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Development of cooperative communication techniques for a network of small satellites and CubeSats in deep space: The SOLARA/SARA test case ☆

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ABSTRACT

In the last decade, great progress was made in the development of small satellites and CubeSats. Several small spacecraft were designed, fabricated, launched, and successfully operated in low Earth orbit. While more companies and space agencies are becoming interested in CubeSats and small satellite, also the mission goals for these spacecraft are gradually changing: these small spacecraft are starting to be considered for deep-space, interplanetary exploration.

Given the limited size, mass and power capabilities of these small platforms, one of the most interesting problems to address is how to develop a communication system to allow small satellites to communicate from very far distance in the solar system.

This paper aims to address this problem by proposing cooperative communication approaches in which multiple CubeSats communicate cooperatively together to improve the link performance with respect to the case of a single satellite transmitting. Three approaches are proposed: a beam-forming approach, a coding approach, and a network approach. The approaches are applied to the specific case of the SOLARA/SARA concept: a proposed constellation of CubeSats at the Lunar Lagrangian point L1 which aims to perform radio astronomy at very low frequencies (30 kHz to 3 MHz). The paper describes the development of the approaches, the simulation and a graphical user interface developed in Matlab which allows to perform trade-offs across multiple constellation's configurations.

1. Introduction

In[1] the last decade, great progress was made in the development of small satellites and CubeSats. Many small spacecraft were designed, fabricated, launched, and successfully operated in low Earth orbit [1,2]. Currently (February 2015), there are approximately 90 CubeSats in orbit between approximately 100 km and 400 km of altitude [3]. 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 and from farther distances in the solar system. The increase in data requirements can be seen in new proposed mission concepts as well in missions like the PlanetLab constellation [4], which is the first

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CubeSat constellation for Earth observation. The increase in range and distance for SmallSat and CubeSat can be observed in the development and implementation of mission concepts for "interplanetary CubeSats and SmallSats" such as INSPIRE [5], Lunar Flashlight [6], NEAScout [7], BioSentinel [8].

Given the increase in data requirements and in distances, one of the most interesting technological challenges for SmallSats and CubeSats is the development of adequate communication technology. Current developments in the field range from antenna development (Folding-rib deployable [9], Astromesh [10], Reflectarray [11], Inflatable [12,13]), to amplifiers development [14] and to coding techniques [15].

Another interesting idea to improve communication capabilities for SmallSats and CubeSats is to focus on cooperation which means focusing on how to improve the communication of many spacecraft instead of focusing on improving the single spacecraft communication capabilities. This approach is also known as cooperative communication techniques [16].

Cooperative communication techniques have generally the advantage of being 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 disadvantages of cooperative communication techniques are in the complexity of the system and in the level of coordination and synchronization required to communicate which varies depending on the solution implemented.

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.

In Section 2 of this paper, we briefly introduce and characterize the cooperative communication methods previously listed. The different cooperative approaches are proposed for the specific case (SOLARA/SARA) of a constellation of CubeSats located at the Lunar Lagrangian point L1 which aims to perform radio astronomy at very low frequencies (30 kHz to 3 MHz). The constellation is described (Section 3) and simulated results of the implementation of the different cooperative communication techniques are discussed (Section 4). Finally, conclusions and suggestion for future work are presented.

2. Cooperative communication techniques: overview

This section is dedicated to an overview of the three different cooperative communication techniques which are considered as support of the SOLARA/SARA mission concept.

2.1. 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. A beam is required to compute the phase, as well as inter-communication between the satellites and very precise (atomic) clocks are needed to synchronize transmission. In addition, these 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.

2.2. 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 can be also applied to a constellation of small satellites: for example they can transmit the same information and the receiver can 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 [16] can be applied to allow multiple CubeSats/small satellites to transmit simultaneously and to share the same band.

2.3. Network

The network approach implies identifying the best network configuration to achieve certain objectives. Possible network configurations are: peer to peer networks, master–slave networks, and hierarchical networks. Peer to peer networks are networks in which all the satellites have the same transmitting, receiving, and processing characteristics. Peer to peer systems are great for redundancy since the system can work independently from the number of satellites which fail over time. However, 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. In the master–slave network instead, a master is a special satellite which is equipped to transmit at higher data rate than the others. The master is also able 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. The disadvantage of the master–slave network is the high sensitivity to failure: a unique master is a unique point of failure which could potentially compromise the entire mission of the constellation. Finally, the hierarchical network is 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. The masters are more than one which guarantees redundancy against failures. However, this third kind of network is certainly the more expensive and complex to design and implement.