Development of cooperative communication techniques for a network of small satellites and CubeSats in deep space

65th International Astronautical Conference
IAC-14-B2.3.3

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Part of this work was performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Outline

- Introduction
- Cooperative Communication Techniques
  - Beam-forming
  - Coding
  - Network
- SOLARA/SARA* Mission Overview
- Analysis of Cooperative Communication Techniques
  - Beam-forming
  - Coding
  - Network
- GUI Development Effort
- Conclusion and Future Work

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Introduction

- In the last decade, great progress was made in the development of small satellites and CubeSats
- Currently (September 2014), there are approximately 40 CubeSats in orbit between approximately 400 Km and 100 Km of altitude
- Design, fabrication and operation of SmallSats and CubeSats started in academia, but are now very widely widespread in companies and space agencies.
- As the interest in the development of these spacecraft increases, also the mission objectives for SmallSats and CubeSats become more challenging. Small spacecraft are required to
  - Relay more data: PlanetLab constellation
  - Relay data from farther distances: development and implementation of mission concepts for "interplanetary CubeSats and SmallSats" such as INSPIRE, Lunar Flashlight, NEAScout, BioSentinel.
- Technological challenge→ development of adequate communication technology.
- Current developments:
  - Antenna development (Folding-rib deployable, Astromesh, Reflectarray, Inflatable)
  - Amplifiers
  - Coding techniques
  - amplifiers development
- Another interesting idea is to focus on cooperation → improve the communication of many spacecraft together instead of focusing on the single spacecraft (**cooperative communication techniques**)

Cooperative Communication Techniques

- Cooperative communication techniques can br more robust against failure because the different spacecraft can, in most of the cases, relay data autonomously. Hence, in case of failures of some spacecraft, the mission is not completely lost.
- The disadvantage of cooperative communication techniques are in the complexity and in the level of coordination and synchronization required.
- Cooperative communication can be developed in different forms/approaches:
  - Beam-forming or antennas array on multiple spacecraft: it develops cooperation at the physical level by arraying electromagnetic signals from different sources.
  - Coding: it is also defined as network coding and it looks at how coding schemes can improve the quality of the signal by using multiple platforms.
  - Network: CubeSats or SmallSats are treated as nodes in a communication network.

Beam-forming

- Beam-forming is the concept of forming a unique radiating beam out of small antennas.
- This is very challenging for the level of control required onboard.
- It requires:
  - A beam (transmitted from the ground station) to compute the phase.
  - Inter-communication between the satellites
  - Precise (atomic) clocks are to synchronize transmission.
- In addition, requirements become more stringent as the frequency increases since the precision of phase and time knowledge needs to be known at fractions of the wavelength.

Coding

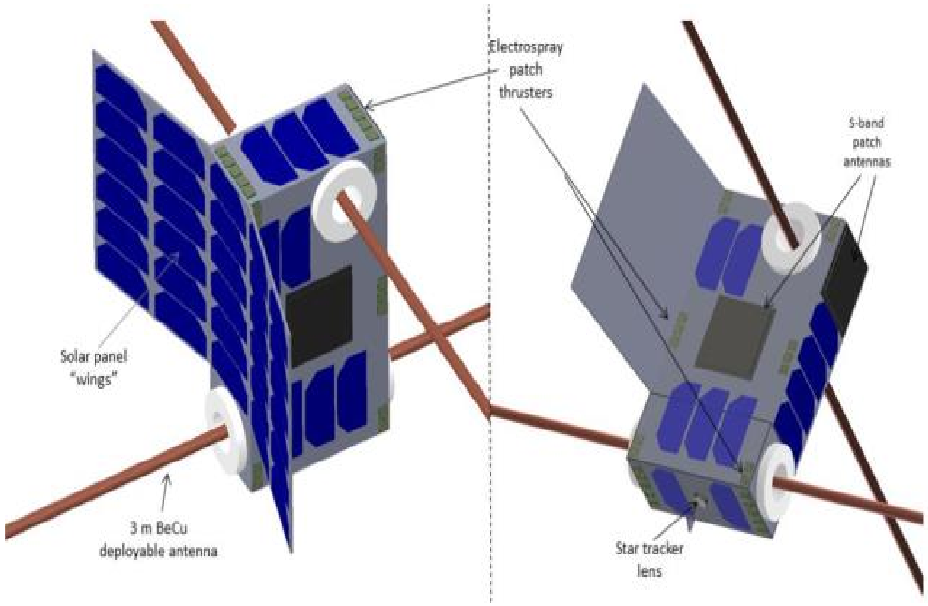
- The key concept of coding in information theory is the idea of applying redundancy to improve the chance for the receiver of detecting and correcting communication errors.
- Redundancy is represented by extra bits which are a combination of the information bits according to a certain set of rules.
  - One of the simplest possible combinations is the repetition: information bits are repeated multiple times.
- This concept could be also applied to a constellation of small satellites: for example they could transmit the same information and the receiver could use the fact that the same information is relayed from multiple small satellites/CubeSats as a way to correct transmission errors.
- Additionally, multiple access techniques like CDMA can be applied to allow multiple CubeSats/small satellites to transmit simultaneously and to share the same band.

