Software Defined Radio Implementation of DS-CDMA in Inter-Satellite Communications for Small Satellites

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***Abstract*—In this paper, we study the problem of multi-user inter-satellite communications in a network of small satellites and design and implement of an optimum CDMA-based multiple access communication using Software Defined Radios. Inter-satellite links (ISL) enable small satellites to exchange information and share resources while reducing the traffic load to the ground. The ISL assist in performing advanced functions including distributed processing and autonomous applications. By utilizing the ISL in maintaining the relative distance between the satellites, navigation, and positioning accuracy is improved greatly. The ideology proposed here is to implement remote modifications in inter-satellite communication after launch using Software Defined Radios (SDRs), while accommodating an adaptive autonomous small satellite network. Remote upgrades from the ground as well as the potential to accommodate new applications and future services without hardware changes is very promising. Software defined radio-based implementation of an ISL can assist in enabling an adaptive and reconfigurable communication system, which can achieve higher data rates and modification of frequencies. In this paper, we designed and implemented a multi-user inter-satellite communication network using SDRs, where Code Division Multiple Access (CDMA) technique is utilized to manage the multiple access to shared communication channel among the satellites. This research is the first work to study and implement the utilization of SDRs for inter-satellite communications in small satellite systems.**

I. Introduction

In the upcoming years, space observation will have seen a decline in cost and size of satellites, given the growing interest in replacing or enhancing large satellites by much smaller satellites. The current usages of small satellites are attractive due to reduced development time, more frequent launch opportunities, larger variety of missions, more rapid expansion of the technical and/or scientific knowledge base, and greater involvement of small industries and universities [1]. Small satellites are categorized into several classes based on their mass. For instance, a nano-satellite is less than 10 Kg in mass and a pico-satellite is less than 1 Kg in mass [2]. CubeSats are small satellites that have been designed, built, and launched by various universities and researchers due to its size, development cost, and cost to launch. Their dimensions are based on a 10 cm x 10 cm x 10 cm cube (1 U) and can be configured in the following way: 1U, 2U, 3U, or 6U. Total launch cost for small satellites are under a few million dollars in comparison to $200-1000 million for a full-sized one [3], [4].

Instead of using a single large satellite, various smaller satellites are being deployed in a constellation or clusters for various distributed space science missions because of their potential to perform co-ordinated measurements of remote space. This helps to provide greater spatial and temporal resolution of the target. Examples of multiple satellite missions with inter-satellite communications are Iridium, Orblink, Teledesic, PROBA-3 and Edison Demonstration of Smallsat Networks (EDSN) mission [5]. However, there are several constraints that limit the applications of small satellites both at the transmitting and receiving end, for example, limited power, mass, antenna size, on board resources, and computing capabilities, and intermittent communication links. The main issue with small satellites is the power consumption. With enough power available, the small satellite can support high frequency inter-satellite links ranging from 30 MHz (VHF) to even 40 GHz (Ka band) for transmission and reception [1]. Currently small satellites are utilizing the UHF/VHF and S bands for this purpose.

Large number of small satellites can be deployed in various configurations which fall into the general class, Distributed Space Systems (DSS). The most common types of these formations are: trailing or leader-follower, cluster, and constellation [6]. Fractionated spacecrafts and satellite swarms are the new cutting edge technologies for future space missions, which are also subsets of the DSS [7], [8]. Various small satellite configurations including clusters, constellations, and swarms can provide affordable solutions to perform scientific and technological missions. As objectives of these missions become more ambitious, we still have to address numerous issues such as supporting multiple signals and increasing data rates over reliable inter-satellite and ground links to Earth. Also, as the number of cubesats orbiting the Earth is increasing, there is a shortage of available frequencies leading to further regulatory issues. The dynamic nature of the space environment may lead to failure of nodes or change in network topology and hence the overall architecture should adapt according to the change in system dynamics [9]. Existing communication systems cannot fully address these challenges. One of the possible strategies to solve these issues is by equipping satellites with a Software Defined Radio (SDR), which facilitates software implementations to enable an adaptive and/or reconfigurable communication system without changing any hardware devices or features.

