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DEVELOPMENT OF COOPERATIVE COMMUNICATION TECHNIQUES FOR A NETWORK OF SMALL SATELLITES AND CUBESATS IN DEEP SPACE

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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 a proposed constellation of CubeSats at the Lunar Lagrangian point L1 which aims to perform radio astronomy at very low frequencies (30 KHz -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.

I. INTRODUCTION

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 [1] [2]. Currently (September 2014), there are approximately 40 CubeSats in orbit between approximately 400 Km and 100 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 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

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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 disadvantage 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 this paper, we briefly introduce and characterize the cooperative communication methods previously listed (Section 2). The different cooperative approaches are proposed for the specific case of a constellation of CubeSats located at the Lunar Lagrangian point L1 which aims to perform radio astronomy at very low frequencies (30 KHz -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.

II. COOPERATIVE COMMUNICATION TECHNIQUES: OVERVIEW

This section is dedicated to an overview of the three different cooperative communication techniques which are considered for this project.

II.I 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.

II.II 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.

II.III 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 and receiving 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.

III. SOLARA/SARA MISSION CONCEPT OVERVIEW

SOLARA/SARA (Solar Observing Low frequency Array for Radio Astronomy/Separated Antennas Reconfigurable Array) is a concept for a 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 CubeSats would improve our knowledge of heliophysics and space weather, it would contribute to the identification of extrasolar planets, and it would add to our knowledge of the interior structure and dynamo mechanics of the outer planets by pinpointing the source of radio bursts [17]. SARA is the name of the proposed communications system which aims to transmit data to Earth by applying a set of cooperative communication strategies.

SOLARA/SARA (Figure 1) would be a very significant platform to explore cooperative communication techniques since it would be located at a point in the solar system (LL1) for which the conventional CubeSat communication system would struggle to transmit a high volume of data. In addition, the constellation would be composed by a very big number of spacecraft (20) for which the combined gain from using cooperative communication techniques can be significant.

The cooperative communication techniques currently explored for SOLARA/SARA and some preliminary results are discussed in the next section.

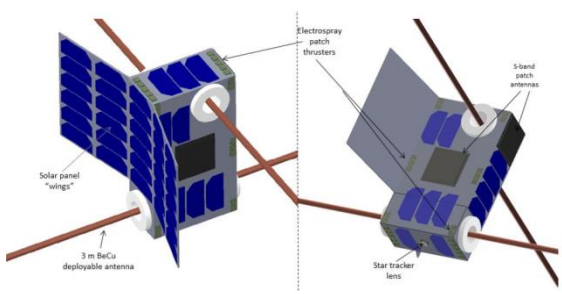

Figure 1: CAD model of the SOLARA/SARA mission concept [17].

IV. COOPERATIVE COMMUNICATION ANALYSIS

This section of the paper is dedicated to the results from the preliminary analysis on the applications of cooperative communication techniques. For SOLARA/SARA, 3 possible techniques are currently in analysis: beam-forming, coding and network. It is important to underline that these techniques could also be used in combination. However, the more cooperative communication techniques are applied, the more complex the system would result.

In this preliminary phase of the project, all the three techniques are explored separately to quantify advantages and challenges associated with each of them. In the future, as the design of the entire SOLARA/SARA mission concepts becomes more refined, a subset of these techniques will be further analysed, maybe combined, and possibly selected for the final design.

IV.I 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 software [18]

In the simulated analysis, the CubeSats are assumed to communicate at the S-Band and specifically at a central frequency of 2.4 GHz. Each CubeSat would be equipped with a patch antenna to communicate with each other and a patch antenna for the array. The two antennas would be identical with a peak gain of approximately 8.31 dBi. The distance between the elements has been varied in different simulations between few wavelengths and few hundreds of wavelengths. The results presented in this case are for a spacing of ten wavelengths, although they are very similar for longer distances.

Figure 2 shows one of the outputs of the array simulation. It can be noticed that a peak of 21.15 dBi is achieved in the z direction with an array composed of 20 spacecraft. Unfortunately, the simulation generates several side lobes which can be problematic. Future studies will focus on solving the issue related to side lobes.

