CubeSat Communications Transceiver for Increased Data Throughput

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Abstract—CubeSat communication links require small size, low power, and low cost transceivers. Link parameters resulting from the satellite's Low Earth Orbit (LEO) can impair transceiver performance, degrading mission data throughput. This paper describes the characteristics and control of a new CubeSat transceiver. The new transceiver provides an estimated 300% increase in data throughput for a typical 45–degree maximum elevation angle LEO pass over the Aerocube-2 transceiver. [1][2]

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1. INTRODUCTION

There has been considerable interest in the development of inexpensive, Low Earth Orbit (LEO) based satellites for scientific missions. This has spurred the development of the CubeSat standard [1]. The standard defines satellite size as a 10 centimeter cube and weight as less than 1 kilogram. The goal of the standard is to make the launching of these satellites easy by providing a reliable deployment system. A recent example of a coordinated CubeSat deployment occurred in April 2007 with the launch of seven CubeSats using the DNEPR launch vehicle. The CubeSats were launched into a nearly circular, 700 km polar orbit. One of the CubeSat's deployed was The Aerospace Corporation's Aerocube-2, shown in Figure 1. The communications transceiver of Aerocube-2 operated in the 900–928 MHz Industrial Scientific Medicine (ISM) frequency band with a data rate of 38.4 Kbps. Though this transceiver has been very reliable, it is not optimized for orbital operations. A new transceiver, presented here, has features that will maximize data throughput.

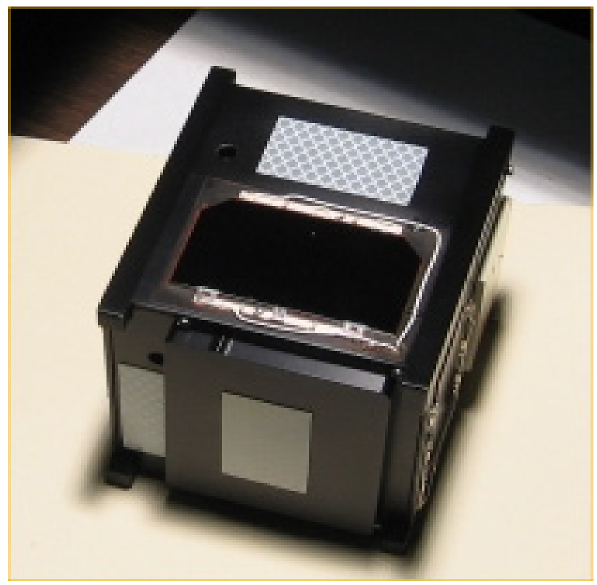

Figure 1. The Aerocube-2 CubeSat

For CubeSat missions, the DC power supplied to the satellite subsystems is at a premium. This is due to the physical limitations of the on-board Li-Ion batteries and available area for solar cells [2]. The DC power constraints are critical to CubeSat transceiver design and operation. Transceiver DC power requirements are primarily set by the transmit power amplifier (PA). Frequency-shift-keying (FSK) modulation is often chosen for its constant envelope property, allowing saturated PA operation with low DC power consumption. In transmit mode, the Aerocube-2 transceiver provides 2W RF output power from 8 W of DC power. High performance FSK receivers can be implemented with relatively low DC power consumption [3]. In receive mode, the transceiver consumes 0.9 W of DC power while providing a sensitivity level of –105 dBm [38.4 Kbps data rate, 0.01 packet-error rate (PER), 20 bytes/packet].

The RF port of the satellite transceiver is connected to a transmit/receive microstrip patch antenna. This antenna

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[1] 978-1-4244-2622-5/09/$25.00 ©2009 IEEE.
[2] IEEEAC paper #1737, Version 2, Updated January 5, 2009

was chosen for its low profile and isotropic (spherical) pattern coverage. It provides a worst case loss of 10 dB over 90% of isotropic pattern coverage. The Aerocube-2 mission achieved communications link closure using a 28 dB gain, 16 foot diameter dish antenna at the El Segundo, CA ground station. The ground station operated with 10 dB higher RF output power than the satellite. This helped ensure error-free control of the satellite transceiver through the uplink path.