Software Defined Radio is beginning to be used in small satellite communications for applications such as base stations. SDR is simply a system that implements all its baseband functionalities in software instead of having physical hardware components. The usage of SDR might be able to accommodate challenges simply by upgrading the software, when future frequency allocation changes. Increasing the frequency results in the reduction of the size and mass of the transceiver and antenna, and gain higher bandwidth needed for high data rate applications. In [1], a new SDR architecture for small satellites is proposed to utilize a combination of Field Programmable Gate Array (FPGA) and field programmable Radio Frequency (RF) transceiver to solve back-end and front-end challenges and thereby enable reception of multiple signals or satellites using single user equipment. SDR technologies can provide adaptive radios, cognitive radios, and intelligent radios with the flexibility necessary for them to achieve their full potential, the benefits of which can help reduce cost and increase system efficiencies [1].

The implementation of DS-CDMA in SDR has been studied for years. In [10], the authors provide an SDR solution to provide flexibility and handle the processing speeds required of 3G receivers. However, the study of this implementation in small satellite communications has not been done. In this paper, we provide a practical solution for adaptive multi-user inter-satellite communications in a network of small satellites using software defined implementation of Direct Sequence Code Division Multiple Access (DS-CDMA) technique. The Inter-Satellite Communication (ISC) system largely depends on the design of the Multiple Access Control (MAC) protocol. The basic function of the MAC protocol is to avoid collision by arbitrating the access of the shared medium among the nodes in the network [5], [11], [12]. There are two different types of MAC protocol: contention based and collision free protocols. Numerous contention based protocols have been proposed in the literature, for example, ALOHA, CSMA (Carrier Sense Multiple Access), BTMA (Busy Tone Multiple Access), ISMA (Idle Signal Multiple Access), etc. The collision free protocols ensure that collision of data packet never occurs. Some of the basic protocols of this type are TDMA (Time Division Multiple Access), FDMA (Frequency Division Multiple Access) and CDMA (Code Division Multiple Access) [13]. Authors in [14], [15] propose to use Carrier Sense Multiple Access (CSMA) with Request-to-Send and Clear-to- Send protocol (CSMA/CA/RTS/CTS) for various formation flying patterns of small satellites. However, it is concluded that this protocol cannot be used for missions that require real to near real-time communication between the satellites [14]. We propose to use collision free protocols in particular DS-CDMA since it addresses the design needs of a large scalable network and provides high throughput. Frequency Division Multiple Access (FDMA), in which the radio spectrum is divided among different users, is not an economic choice for inter-satellite communication, as it requires a wide bandwidth [5].

Time Division Multiple Access (TDMA) restricts fixed time slots to each user and has strict timing synchronization; hence it is not a practical option for heterogeneous small satellites networks with various data transmission rates and also simultaneous transmission at different times. Also, as TDMA systems become more crowded, the lock-up time becomes a significant portion of the total available time, thus corresponding to an overall reduction in system data throughput. For future space missions, small satellites may be deployed in different phases in order to accomplish a mission objective, for instance, the FORMOSAT-7/COSMIC-2 [16] is a Taiwan/USA project, which is scheduled to launch in two phases in 2016 and 2018. This will use a constellation of 12 small satellites to collect meteorological and ionospheric data with better precision with respect to FORMOSAT-3/COSMIC-1. Hence, in a large and scalable small satellite network, for a TDMA system, the master satellite may not have the power to cover the entire system. Each satellite in the network has a predefined slot. Thus it may be difficult to allocate time slots for the satellites joining the network at a later stage. Also, the small satellite network may have unexpected failures. Considering all these objectives CDMA is chosen for this project because it enables multiple users to transmit simultaneously using their own Pseudo Random Noise (PRN) codes or their truly orthogonal codes [5].

A CDMA system has several limitations such as cross correlation and the near-far effect. Cross correlation results from the non-perfect orthogonal PRN codes. This will cause multiple access interference which can be avoided by restricting the number of satellites in each cluster [9]. The near-far effect can be mitigated by appropriate power control mechanism. The suggested protocol requires strict time synchronization which can be achieved by using GPS/GNSS clock or clock synchronization in conjunction with a highly accurate on-board clock.

In this paper, we propose a novel inter-satellite communication model for a network of small satellites based on implementing a CDMA protocol in GNU Radio. The performance of this model has been evaluated and compared for different modulation (BPSK and QPSK) and channel coding techniques (un-coded and convolutional coding). In this work, we used an open source hardware and software to make it adaptable for other researchers to utilize this system in their projects. This model can be easily reconfigured to support any encoding/decoding, modulation, and other signal processing schemes. To the best of the authors knowledge, this is the first work to study implementation of CDMA with SDRs for inter-satellite communications in a network of small satellite systems.