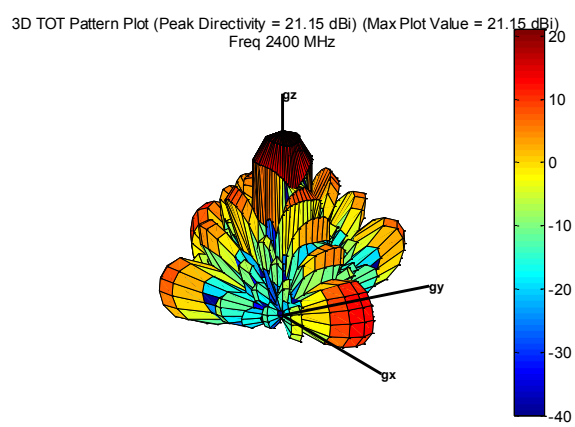

Figure 2: 3D Polar plot of the radiation of an array of 20 CubeSats transmitting in beam-forming using a

~6dBi patch antenna at the S Band (central frequency: 2.4 GHz).

In addition, all the transmitters in the simulation are assumed to be coplanar, as it can be seen in Figure 3. Losses due to placements of the elements in different planes will need to be furthered explored.

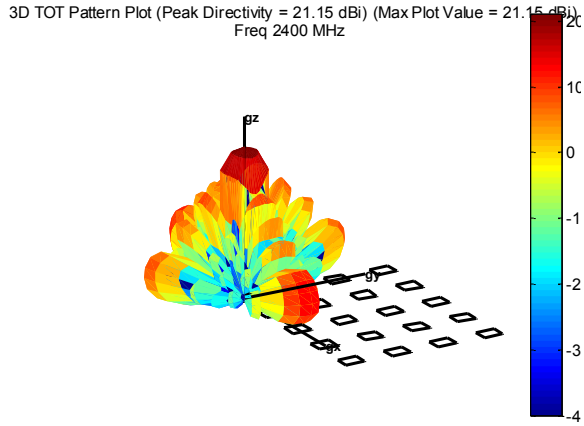

Figure 3: Radiation plot of the array with location of the CubeSats.

IV.II Coding and CDMA

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 [16].

Regarding the implementation of the CDMA, the complexity of a coded CDMA transmitter is lower than the complexity of the CDMA receiver therefore for downlink communications it makes sense to use encoders such LDPC followed by a spread spectrum transmitter for CDMA systems for CubeSats.

For the 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. Future research will look into a filtered offset QPSK with phase modulation (a CCSDS standard) for constant envelope signal, which allows a nonlinear amplifier to operate at saturation point for the highest efficiency. More information on the CDMA implementation can be found in [16].

IV.III Network

The network approach for the constellation assumes to consider the 20 CubeSats as part of a network in which all or some of the nodes relay data back to the Earth. Depending on the network configuration chosen (peer to peer, master-slave, multi-master), some of the CubeSats may be equipped with different communication capabilities, such as a larger antenna, while others may not. Hence, the idea is to use the masters to establish higher data rate links to the Earth.

A simulation study [19] was developed to compare the capabilities of the three possible network scenarios (peer to peer, master-slave, multi-master). In the simulation, the user can choose CDMA or TDMA, and the amount of time allotted for each TDMA slot can also be determined by the user. Finally, the goal of the simulation is to determine how much science data can be relayed by the different communication scenario.

Specifically, the computation is performed assuming an accumulation of science data governed by the following expression:

$$R = 2 \cdot B \cdot n \cdot p \qquad [1]$$

Where R is the data rate of accumulation, B is the bandwidth, n is the number of bits per sample and p is the number of polarizations per samples. The amount of data cumulated can also be reduced by employing compression, but for this initial study, compression was not considered. It can be noticed how the amount of science data cumulated is strictly correlated with the bandwidth of observation. 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. The network analysis is based on a link analysis estimates described in [16]. The estimate was revised with respect to [16] with the addition of a patch antenna at the S-Band instead of a monopole. Hence, the maximum data rate for each peer to peer node, when communicating to the Earth, is estimated at 115 Kbps. In the case of the masters, a more powerful antenna is assumed with an approximate gain of 20 dBi. As a result, the data rate for the Masters is estimated to be approx. 3.125 Mbps.