Network Analysis

- The network approach implies identifying the best network configuration to achieve certain objectives.
- Possible network configurations are:
  - **Peer to peer:** all the satellites have the same transmitting and receiving characteristics.
    - ADVANTAGE: Peer to peer systems are great for redundancy since the system can work independently from the number of satellites which fail over time.
    - DISADVANTAGE: the peer to peer system requires distributed algorithms to handle the coordination of the network and it does not have any special satellite which could handle higher data rate links.
  - **Master-slave:** a master is a special satellite which is equipped to transmit at higher data rate than the others.
    - ADVANTAGE: higher data rate and the fact that the master is also to handle the coordination of the network in a much simpler way than in the case of the distributed algorithms which are needed in the peer-to-peer case.
    - DISADVANTAGE: high sensitivity to failure: a unique master is a unique point of failure which could potentially compromise the entire mission of the constellation.
  - **Multi-master or hierarchical network:** a middle-of-the-road solution between the peer-to-peer and the master-slave. In the hierarchical network there are a set of slaves and a set of masters. Each slave selects the master to use in function of specific criteria such as time, orbits, distance.
    - ADVANTAGE: The masters are more than one which guarantees redundancy against failures.
    - DISADVANTAGE: this network is the more expensive and complex to design and implement.

SOLARA/SARA

- SOLARA/SARA *(Solar Observing Low frequency Array for Radio Astronomy/Separated Antennas Reconfigurable Array) is a concept for constellation of small satellites composed of 20 CubeSats (6 Unit) at the first Earth-Moon Lagrange point.
- The CubeSats would collect data using dipoles and a distributed correlator for aperture synthesis imaging.
- The proposed array of would improve our knowledge of heliophysics and space weather, identification of extrasolar planets, and interior structure and dynamo mechanics of the outer planets by pinpointing the source of radio bursts.
- SARA would be the name of the communications system which aims to be developed through cooperative communication strategies.
- SOLARA/SARA would be a very significant platform to explore cooperative communication techniques:
  - It would be located at LL1 → CubeSat communication system would struggle to transmit a high volume of data.
  - A very big number of spacecraft (20) for which the combined gain from using cooperative communication techniques can be significant.



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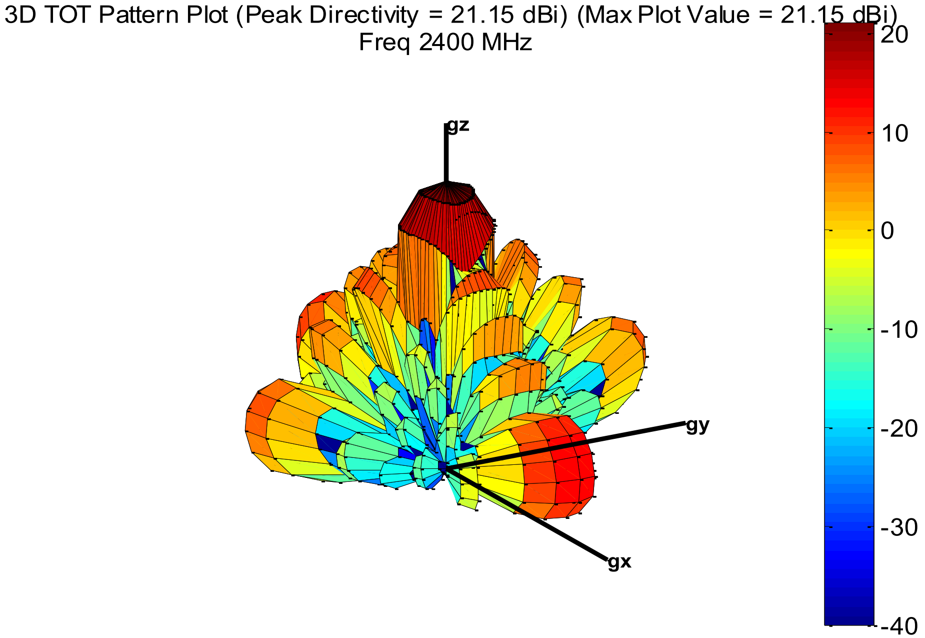
Analysis of Cooperative Communication Techniques: Beam Forming