This paper is organized as follows: Section II presents a brief introduction on SDRs and describes the hardware and software being used in this paper. Section III describes the targeted design parameters for the system and implementation of the CDMA system in SDR. Section IV discusses the results of this work and a synopsis of this research is put forth in Section V, the Conclusion.

II. BACKGROUND INFORMATION

A. Software Defined Radio

Software Defined Radio was firstly introduced to enable new features and capabilities to existing infrastructure without requiring major new capital expenditures. For end users, from business travelers to soldiers on the battlefield, SDR technology aims to reduce costs in providing access to ubiquitous wireless communications.

Tethers Unlimited SWIFT-RelNav [17] is a SDR RF-based system that provides relative range and attitude determination capabilities as well as inter-satellite communications. The SDR RelNav provides range sensing between satellites to better than 10 cm accuracy, inter-satellite crosslink data rates at $\geq 12\ Mbps$, Bit Error Rates of $< 10^{-6}$, and timing/frequency synchronization to better than $1ns$, $0.1\ ppb$. The SDR application in the ISL enables this system to perform ISL communication up to 10 km in range [17].

Traditional radios consist entirely of specialized hardware. Despite them employing software to handle certain internal operations such as control of the analog to digital components, a majority of the signal processing resides in the hardware domain. The overall idea of SDR is to move the hardware-software boundary as close as possible to the antenna, as illustrated in Figure 1. Nearly all the baseband signal processing on both the transmission and receiving ends is performed in the software domain. In summary, the ultimate software defined radio would be lightweight, consume very little power, require no external antenna [18], accepts fully programmable traffic, support broad range of frequencies, and configure itself.

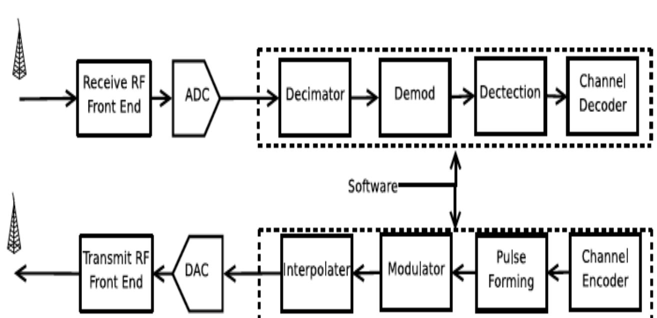

Figure 1: Block diagram of a typical software defined radio system

B. USRP & GNU Radio

The Universal Software Radio Peripheral, also known as USRP, is a flexible open source and low cost platform for SDR. The USRP N210 model in this study consists of a motherboard with a Xilinx Spartan 3A-DSP 3400 FPGA and operates from 0 to 6 GHz. Interfacing is achieved with the PC using a Gigabit Ethernet. The architecture includes a 100 MS/s dual ADC sample rate, 400 MS/s dual DAC sample rate, and the USRP N210 can stream up to 50 MS/s to and from host applications. The chosen RF front end, known as the daughter board, for this research is the SBX daughterboard. This transceiver supports up to 100 mW of output power, noise figure of 5 dB, and a 400-4400 MHz range.

GNU radio serves as the simulation tool, in conjunction with the USRP, to better understand the workings of the existing/generated filters, demodulators, and other processing blocks. The wide usage of GNU radio in several research studies, including NASA has made it favorable. GNU Radio is an open-source initiative, where signal processing is carried out on GPP computers. GNU radio is adapted to the Universal Serial Radio Peripheral (USRP), which converts between base band and RF signals.

III. PROPOSED IMPLEMENTATION

In this section, we first describe the proposed small satellite network and the corresponding communication design parameters, followed by a description of the proposed inter-satellite communication technique using the SDR test-bed.

A. Design Parameters

In this paper, we address the intersatellite communication among a cluster of small satellites operating in LEO orbits. The corresponding design parameters are summarized in Table I. Each cluster consists of 3 satellites. Each cluster, operating in a formation-flying pattern, employs a distributed mesh topology. In the case of a satellite failure, it can be replaced by another satellite. An orbital velocity of 3 km with the separation distance between satellites in different orbits to be no wider than 3 Km is chosen as well. S-band is chosen as the frequency for the ISL due to achievable high data rates, which in turn assists in the satellites exchange of data faster. The transmission range of the ISL is said to be between 10-20 Km with data rates of 3-8 Mbps. We assume an acceptable transmission delay of 150-300 ms with 100,000 numbers of packets to be simulated. Typically a 1U CubeSats maximum power budget range is from 1 to 2.5 Watts (W), while the 2U is 2W to 5W. The USRP N210 FPGA consumes 1 to 2.5 Watts; therefore, we choose the transmission power to range from 500mW to 3W. System performance of the proposed satellite network using CDMA is investigated with BPSK and QPSK modulation over Additive White Gaussian Noise (AWGN) and Rayleigh fading channels.