The network analysis uses the science data cumulation rate described in Equation 1 and the communication data rate estimated through the link budget and looks at how much high in bandwidth the observations could be performed while still relaying data back to the Earth. For the peer to peer case, with no masters, the maximum observation bandwidth that can be reached using a peer to peer network configuration is very low: only 41 KHz. Hence, it is clear that to achieve the mission objectives for the SOLARA/SARA concept, the peer to peer network is not sufficient (even with CDMA and redundancy) and different communication strategies needs to be applied. Specifically, masters can improve the network capacity by providing higher data rate relay links. The results for the master slave network and the multi-masters network are summarized in Table 1. The master-slave configuration is the one with only

one master (first row). The results consider different policies of science acquisition (sampling). A fix number of 2 polarization (*p*) and a fixed number of 8 samples (*n*) per observation are assumed. No failures of masters or slaves are considered in this case.

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

Table 1: Maximum science bandwidth for master-slave and multi-masters network. No failures considered.

The network case represents an improvement with respect to the peer to peer scenario. Interestingly, with 20 total satellites, the maximum bandwidth and number of samples possible is the same for 1, 2, 4, and 5 masters, as long as all other parameters are kept the same. The reason is that each master has an equal number of slaves assigned to it, while with 3 masters, the number of slaves is unequal and therefore each master cannot handle as much bandwidth as before.

Additionally, this simulation does not consider the possibilities of one or more of these masters failing. To simulate failure, a reliability profile [19] is created thanks to some assumptions on the current trends in CubeSat technology. Then, the simulation is repeated multiple times and the mean and variance of the maximum observation bandwidth is computed. Results are summarized in Table 2.

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)

Table 2: Maximum science bandwidth for master-slave network and multi-masters network, case with failures.

The simulation can change greatly if a satellite fails. In the single master-slave scenario, the failure of a slave does not affect the others, but the failure of a master means the remaining satellites return to the peer to peer case. The hierarchical simulation is the most difficult to manage. If a slave fails, it again does not impact the others; if a master fails, then its assigned slaves must be rerouted to the other functional masters. The simulation distributes the slaves evenly amongst the remaining masters. Again, if all masters fail, then the simulation returns to the peer to peer scenario.

It can be noticed that for both the master-slave case and the multi-master case, the bandwidth increases with respect to the peer to peer case. However, even in those cases, the capability is still not enough to support all the science data: the downlink communication system does not allow the science antenna to transmit all the data collected. Specifically, the maximum observation bandwidth does not reach the 3 MHz. To solve the issue, more powerful links need to be established on board the master. Options include: upgrading to a higher frequency (X or Ka-Band), develop a higher gain antenna, introduce an amplifier, add to the architectural concept a larger mothership spacecraft dedicated only to communication.

The last section of the paper is dedicated to the graphical user interface software tool created to perform communication system analysis of the constellation concept.

V. GRAPHICAL USER INTERFACE

To analyse the communication system design for the SOLARA/SARA mission concept a graphical user interface has been designed. This tool is developed using a combination of software (Matlab [20] and STK [21]) and it aims to allow the designer to view different options and to fully characterize the downlink and uplink for the constellation.

A snapshot of the GUI is shown in Figure 4. It is possible to notice that the inputs are divided in three groups:

1. CubeSat data: number of CubeSats (the constellation is baselined for 20 CubeSats, but the tool is designed to analyse a variable number of satellites), inter-satellite distance, constellation pattern (circular, elliptical or a customized pattern), transmitter power, antenna peak gain, pointing loss, line loss, amount of science data collected per day and on board noise temperature.

2. Ground station receiver: station (DSN 34, DSN 70 or the MIT ground station [22]), and the frequency selected (X-Band or S-Band).
3. Options: coding scheme and link margin.

For each of the input fields, default options are available in case of some of the inputs being unknown.

