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Hua Duc Thien, 이윤성, 이동현, 조성래

중앙대학교 컴퓨터공학과

{thien, yslee, dhlee}@uclab.re.kr, srcho@cau.ac.kr

Wireless Communication Technologies in Omnidirectional CubeSat Crosslink: Comparative Study of The Link Budget and Antenna Requirements

Hua Duc Thien, Yunseong Lee, Donghyun Lee, Sungrae Cho

Department of Computer Science and Engineering, Chung-Ang Univ.

Abstract

Advanced CubeSat missions must be designed such that each nano-satellite in a constellation is assured of resource-efficient whilst succeed in carrying out their complex task. In this paper, we propose a study of ubiquitous wireless technology for omnidirectional CubeSat Crosslink platform in regard of the link budget parameters and the appropriate antenna size. The communication distance is also studied thoroughly for different communication systems. The analyses show that an optical communication link is capable of delivering more than two orders of magnitude higher data throughput than that of microwave links in an omnidirectional platform.

Ⅰ. Introduction

CubeSat technology is evolving in order to tackle more complicated and challenging space missions. A CubeSat is a miniature satellite that is constructed in modules of multiples units (U), 1U ≈10 ×10×10 cm3. In addition, its typical weight of a 1U CubeSat is approximately 1.33 kg and the available average power with the non-deployable solar panel is less than 2.5 W/U here performance metrics clash with available size and power [1],[2].

Therefore, a comprehensive examination of the strengths and limitations of wireless technologies in light of the link budget, appropriate antenna size and technological constraints placed by the CubeSat technology is necessary for the effective implementation of the omnidirectional communication. Microwave (Radio Frequency and millimeter-wave) and optical communication offer different benefits and challenges to enable omnidirectional communication in such a platform. In this paper, we study the feasibility of wireless technologies in achieving omnidirectionality in terms of antenna requirements. In particular, we study and compare the performance of RF, mm-Wave, and optical communication medium with self-imposed boundary conditions to satisfy the CubeSat SWaP-C constraints.

Ⅱ. Comparative Study of the Link Budget Parameters

In this section, we begin with the link budget equation that estimates the received Power P_{rcv} based on the formular expressed as

$$P_{rcv} = P_T G L \eta$$

where P_T is the transmitted power, G is the total antenna gain, L is the total loss and η is the combined antenna efficiencies.

The total antenna gain G is the combined gain of the transmitter (Tx) antenna gain $G_T = f(D_T, \lambda)$ and receiver (Rx) antenna gain $G_R = f(D_R, \lambda)$) i.e. $G = G_T G_R$. Here D_T , D_R , and λ represent transmitter diameter, receiver diameter, and operating wavelength, respectively. The calculation of Total loss L bases on the transmitter feeder loss L_{Tx}, receiver plumbing loss L_{Rx}, the path loss L_R, the pointing loss $L_P = f(G_T)$ in an equation expressed as $L = L_{Tx} L_{Rx} L_R L_P$. Given that η_T and η_R are transmitter and receiver antenna efficiencies, respectively, the combined antenna efficiency is defined as $\eta = \eta_T \eta_R$. It is apparent that these parameters depend on the antenna sizes, available electrical power, and wavelength. Hence, constraints imposed by CubeSat dimensions significantly differ from the constraints imposed by conventional satellite regardless of their somewhat similar performance expectations. Several boundary conditions pertinent to the CubeSats platform, therefore, is imposed to accommodate multiple antennas to achieve omnidirectionality. The first condition is that CubeSats are smaller than 12U [3]. Next, total power consumption of the communication payload is less than 50W (12U limit) [4], whilst microwave antenna size (dish size) is less than 200 mm and maximum optics diameter is 50 mm. The fifth and the sixth conditions are $P_T = 1W$ and antennas are non-deployable, respectively.

The major distance dependent loss parameter in the above link budget is the path loss $L_R = f(f,r)$ that depends on the carrier frequency f and distance r. Due to higher carrier frequency, the optical communication experiences a higher path loss (more than 50 dB) compared to that of the RF and the mmWave frequencies. However, this large path loss at optical frequencies are usually compensated by the high antenna gains (i.e. Tx and Rx gains) in the link budget equation.

The transmit antenna gain G_T and G_R is estimated as $G_T \approx \left(\frac{\pi D_T}{\lambda}\right)^2$ and $G_R \approx \left(\frac{\pi D_R}{\lambda}\right)^2$, respectively. It can be realized that the larger the antenna diameter, the higher is the gain. In contrast, smaller wavelengths (or higher carrier frequencies) realize higher antenna gains for a given antenna dimension. The maximum antenna size is limited by the CubeSat platform's available volume, size, and weight. The RF and mm-Wave communication systems usually use the same physical antenna to send and receive the signals, therefore $G_T = G_R$. Most optical transceivers, on the other hand, have transmitters with smaller optics (D_T) and receivers with bigger optics (D_T). As a result, in optical communication, the antenna gains G_T and G_R can be significantly different.

A sophisticated pointing and acquisition system is implemented to maintain effective data transfer in the optical communication system. To achieve a throughput loss of less than 3.0 dB, the required pointing accuracy ϵ (in degrees) of an inter-satellite communication should be small, i.e.: $\epsilon \approx \frac{180\lambda}{20\pi D_T}$. In addition, the required pointing angle in optical communication directly depends on the beam divergence of the transmit beam. The higher the beam divergence, the lesser the pointing accuracy is required.

III. Tx Antenna Requirement

To achieve an omnidirectional communication, both the transmitter and the receiver need to possess a full Field of Regard (FOR). The required number of transceivers to achieve a FOR of α_{reg}(in degrees) can be given as

$$n \approx ceiling\left(\left(\frac{\sin\left(\frac{\pi\alpha_{reg}}{720}\right)}{\sin\left(\frac{\pi\alpha}{720}\right)}\right)^2\right) \quad (1)$$

where α is the FOR (in degrees) of a single transceiver system. In the case of directional RF and mm-Wave antenna (patch antenna, dish antenna), α corresponds to the antenna beamwidth (or divergence angle).

The requirements of a large number of antennas is a direct consequence of transmitting a high directional beam to achieve a large antenna gain. Transmission of a high directional beam to obtain a significant antenna gain necessitates the use of a large number of antennas. Furthermore, a higher working frequency implies a greater n. Due to the trade-off between G_T, G_R, and n, implementing omnidirectional high-speed and long-distance communication in RF and mm-Wave with dish antennas or patch antennas is exceedingly challenging. Despite the fact that non-directional microwave antennas like dipole antennas can attain full FOR with fewer antennas, the communication range will be severely limited because to low antenna gains.

IV. Summary and Discussion

In this section, we investigate the performance of existing wireless technologies for establishing omnidirectional CubeSat crosslinks. We give an evaluation of the performance of communication links in terms of design parameter, because each technology has specific benefits and limits on the CubeSat platform. Our study indicates that including the requisite number of large microwave antennas and phased array antennas to accomplish omnidirectional communication in a CubeSat is tremendously challenging. In a CubeSat crosslink, the effective communication medium relies on the integrable antenna size, and the desired communication range. With the proper design parameters, the analysis described in this study may be utilized as a guide for developing high-speed omnidirectional CubeSat.

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