Adaptive Power Control for Space Communications

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Abstract—This paper investigates the implementation of power control techniques for crosslinks communications during a rendezvous scenario of the Crew Exploration Vehicle (CEV) and the Lunar Surface Access Module (LSAM). During the rendezvous, NASA requires that the CEV supports two communication links: space-to-ground and crosslink simultaneously. The crosslink will generate excess interference to the space-to-ground link as the distances between the two vehicles decreases, if the output power is fixed and optimized for the worst-case link analysis at the maximum distance range. As a result, power control is required to maintain the optimal power level for the crosslink without interfering with the space-to-ground link. A proof-of-concept will be described and implemented within Goddard Space Flight Center (GSFC) Communications, Standard, and Technology Lab (CSTL).[1,2]

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1. INTRODUCTION

Embracing the Vision for Space Exploration, NASA is developing the next-generation of space communication systems. Communication requirements and specifications are being formulated for several link types: Earth-to-Lunar, Earth-to-Mars, space-to-ground, and space-to-space (crosslinks). In particular, crosslink communications will be essential for exploration due to the numerous rendezvous that are being proposed for human space flight missions to the Moon and to Mars. Direct-Sequence Spread Spectrum (DSSS) is being implemented on all communication links. For terrestrial applications, DSSS systems are advantageous because they provide increased capacity and security. However, DSSS systems are interference-limited. As a result, power control techniques are used to minimize the interference. In current space communication systems, power control techniques are not implemented and are sensitive to interference from other users. The possibility of failure to acquire or false carrier lock increases as the interference increases. Without power control, space communication systems are not able to optimize the power level while minimizing interference, especially for crosslink communications.

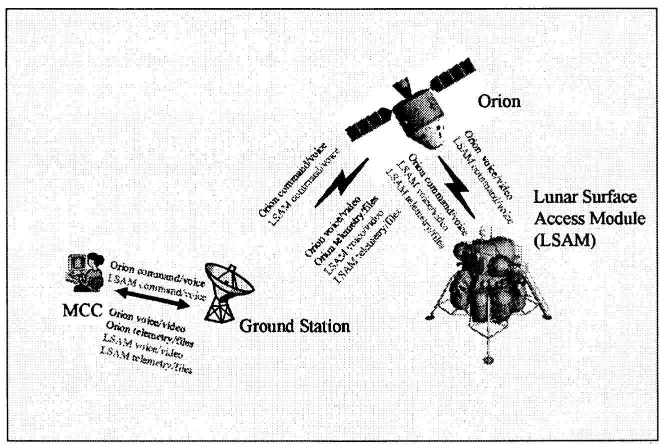

Figure 1: NASA Communication Scenario

Figure 1 illustrates a typical communication scenario for future Lunar missions. As demonstrated, the CEV will be required to simultaneously support a space-to-ground link to Mission Control Center (MCC) and a crosslink between the CEV and LSAM. Using traditional specifications, the power amplifiers for the links would be optimized for worst-case link budget conditions, independently. In particular, crosslink will generate excess interference for the space-to-ground link due to the dynamic power requirements when communicating from ranges of a few meters versus thousands of kilometers.

The focus of this work was to research and demonstrate adaptive power control to optimize crosslink communications. The initial work focused on the development of power control algorithms. Several algorithms were investigated for integration into GSFC

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[1] U.S. Government work not protected by U.S. copyright
[2] IEEEAC paper #1188, Version 5, Updated December 3, 2007

CSTL. Section 2 describes the power control algorithms that were investigated. We analyzed their feasibility for infusion into space communication systems. Section 3 describes the implementation of a proof-of-concept demonstration within the CSTL. Lastly, we describe the future activities of adaptive power control development for space communications.