The purpose of this paper is to discuss the development of a new CubeSat transceiver to increase mission data throughput. Section 2 presents the relevant parameters of a CubeSat LEO link. Section 3 discusses the transceiver characteristics necessary to exploit the link parameters while simultaneously meeting the small size, low power, and low cost constraints. Section 4 presents the transceiver's control algorithm which helps optimize the data throughput performance. Section 5 summarizes the expected data throughput performance and provides suggestions for future improvement.

2. LEO LINK PARAMETERS

During a CubeSat LEO pass, the elevation angle goes through a cyclical variation; smallest at the beginning and end (when the satellite is on the horizon), and highest at the middle of the path (when the satellite is at the zenith). As the elevation angle of the ground station antenna increases, the propagation distance shortens and the atmospheric loss and signal delay correspondingly decreases. Since the CubeSat transceiver transmits with a constant output power, the decrease in link loss during the pass will result in a variation of received signal power. Figure 2 shows received signal power from the El Segundo ground station for a typical 45–degree maximum elevation angle LEO pass, with the satellite transceiver PA operating at 1 W RF output power. The ground station antenna noise temperature also varies during the pass, but since the receiver noise temperature is dominant, the system noise power remains effectively constant. Therefore the data rates that are possible during a pass can be estimated using the sensitivity of the transceiver and the received signal power. When the received power is higher, the data rate can be increased, providing improved data throughput for the pass.

In addition to the variable received signal power, the ground station also observes variable Doppler RF frequency shift during the pass. The Doppler shift is the apparent shift in RF frequency caused by the velocity of a satellite relative to the ground station. It is a function of both the absolute RF frequency of the transmitter and the relative velocity. This shift in RF frequency must be estimated and compensated for in order to enable reliable and efficient communication. Figure 3 shows the Doppler frequency shift curve for a typical LEO pass as experienced from the El Segundo ground station. The use of ± is to denote the two opposite values of Doppler shift that occur when the satellite is moving directly towards (+) or away (–) from the ground station.