- Combining signal from different sources can provide an increase in the total EIRP minus the combining loss.
- This increasing in gain assumes the accurate knowledge of the phase and the accurate synchronization of the signals.
- To characterize the combined gain which can be obtained by arraying a set of 20 CubeSats, a simulation has been developed using the array software (ActiveFrance)
- Simulation assumptions
  - Frequency → 2.4 GHz.
  - Patch antenna → 8.31 dBi.
  - Distance between the elements has been varied between few wavelengths and few hundreds of wavelengths.
- For 10 lambda → 21.15 dBi
- To improve →several side lobes can be problematic. In addition, all the transmitters in the simulation are assumed to be coplanar.



Analysis of Cooperative Communication Techniques: Coding

- According to the coding scheme, each CubeSat would be transmitting independently to the Earth using a single patch antenna.
- The information is repeated, since each CubeSat would be sending the same content and the system can be compared to a repetition code of a factor 20.
- The CubeSats would be transmitting simultaneously using a CDMA access scheme
- CDMA implementation: the complexity of a coded CDMA transmitter is lower than the complexity of the CDMA receiver.
  - DOWNLINK: encoders such LDPC followed by a spread spectrum transmitter for CDMA systems for CubeSats.
  - UPLINK: an uncoded CDMA system allows the receivers for CubeSats to have low complexity implementation. BPSK modulation with rectangular and half-sine pulse shaping is considered for this case.

Analysis of Cooperative Communication Techniques: Network

- A simulation was developed to compare the capabilities of the three possible network scenarios (peer to peer, master-slave, multi-master).
- Goal of the simulation→ to determine how much science data could be relayed by the different communication scenario.
- Science accumulation rate depends on the bandwidth of observation:

$$R = 2 \cdot B \cdot n \cdot p$$

- As the observation bandwidth moves from 30 KHz to 3 MHz, the amount of science data increases, and the problem of relaying data back to Earth becomes more significant
- Downlink data rate assumptions: 115.2 kbps (8.31 dBi antenna) for peer to peer, 3.125 Mbps (20 dBi antenna) for masters
- Result for peer to peer: the maximum observation bandwidth that can be reached is only 41 KHz.

Master-Slave and Multi-Master Results

Number of Masters	Maximum Bandwidth (KHz)		
	Sample time: 60 min/day Tx time: 12 h	Sample time: 30 min/day Tx time: 12 h	Sample time: 15 min/day Tx time: 12 h
1,2,4,5	54	108	217
3	51	103	207