2. POWER CONTROL ALGORITHMS

The signal-to-interference ratio (SIR) for a crosslink communications can be expressed as:

$$SIR_i = \frac{P_{Ri}}{P_R - P_{Ri} + N_o B} = \frac{P_{Ti} G_i}{\sum_{x=1}^{N} P_{Tx} G_x - P_{Ti} G_i + N_o B} \quad (1)$$

where

P_R = Total Received Power
N_o = Noise Density Power
B = Bandwidth
N = Total Number of Transmitters
P_{Ri} = Received Power of Link i
P_{Ti} = Transmitted Power of Link i
G_i = Channel Gain (Loss) of Link i
P_{Tx} = Transmitted Power of Link x
G_x = Channel Gain (Loss) of Link x

Equation 1 shows that the SIR is a function of the various transmitted powers and the channel gains, which models the current channel condition of the link. The energy per bit can be expressed in terms of the given channel conditions:

$$\begin{aligned} E_b &= P_R T_b \\ E_b &= P_R / R_b \\ E_b R_b &= P_R \\ E_b R_b &= P_T G \end{aligned} \quad (2)$$

where

E_b = Energy per bit
T_b = Bit Period
R_b = Data Rate

For space communication systems, it is typical for each link to have different communication specifications. Consequently, Equation 2 shows that each link has a unique transmitter power requirement based on its communication specifications. The SIR requirement based on the communication specifications and the current channel conditions can be expressed by Equation 3.

$$SIR_i = \frac{E_{bi} R_{bi}}{\sum_{x=1}^{N} P_{Tx} G_x - P_{Ti} G_i + N_o B} \quad (3)$$

For crosslink communications, the channel gain is a direct function of the distance between transmitter and receiver. It has an extremely dynamic operating range. For given a fixed worst-case transmitted power and the channel gain decreases, the E_b increases beyond the required level for a reliable communication link, thus creating excess interference to other receivers.

The objective of adaptive power for space communication is to optimize the P_T of each receiver to achieve the minimum E_b for its individual communication specifications and channel conditions.

Adaptive power control will allows for:

- Minimum interference to other receivers
- Maximum capacity of spectrum allocation
- Increased power efficient of spacecraft
- Adaptability to dynamic mission & communication condition.

Power control algorithms can be grouped as being an open-looped or closed-looped algorithm. Open-looped algorithms do not provide power commanding between the transmitter and receiver. The P_{Ti} is adjusted based on measurements at the transmitter. Closed-looped algorithms provide power commanding. The P_{Ti} is adjusted using measurements at the Receiver and power commanding is provided to the transmitter.

Open-Looped Algorithms:

We investigated two open-looped approaches: SIR-based [1] and distance-based power allocation [2]–[3]. Using open-looped SIR-based, the P_{Ti} is adjusted using the received SIR at the transmitter. Using Equation 1, the transmitter calculates the optimum power level based on the received channel conditions. In distance-based power allocation, the transmitted powers are adjusted using the distance between the transmitter and receiver. Models are used to calculate the optimal P_T. The main disadvantage of these approaches is that the SIR for receiver is not optimized, since the channel conditions for the receiver can be different than the transmitter due to its location. As a result, we concluded that open-looped algorithms are not feasible and will not be developed for integration into the CSTL.

Closed-Looped Algorithms:

Closed-loop approaches can be classified by the methodology used for controlling the SIR at the receiver. The two methodologies are distributed SIR balancing [1]-[2]