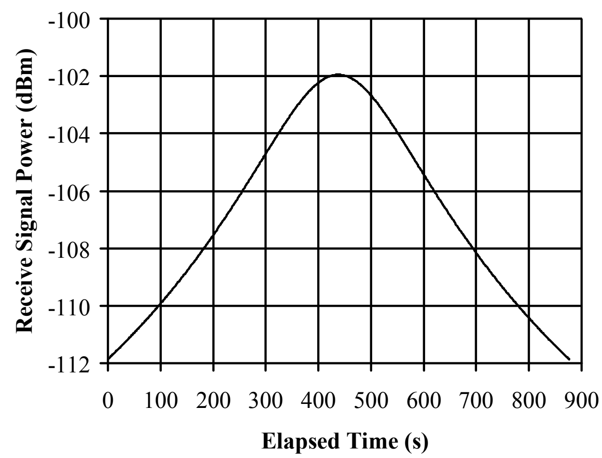

Figure 2. LEO Pass Receive Power vs. Time

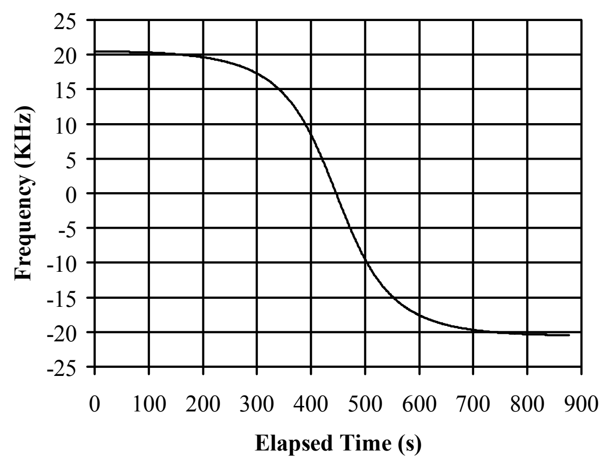

Figure 3. LEO Pass Doppler Shift vs. Time

One method of dealing with Doppler shift is to increase the bandwidth of the receiver filters on both ends of the link so that even with the Doppler shift, the modulated transmitted signal is always contained within the receiver bandwidth. Since the extra bandwidth adds thermal noise, the sensitivity performance is reduced. Additional degradation can occur with this method since the signal is not centered in the band of the FSK demodulator. The preferred method is to use an automatic frequency control (AFC) system where the signal remains in the center of the receiver filter without requiring continual manual adjustment of the receiver tuner frequency. The receiver bandwidth can also always be set to the value in which the optimal sensitivity is achieved throughout the LEO pass, regardless of data rate and Doppler shift. The AFC system must be designed to reliably acquire and track both the rate and range of the expected Doppler shifted frequency.

3. TRANSCEIVER CHARACTERISTICS

In order to obtain adjustable data rate and AFC capabilities along with small size and low power, the Texas Instruments CC1101 single chip transceiver [4] was evaluated. The transmitter section of the chip has configurable data rates up to 500 kbps and provides up to 10 mW RF output power while using only 100 mW of DC power. The receiver section has adjustable channel filter bandwidths between 58 and 812 kHz and consumes only 50 mW DC power. An internal 64 byte FIFO is used for efficient packet handling, data buffering, and burst transmissions. The CC1101 is designed to be interfaced with a programmable intelligent computer (PIC) for control and data flow purposes. An important feature of the CC1101 is the ability to estimate both received signal strength indication (RSSI) and frequency offset. These indicators allow for increased data throughput by enabling optimal adjustment of data rate, receiver bandwidth and RF frequency throughput the LEO pass.

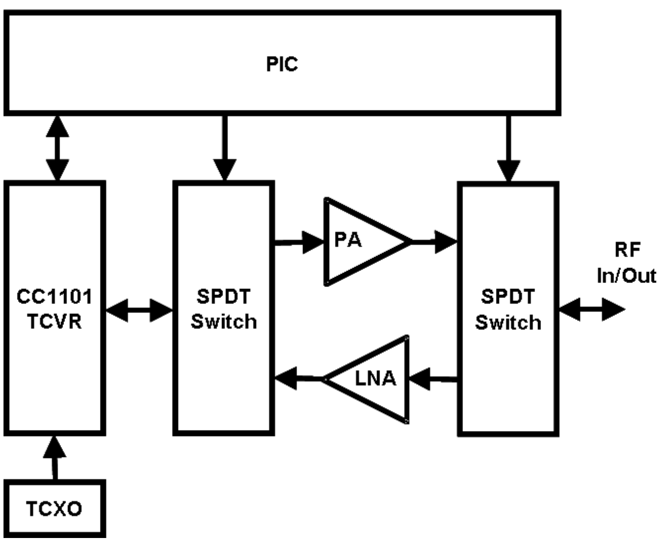

Figure 4. CubeSat Transceiver Block Diagram

A block diagram of a CubeSat transceiver using the CC1101 is shown in Figure 4. In addition to the PIC, several external RF components are included to improve performance. The low noise amplifier (LNA) provides 1.3 dB noise figure and 17 dB gain. The PA provides 1 Watt saturated output power with up to 32 dB small signal gain. Single pole double-throw (SPDT) switches are required to allow connection of the LNA and PA to the antenna RF In/Out port. A bidirectional data/control path exists between the PIC and the CC1101. The PIC also controls the SPDT switches and turns off the PA and LNA whenever they are not in use to minimize DC power consumption. A 26 MHz temperature compensated crystal oscillator (TCXO) is used as the frequency reference for the CC1101. This enhances the both phase noise and temperature stability performance of the transceiver.

Figure 5 shows the average sensitivity performance of three fabricated CubeSat transceiver units. The 0.01 PER sensitivity is –120 dBm at 250 bps data rate and degrades to –94 dBm at 500 kbps. This performance is approximately 6 dB better than the CC1101 chip alone. The improvement is due to the lower overall receiver noise figure achieved by using the off-chip LNA. The performance is also a 6 dB improvement over the Aerocube-2 transceiver at the 38.4 kbps data rate.

