Interesting Problems in Deep Space Communications

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Interesting Problems in Deep Space Communications

Agenda

- What makes deep space unique?
- Case study 1: Galileo mission to Jupiter
- Case study 2: Cassini/Huygens mission to Saturn
- Future trends in deep space communications
- What worries me today?
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Some Current Deep Space Missions

- Cassini: Saturn
- SIRTF: Astronomy
- Mars Odyssey
- Mars Global Surveyor
- Dawn: Asteroids
- Kepler: Extrasolar Planets
- Voyager: Interstellar
- WMAP: Astronomy
- Mars Express
- New Horizons: Pluto
- Rosetta: Comet
- Hayabusa: Asteroid
- GRAIL: Moon
- ISIS: Mars
- Mars Reconnaissance Orbiter
- MESSENGER: Mercury
- Mars Science Laboratory
- MGS: Mars
- MRO: Mars
- MAVEN: Mars
- LRO: Moon
- THEMIS: Moon
Deep Space is Unique

- Spacecraft mass and power are precious
- Spacecraft go huge distances from Earth
- Navigation is highly dependent on Earth
- Communications system is a mission science instrument
- Every mission is unique
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Space Loss

- All else being equal, communications performance is inversely proportional to distance squared

\[ \frac{P_T}{N_0} = \text{constant} / d^2 \]

- Need to overcome this problem of physics to be successful in deep space

Why Telecom is Hard

Performance \sim 1/distance^2

<table>
<thead>
<tr>
<th>Place</th>
<th>Distance</th>
<th>Difficulty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geo</td>
<td>4x10^4 km</td>
<td>Baseline</td>
</tr>
<tr>
<td>Moon</td>
<td>4x10^5 km</td>
<td>100</td>
</tr>
<tr>
<td>Mars</td>
<td>3x10^8 km</td>
<td>5.6x10^7</td>
</tr>
<tr>
<td>Jupiter</td>
<td>8x10^8 km</td>
<td>4.0x10^8</td>
</tr>
<tr>
<td>Pluto</td>
<td>5x10^9 km</td>
<td>1.6x10^{10}</td>
</tr>
</tbody>
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NASA’s Deep Space Network

- Giant (34m and 70m) antennas in three locations around the world
- Provides communications with missions beyond GEO
Spacecraft Mass & Power

• Deep space missions must leave Earth’s gravity well – very difficult
  – An Atlas V 551 can lift about 19,000 kg to LEO but only ~500 kg to deep space

• Power generation is very difficult for a spacecraft far from the sun
  – Solar flux goes down by a factor of four each time the distance from the Sun doubles, so a solar panel at Jupiter can only generate a billionth the power as at Earth
  – Nuclear-based generators are both expensive and politically sensitive
Deep space missions operate close to theoretical communications efficiency limit (within 1 dB, typically)

Example: If a spacecraft, designed to work with a 70m antenna, lost a dB of performance, it would take an additional 32m antenna to make up the difference!

- Cost for three 32m antennas = ~$100M!
Autonomy

• It can take minutes to hours for signals to travel between the spacecraft and Earth
• Decisions must often be made faster than this – requiring spacecraft autonomy
• Spacecraft are usually “sequenced”, meaning they are programmed to operate for long periods without commands from Earth
• Spacecraft manage the data they acquire, storing it until it can be sent back to Earth
• Emergencies require special “safing” algorithms
Case Study 1
Galileo Mission to Jupiter

- NASA flagship mission launched in October 1989
  - Delayed several years by Challenger accident
  - Radioisotope generators already partially depleted
- High gain antenna (HGA) failed to deploy
- Left the comm system with $10^{-4}$ disadvantage
  - Hemispherical antenna instead of HGA
  - S-band instead of X-band
- Spacecraft was fully functional except for the HGA
- Lucky break
  - Twice as much RAM onboard as in the original design
Before Galileo, deep space missions used “lossless” compression
- Low compression ratios - typically no better than 2:1
- Well understood, deterministic errors, caused mainly by data overflow

We added Integer Cosine Transform algorithm – similar to JPEG
- Compression ratios could be set – typically between 5:1 and 20:1
- New error containment strategies made this viable for deep space
- Error artifacts are better understood due to research in support of Galileo

Galileo was forced to determine which information is most important from each instrument and subsystem – data editing

All subsequent deep space missions have used compression and editing
Packetized Telemetry

Old System: Time Division Multiplexing

Data from each instrument fits in a particular time slot

This space is wasted if instrument 2 has no data to transmit at this time!