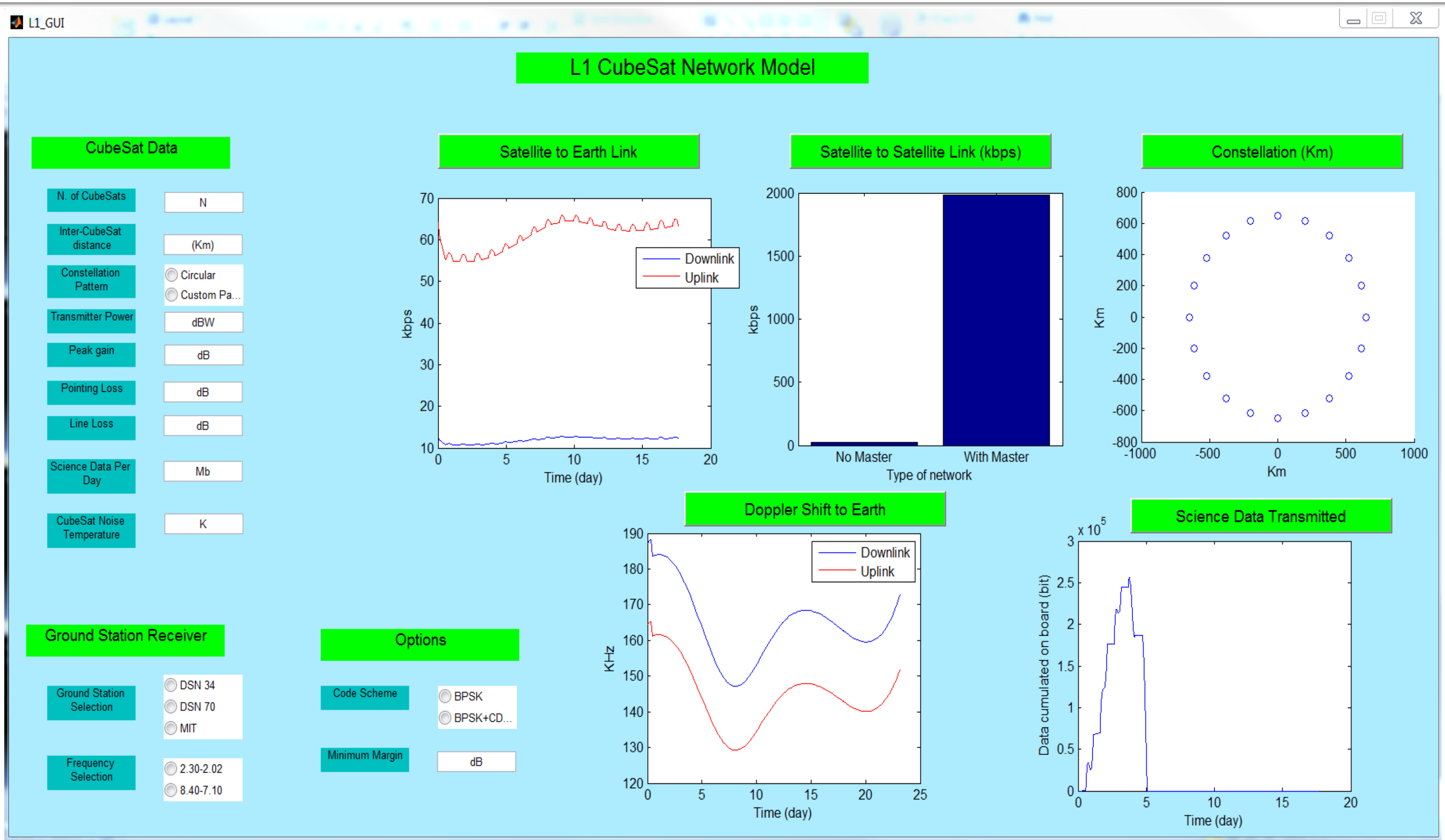
Maximum science bandwidth for master-slave and multi-masters network. No failures considered.

Number of Masters	Maximum Bandwidth (KHz) (Mean, Variance)		
	Sample time: 60 min/day Tx time: 12 h	Sample time: 30 min/day Tx time: 12 h	Sample time: 15 min/day Tx time: 12 h
1	(49.4, 16.4)	(115, 0.8)	(227.8, 1.49)
2	(44.8, 1.03)	(117.6, 0.8)	(274.6, 1.98)
3	(46.6, 4.12)	(126, 0.78)	(229, 1.48)
4	(61.8, 24.6)	(144, 0.86)	(292.4, 1.97)
5	(57.2, 21.6)	(152, 1.09)	(344.8, 2.29)

Maximum science bandwidth for master-slave and multi-masters network. A failure profile is assumed and mean and variance of the maximum bandwidth for the different cases are computed.

We are still very far from 3 MHz (upper limit of the science observation). A combination of the network strategy with other components/ techniques is required.

GUI Development



Conclusion and Future Work

- The paper describes the effort in developing cooperative communication techniques for a constellation of interplanetary small satellites.
- The techniques are meant to improve the state of the art for Cubesats communicating at interplanetary distance by exploiting the idea of using multiple assets communicating at the same time.
- In this paper three techniques are explored: beam forming, coding and network.
- A test case to validate the techniques is given by the SOLARA/SARA* mission concept which features 20 6U CubeSats at the Lunar Lagrangian Point 1.
- Each of the cooperative communication techniques is analysed and results in terms of advantages and disadvantages for each of these methods are identified.
- Finally, a graphical user interface to analyse the constellation communication system is presented.
- Future work will be devoted to further analyse the cooperative communication scheme proposed, to identify advantages of combining the methods and to correlate these results with science and mission constraints.

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Acknowledgment

- Part of this work was performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. A special acknowledgment is to Janna Finn for her contribution on the network analysis.

Thank You

Questions?