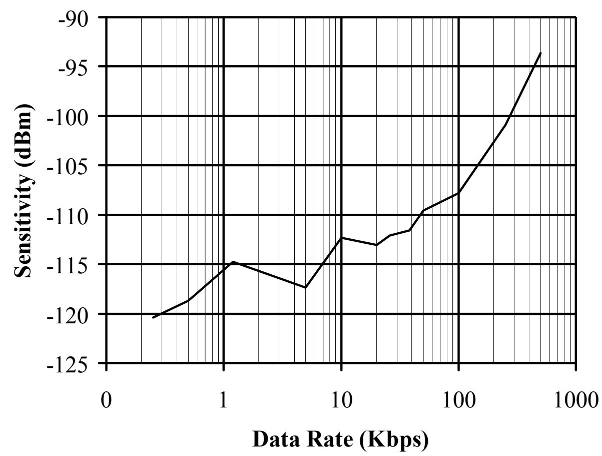

Figure 5. CubeSat Transceiver Sensitivity

4. TRANSCEIVER CONTROL ALGORITHM

This section describes a simple transceiver control algorithm (TCA) for increasing the data throughput for each LEO pass. A simplified flow chart of the TCA is shown in Figure 6. The ground station transceiver functions as the master in a master/slave configuration. The acquisition mode of the TCA is shown in the first three blocks. In this mode, both the ground station and satellite transceivers are set to the nominal center RF frequency and lowest data rate. The ground station transceiver continually sends command (CMD) packets requesting a response from the satellite transceiver. Once an acknowledgement is received, the ground station transceiver begins the data transfer mode as shown in the bottom three blocks of Figure 6.