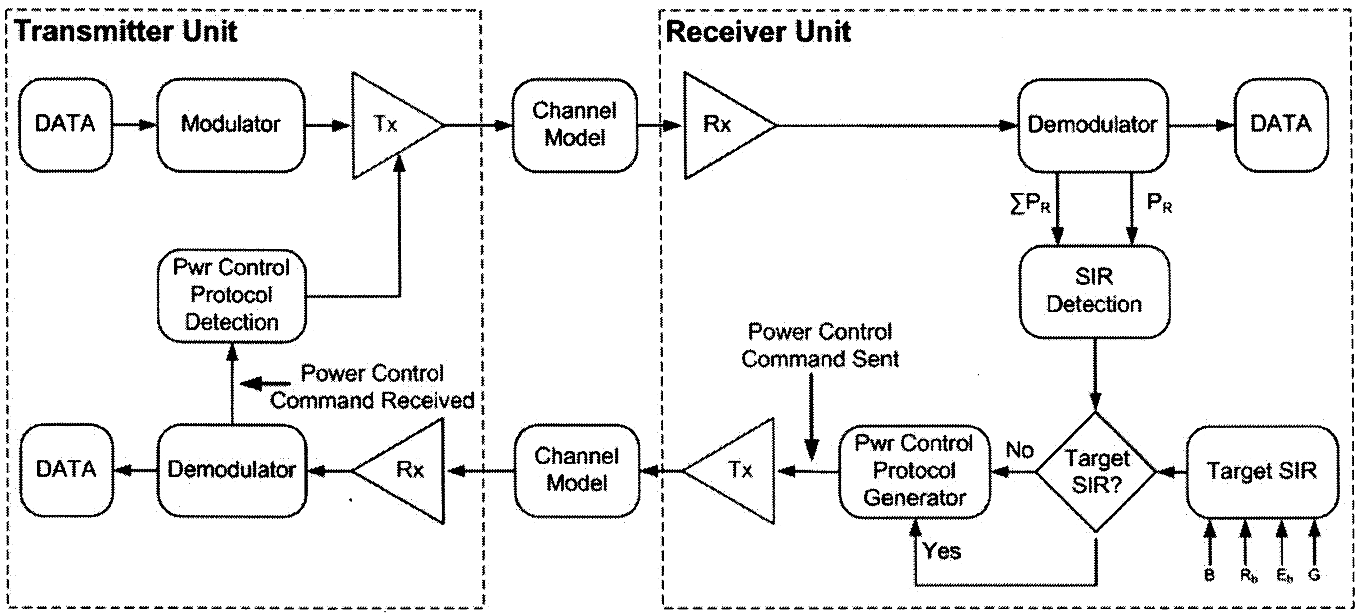

Figure 2: Function System Diagram

and de-centralized SIR balancing [4]. In the distributed SIR balancing, the optimal P_T is calculated for each link based on the SIR at the receiver, while taking into consideration of all the other links. This methodology is a centralized approach. For crosslink communications, this approach is not feasible since the total received power (P_R) is a function of transmitters that the receiver does not control. This approach is implemented in cellular systems, where all receivers communicate to a base station. In the de-centralized SIR balancing, the P_{Ti} is adjusted based the received SIR at the receiver. The power is adjusted using fixed or adaptive power control steps. This methodology is a de-centralized methodology.

As a result of the investigation, we concluded that the de-centralized SIR balancing approaches are feasible for crosslink communications. The initial proof-of-concept implemented fixed power control steps. Adaptive power control steps will be implemented in the future.

3. PROOF-OF-CONCEPT

The next generation of space communication systems will be IP-based with multiple space assets providing routing function for voice and data applications. To assist in the formulation of the specifications and requirements, GSFC has development the CSTL. The CSTL is an IP-based communication testbed that is able to test and demonstrate advanced communication technologies and standards for infusion in space communication systems.

Software & Hardware Components:

Figure 2 illustrates the functional system diagram for the proof-of-concept demonstration. There are four software components:

1. SIR Detection: Calculates the received SIR
2. Power Control Protocol Generator: Generates command packet
3. Power Control Protocol Detection: Interprets the command packet into the adjustment of the P_T
4. Target SIR: Calculates the optimum SIR for the channel conditions

This work focused on the software development of SIR detection and the protocol components. All software components were developed using LabView.

Two approaches for adjusting P_T were implemented. The first approach utilizes digital programmable step attenuators. The step attenuators provide excellent attenuation range; however, data is lost during the mechanical switching of the attenuators. The second approach is based on a voltage gain amplifier (VGA) design. The VGA has a limited attenuation range, but provides linear transition between steps. In addition, the VGA is a low power solution.