When all the inputs are inserted in the GUI, the results are computed by pressing on each of the plots button. In this way, the plots are refreshed and the new results are visualized. The output plots show:

1. Satellite to Earth link over time: It shows the maximum available data rate in uplink and downlink for each single CubeSat over time in function of the distance between the satellite and the receiving ground station on Earth
2. Satellite to satellite link: it shows the maximum data rate achievable in inter-satellite link. It is computed for the case in which a master (20 dBi gain) is available and for the case of a peer to peer network without a master.
3. Constellation: it shows the desired geometry of the constellation. It can be generated by the software on the base of two inputs (shape, inter-satellite distance), or it can also be uploaded using a separate array structure with coordinates.
4. Doppler shift to Earth: it shows the variations of Doppler in downlink and uplink over time.
5. Science data transmitted: it shows when the science data are cumulated and when they are transmitted (similar to [23]). The plot is important to analyse if the communication system designed is a feasible approach to close the link. The peak of the curve indicates how much data will be cumulated over time before a download. This is an important parameter as it helps to size the buffer memory required for the avionics. Every time the amount of data stored reaches zero, it means that every data collected has been successfully downloaded. It is important to ensure that the data storage plot goes periodically to zero, otherwise the data rate needs to be increased.

The tool allows to analyse the communication system for the proposed constellation and to compare different possible ground stations and satellite components. This tool is not yet fully equipped to simulate the different cooperative communication techniques. However, it is meant to provide a single satellite link characterization which can then be used as an input for the different cooperative communication technique tools.

VI. CONCLUSION

The paper describes the effort in developing cooperative communication techniques for a constellation of interplanetary small satellites. The cooperative communication 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 for the case of the SOLARA/SARA constellation 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.

VII. ACKNOWLEDGMENT

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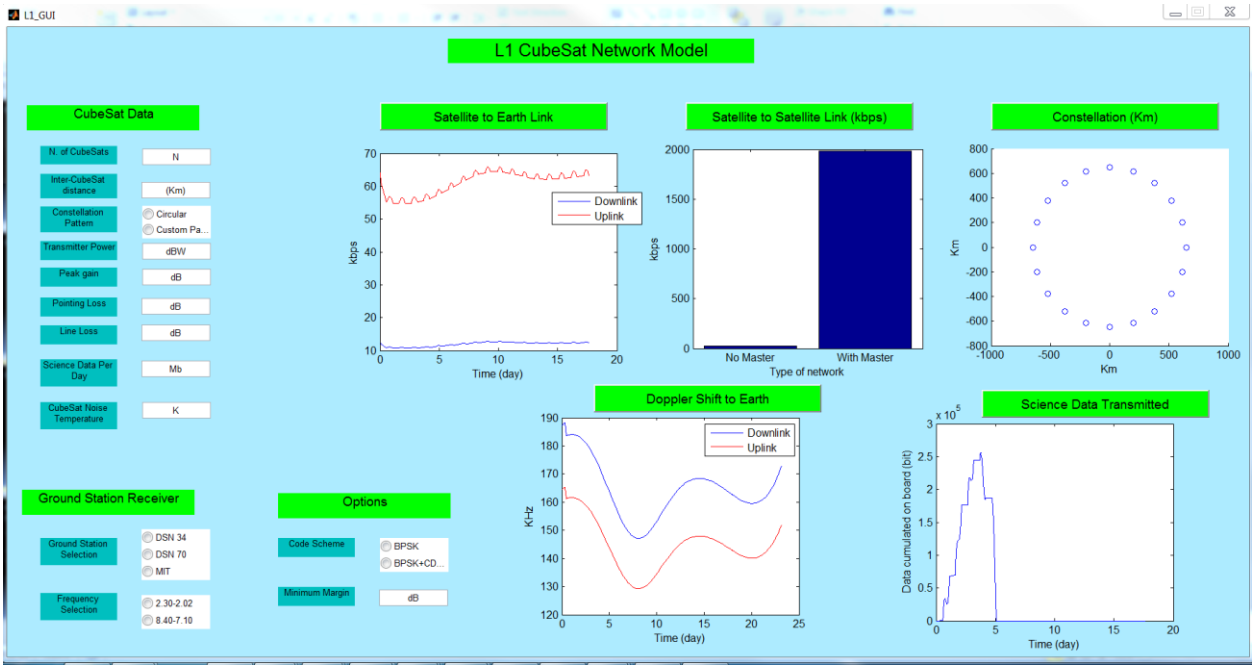

Figure 4: Matlab GUI developed for communication system analysis and design of the constellation.