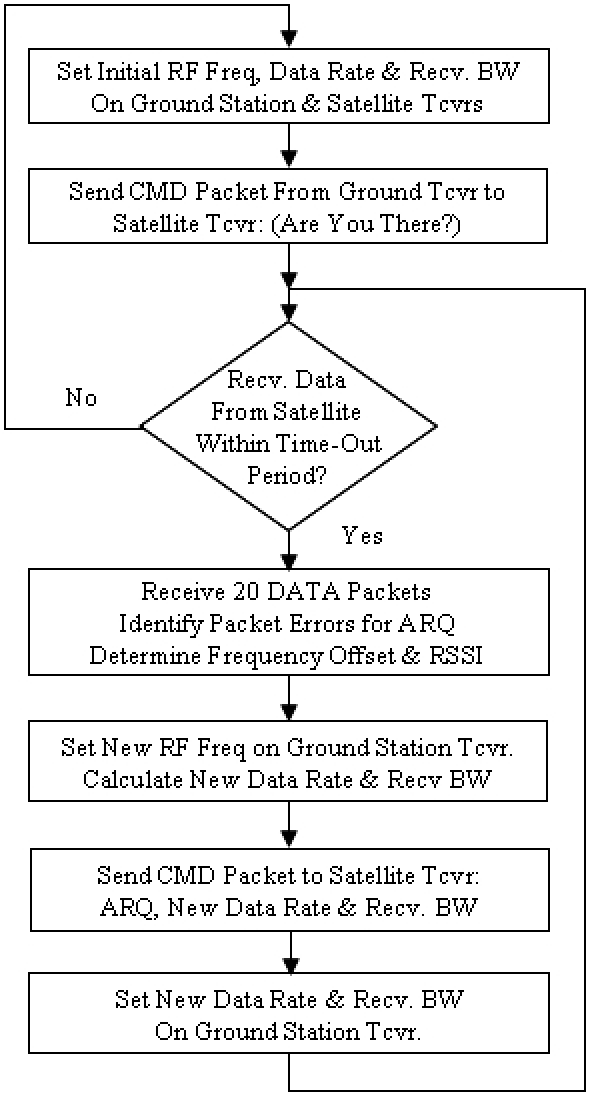

Figure 6. Transceiver Control Algorithm

In data transfer mode, the satellite transceiver sends payload data to the ground station in frames of 20 packets. The ground station transceiver receives the data and identifies packets with errors for automatic-repeat-query (ARQ) re-transmission. It also accurately determines the RF frequency and RSSI by averaging the values estimated from each packet. From this information, a new data rate and receiver bandwidth is determined using a look up table (LUT) so as to maximize data throughput. The RF frequency of the ground station transceiver RF frequency is then adjusted to minimize the effects of Doppler shift. A CMD packet requesting more data is then sent to the satellite transceiver. In addition to the new data rate and receiver BW, ARQ information is provided to identify which packets need to be resent from the last frame. The algorithm will automatically revert back to acquisition mode if data from the satellite is not received within the allotted time-out period.

To fully take advantage of the transceiver's adjustable data rate capability, a continuously variable data rate is required [5]. In practice, a discrete step-size LUT and overhead time limit the achievable performance. A fixed amount of overhead is due to execution/control times within the PIC and CC1101. Overhead is required for the preamble, synchronization and CRC bits within each packet. Signal propagation time also results in an overhead between 6 and 20 ms for each frame during the pass. To estimate data throughput, simulations were performed using the expected overhead, as well as the received signal power and transceiver sensitivity from Figures 2 and 5, respectively. Figure 7 shows a performance comparison of the Aerocube-2 transceiver to the new transceiver using the TCA. Data throughput is increased due to both the extended data transfer period and higher data rates. A data throughput increase of 300% can be achieved. Further improvement is possible by using a higher speed, more powerful PIC to decrease the execution/control overhead time.

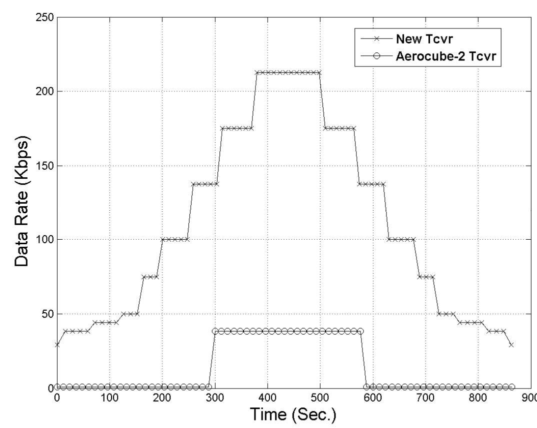

Figure 7. TCA Simulated Data Rate vs. Time

5. CONCLUSION

This paper describes the development of a Cubesat transceiver for increased data throughput. The design is based on a commercial transceiver chip developed for the 900–928 MHz ISM band. The transceiver's sensitivity at a 38.4 kbps data rate is 6 dB better than the previously used Aerocube-2 transceiver. The new transceiver allows for the flexible adjustment of data rate, receiver bandwidth, and RF frequency throughout a given LEO pass. The effects of variable received signal power and Doppler shifted RF frequency can be minimized with a control algorithm that effectively utilizes the transceiver's capabilities. A simulation for a typical 45–degree maximum elevation pass has shown that the data throughput performance can be increased by 300%. Further improvement is possible by using a higher speed, more powerful PIC to decrease the execution/control overhead time.

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Biography

Christopher Clark *received the BSEE and MSEE degrees from the University of Maryland, College Park, in 1983 and 1986 respectively. From 1984 to 1986 he worked for the Watkins-Johnson Company, where he was responsible for the design and development of RF receiving systems. From 1986 to 1992 he worked for TRW, Inc. (now NGST) where he developed HEMT and HBT GaAs MMICs for satellite payloads. From 1992 to 1999 he worked at The Aerospace Corporation where he was involved in the design of space communication systems. From 1999 to 2003 he was a Principal Engineer at Multilink Technology Corporation, where he was responsible for the development of transceivers for use in fiber optic telecommunication systems. He is currently a Senior Engineering Specialist at The Aerospace Corporation in the Communication Electronics Department, Electronic Systems Division. His work involves the design, analysis, and hardware development for several space communication systems.*