The channel model was implemented using an adjustable attenuator to model the free-space path loss for crosslinks. Future enhancement to the channel model includes the implementation of RF path loss emulator, which models the path loss and delay for crosslinks. The path loss emulator is currently being developed at GSFC.

The power control protocol was implemented using UDP packets. UDP packets are the preferred baseline for the CSTL network protocol and future NASA applications. UDP is advantageous in the bandwidth-limited environment of space, since it does not require an acknowledgement message from the receiving system.

SIR Detection:

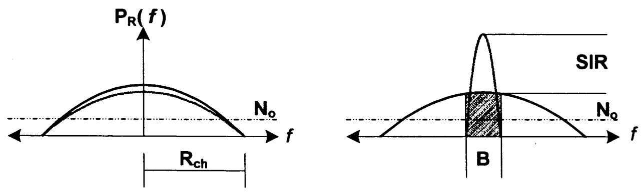

Figure 3: Signal-to-Interference Ratio for DSSS systems

For DSSS systems, the SIR can be defined as the ratio of the despreaded power signal to the spreaded power within the bandwidth as illustrated in Figure 3. The bandwidth is defined as the bandwidth of the despreaded signal and not the total bandwidth of the channel. From Equation 1, we know that the SIR is a function of the channel gain, which dynamically changes for crosslink communications. As a result, the optimum SIR changes as a function of the channel gain or to the first-order the distance between the transmitter and receiver.

Power Control Conditions:

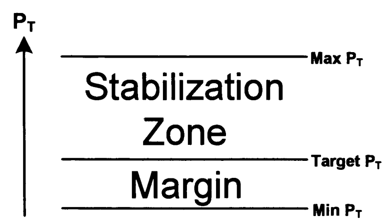

Figure 4: Power Control Conditions

Based on the channel conditions, the minimum SIR can be obtained for a reliable communication link. The associated P_T for this minimum SIR defines the minimum P_T as shown in Figure 4. To ensure a reliable link, a margin region is used to prevent overcompensation of the P_T. The target P_T is defined as the minimum P_T plus the margin. To prevent oscillation around the target P_T, a stabilization zone is defined that allows the P_T to remain unchanged [5]–[6]. The size for the stabilization can be optimized for the channel conditions. A smaller stabilization zone decreases the amount of excess interference to other receivers, while increasing the amount of power control adjustment.

The adaptive power control conditions are:

- When P_T is above the stabilization zone, the P_T will be decreased.
- When P_T is within the stabilization zone, the P_T will be unchanged.
- When P_T is below the stabilization zone, the P_T will be increased.

4. FUTURE ACTIVITIES

This initial work focused on the development of a proof-of-concept to demonstrate the importance of adaptive power control to NASA decision makers for future communication systems. Future activities include, but are not limited to:

1. Development of the target SIR algorithm based on dynamic communication specifications and conditions
2. Analysis of adaptive power control algorithms within NASA mission scenarios
3. Trade study on transmitter power consumptions associated with using adaptive power control
4. Development of improved power control algorithms with fail-safe modes
5. Investigation of adaptable transmitter technology for improved output power, efficiency, and DC consumption

5. SUMMARY

This paper describes an initial proof-of-concept demonstration of adaptive power control for space communication systems. The culture norm for space communication systems is to implement fixed power amplifier for worst-case link analysis. With innovative approaches to support the Vision for Space Exploration, DSSS and crosslink communications are becoming essential for future NASA missions. As a result, adaptive power control for future systems is critical to ensure reliable communication for space-to-ground links. Utilizing the CSTL, GSFC has developed and tested power control algorithms for future implementation of flight projects. Adaptive power control has been implemented in terrestrial applications for many years, however, the unique challenges of space require further investigation of the software and hardware technologies that will enable adaptive power control for space communication systems.

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BIOGRAPHY

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