At the transmitter, the data is generated from a vector random source and modulation is done by either BPSK or QPSK to map the bits to symbols. The model follows a synchronous system, therefore a Walsh Hadamard code is employed for our system using an 8 length code sequence, thus giving the system the ability to handle 8 different users at a given time. The data rate employed is 500 Kbps which results in a chip rate of 4,000 Kchips/s. The carrier frequency for the test bed is 2.4 GHz, S-band. AWGN and Rayleigh Fading channels are observed in this research in the case of CSI being known at the receiver.

TABLE I: System Parameters

Design Parameters	Value
Transmission Power for TX	500 mW -3W
Transmission Power for RX	200 mW - 500 mW
Frequency	S Band/ISM 2.4 GHz
Orbit Altitude	LEO (300 km - 500 km)
Number of Orbital Planes	3 possibly (300 - 500 altitude)
Orbit Shape	Circular (Polar)
Orbit Velocity	3 Km
Topology	Distributed Mesh
Separation Distance Between Satellites in Different Orbits	No wider than 3 km
Number of Satellites per Cluster	3
Number of Clusters	3 - 5
ISL Transmission Range	10 Km - 20 Km
ISL Data Rates	3- 8 Mbps
Acceptable Transmission Delay	150- 300 ms
Number of Packets	100,000

B. Code Division Multiple Access

Code Division Multiple Access (CDMA) is a spread spectrum technology, in which a user is assigned a unique pseudo-random code. In order to improve anti-interference capacity of the satellite communication system, the data communication mostly adopts Direct Sequence Spread Spectrum (DSSS) [19], also called DS-CDMA. In the DS-CDMA, the data signal is directly multiplied by the code signal and modulates the wide band carrier. For a wider bandwidth signal, the chip rate of the code signal has to be much more than the information. The received signal is de-spread using locally generated code, which must be synchronized to the code sequence of the received signal. The synchronization should be achieved at the beginning of the received signal and has to be maintained throughout.

Figure 2 shows the multiple users employing a DS-CDMA system. The use of a DS-CDMA link for multiple access in an autonomous constellation is desirable as these links can provide resistance to intentional jamming, mask the transmitted signal in the background noise to prevent eavesdropping, provide resistance to degrading and multipath effects on the signal, and also provide range-measuring capability.

C. System Description

This SDR CDMA module is intended to build a parameterized CDMA physical layer for usage in GNU Radio. The spreading, modulations, framing parameters, etc. are set by the user, from a global parameter file, thus making the module reconfigurable. The source payload is a repeated random vector with a block, which produces the CDMA frames.

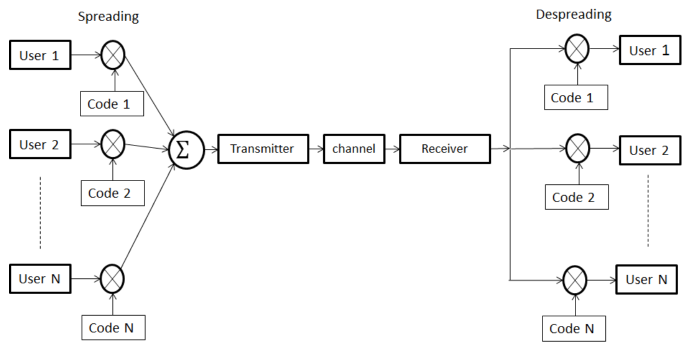

Figure 2: The CDMA System

A channel model, of the users choice, is used to simulate the channel with frequency offset and time delays. At the receiver, a block takes the received samples as input. The received samples are de-spread and demodulated to produce the original signal.

