near Oceanside, the terrain is coastal, thus relatively smooth and flat. The radio waves in this portion of the line are reasonably well-behaved and can be predicted by mathematical models.
- B. On the other hand, the area near Sorrento Valley, depicted in Segment B in Figure 7, is quite rough with multiple hills and canyons. The hills could cause multiple shadows, reflections, and refractions of the waves, causing unpredictable behavior. For example, the designed circular coverage pattern (shown by the pink circle in the center of the figure) may become an irregular patchy coverage pattern that could fluctuate with time.

- C. At the southern end of the line in San Diego, the urban structures, such as the two high-rise buildings shown in the bottom left of Figure 7, could cause PTC radio waves to diffract in a pattern as simulated in the photo shown in the bottom center of the figure.



Source: Google Maps  
Figure 7. NCTD Coaster Line Terrain Details

#### Coaster Line Incoherent Interference

In addition, NCTD is currently already experiencing severe incoherent interference on their ATCS UHF (900 MHz) communications, causing an abundance of communication disruptions in its Coaster line. The main sources of such interference and disruption are:

- A. Navy Base in San Diego – Navy communications systems cause unpredictable noise for the Coaster line, causing impairments and disruptions. These activities unpredictably peak, particularly during military exercises.

- B. High power broadcast stations in Mexico – The power and frequency assignment is not as well regulated and enforced in Mexico as in North America. In the VHF band, during certain weather conditions, signals from high power stations from deep within Mexico can reach the NCTD Coaster RoW in the US and cause communication interference and disruptions. The 220 MHz communications are expected to be more susceptible to such interferences, as this band is close to the harmonics of the FM radio station or VHF TV station bands.

For these reasons, the Coaster line makes an ideal test bed for demonstration of these technologies in the PTC network.

## CONCLUSIONS

In this paper, we evaluated the challenges facing the timely implementation of the PTC system in the United States. The key issue is that it is not possible to guarantee 220 MHz cellular radio coverage at all locations, at all times, particularly in rough terrains and urban areas, before years of testing and tweaking. This is due to various types of coherent and incoherent interferences that mysteriously appear and cause unpredictable dead zones and time-depend fading. We have identified and discussed two space-proven NASA/JPL technologies that can mitigate the risks of PTC implementation in a timely manner. These technologies are Delay/Disruption-Tolerant Networking and Policy-Based Network Management. Due to its unique attributes, we have also identified the NCTD's Coaster Line as an ideal test bed for the demonstration of the technologies and the enhanced architecture.

## ACKNOWLEDGEMENTS

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