Data from instrument is sent whenever it needs to be

Redesigned System: Data “Packets” - no time is wasted

- All subsequent deep space missions use packet telemetry to eliminate wasted space in the transmitted information
Variable data rates

- Galileo was the first deep space mission to use variable data rates during DSN passes
- Used prediction of signal levels
- Led to investigation of Internet-like protocols – DTN
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Modulation

Original system put power into both the carrier and information.

The redone Galileo system put all the available power into the information stream. This was enabled by a new generation of DSN receivers that could demodulate this format at very low signal levels.

- Suppressed carrier modulation is now available to all future deep space missions.

High frequency carrier wave

Constant power

Modulator

Digital information

Modulated carrier - combination of carrier & information

Receiver - uses carrier

Demodulator - uses information

High frequency carrier wave

Constant power

Modulator

Digital information

Suppressed carrier - product of carrier & information

Receiver/Demodulator - uses everything
Errr-correctiong kodes

- Error correcting codes had been used for many years in deep space
- Galileo’s redesigned codes were the best yet flown
- Among the new coding techniques on Galileo were variable redundancy, and redecoding – applicable to future codes as well
- Subsequent missions leverage these techniques and continue to evolve better codes
The DSN now routinely supports arrays – but only within the DSN.

Arrays are be used for special mission events and to synthesize 70m antenna performance from smaller antennas – serving as backups for the 70m antennas.
Asynchronous processing

- For Galileo, all DSN processing after bit detection was performed on demand
- This system is more modular, efficient, and cheaper to maintain than the old serial system
- Although this does not increase link efficiency, the DSN is evolving to this architecture – a lower-cost legacy for all future missions
Summary of Galileo repairs

- Optimized Signal Detector
- Antenna arraying
- Advanced error-correcting codes
- Efficient modulation
- Variable data rates
- Packet telemetry
- Data compression
Galileo – Conclusion

• Galileo was able to increase its effective data rate from less than 10 bps to around 1 kbps

• The mission was a complete success, achieving more than 75% of its original science goals during the 2-year prime mission

• Galileo went into extended mission and was eventually crashed (intentionally) into Jupiter to avoid possible contamination of the moons

• All of the communications improvements that were made to Galileo became standard on subsequent missions

• Additional “lesson learned”: It is good to have reprogrammability on a deep space mission
Cassini/Huygens Mission to Saturn

- Launched in July 2004
- Cassini was the NASA flagship mission to Saturn, Huygens was an ESA-built daughter probe for exploring Titan
  - Huygens would descend into the atmosphere to Titan and use Cassini to relay signals to Earth
- Everything looked great during Cassini/Huygens cruise to Saturn
- A very clever test of Cassini relay radio, using the DSN to mimic Huygens, showed that Huygens was going to fail
Discovering the Problem

S-band (2 GHz) radio signal transmission from Goldstone simulating Huygens Probe transmission (one-way light time was ~ 40 min)

X-band (8 GHz) Cassini telemetry

Data arrive at ESOC 80 min after transmission from Goldstone!

Boris Smeds and Test Equipment
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Test Results

Nominal Delivery at T1. Channel B: % Frames OK

- Bad Communications
- Good Communications
- Huygens Trajectory

Parameters:
- Doppler (km/s)
- $E_s/N_0$ (dB)

Legend:
- Percent of frames without errors

- Values range from 0 to 100%

Note: The graph illustrates the percentage of frames that are delivered without errors under various Doppler and $E_s/N_0$ conditions.
Modeling the Failure Mechanism

- A complete model of the relay system was developed including
  - Symbol loop dynamics as a function of bit transition probability
  - Coding and synchronization

- Symbol cycle slips were generated with a period that is a function of $E_b/N_0$, $D_f$, and $P_t$

- Fingers turned out to be caused by AGC function

- Analysis showed the anomaly was caused by symbol loop bandwidths

- Unfortunately, these parameters were hard-coded and could not be changed in flight

- The Galileo “lesson learned” was not learned well enough
Verifying the Model

- Additional DSN tests were run to verify and calibrate the model.
- Results were excellent.
Ways to Improve Data Return

Varying the critical parameters “moves” the probe curve with respect to the contours - resulting in more good data returned to Earth.

- Increasing SNR moves curve to the right
- Reducing Doppler moves curve downward
- Increasing bit transitions moves contours upward
- Varying the critical parameters moves the probe curve with respect to the contours - resulting in more good data returned to Earth.
A New Retrograde Flyby Saves the Day

- The trick now was to find a high altitude flyby that uses minimal fuel (~150 m/s for simple altitude increase)
- JPL navigators came up with the idea of flying by the opposite side (retrograde) of Titan
- This uses Titan’s gravity to help more with Cassini maneuvers
- New trajectory minimized additional propellant needs (~100 m/s)
- There is actually a class of these trajectories with one ultimately chosen by the Project
Recommended Solution

- The team developed several point designs that showed possible solutions to the anomaly
  - Each of these would return close to 100% of the data with margin
- The trick here was that communication performance had to be bounded both from above and below
  - Too much margin is bad!
- Our experience with Galileo (operating 0.5 dB from theoretical) helped
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Probe Data Playback

- Cassini turned its HGA to receive probe data during actual descent
  - No visibility during actual probe mission was possible
- After turning to Earth, Cassini commenced playing the probe data to the DSN
  - Eight full copies were sent, over all DSN complexes
  - Provided redundancy for the data playback
  - Provided resiliency in case of any two 70m failures
- One of the two communications channels on Huygens failed (no data)
  - Likely caused by operator error in commanding
  - This was a known risk (this is why there were two channels!)
  - All housekeeping data was redundant on the two channels
  - Most scientists planned their data campaign to satisfy their main goals with either single channel
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In the End: Success!
Future Trends

- Deep space missions are limited by the communications link
  - Mars Reconnaissance Orbiter has only mapped 1% of Mars at high resolution
- Things will only get worse as missions carry more data-hungry instruments
  - Radars, multispectral and hyperspectral imagers
- When humans go into deep space, they will need much higher bandwidth comm

**Fig. 9. Comparison of Average Mission Set Downlink Rates as a Function of Time**

- Mission Set with Highest Data Rates
- Mission Set with Lowest Data Rates
- Best Guess Mission Set
- Expon. (Mission Set with Highest Data Rates)
- Expon. (Best Guess Mission Set)
- Expon. (Mission Set with Lowest Data Rates)
Emerging Technologies

• Among the technologies that will likely come into play:
  – Software defined radios
  – High frequency radio communications (e.g. 32 GHz and above)
  – Optical communications
  – More advanced data compression
  – More onboard intelligence and autonomy
  – Space internetworking
  – Quantum communication and sensing
What Keeps Me Awake Today?

• Deciding which emerging technologies to pursue
  – Finite funding and finite researchers mean we have to place our bets carefully

• Ensuring we have future researchers
  – We see fewer students pursuing communications today

• Making sure missions use the new technology
  – Missions are, by nature, risk averse
  – We need new processes that make it easier to infuse these technologies
Conclusion

- There are real problems to be solved in deep space communications
- Most often, smart solutions lead to new kinds of space missions
- Sometimes, smart solutions save spacecraft that are in jeopardy
- The space business needs a next generation of smart problem solvers