1) Transmitter Block Diagram: Figure 3 shows the CDMA transmitter hierarchical block. In the CDMA system, the input is payload bytes (0 to 255 per byte), which is then CRC coded. Header bits are generated from the coded payload streams and modulated by BPSK or QPSK. Coded payload bytes are repacked to symbols representing m bits, which is the number of bits per symbol for the modulation type, and modulated using a 2^m-ary modulation. Modulated header and payload streams are then multiplexed. The multiplexed payload stream is spread by the spreading code sequence and scaled appropriately. The training symbols are also spread by a code sequence (orthogonal to the first spreading code) and scaled accordingly. The two channels are superimposed to form a frame to be transmitted. From this flowgraph we construct a block, which is used as part of the flowgraph connection for the overall transmitter system. The overall transmitter flowgraph system includes the source payload, the ”cdma_tx_hier” block, which produces the CDMA frames, the channel model to simulate channel, tags, and the USRP sink block.

2) Receiver Block Diagram: For the receiver, the ”cdma_rx_hier” flowgraph, when compiled, forms the ”cdma_rx_hier” block. Outside of the block contains the USRP source, which receives the spread signal that gets inputted to the ”cdma_rx_hier” block. Here the beginning of the frame is acquired as well as the frequency offset. The received samples are frequency corrected, input to matched filters, de-spread, phase estimated by a PLL, de-rotated, demodulated, and finally the data symbols are CRC decoded.

D. Bit Error Rate

The Standard Gaussian Approximation method [20] is utilized in to calculate the BER performance for a synchronous

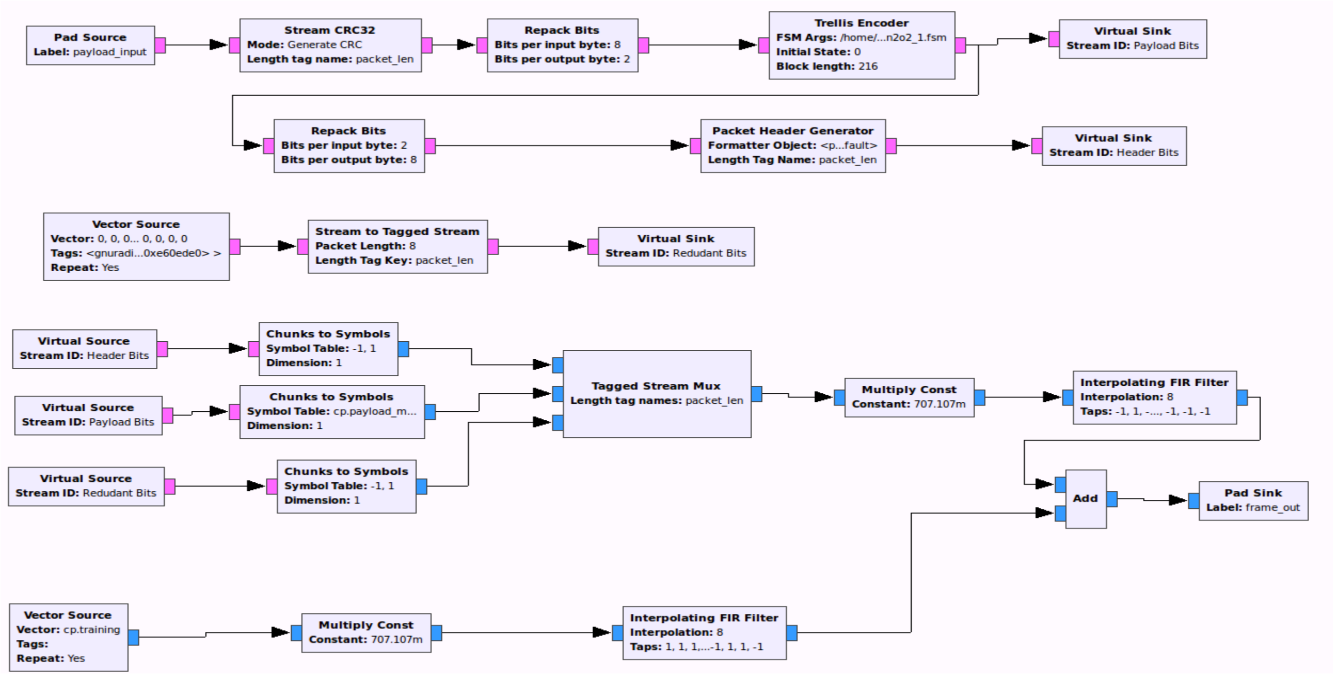

Figure 3: Block diagram of hierarchical transmit block

binary DS-CDMA system operating in AWGN and slow Rayleigh fading channel as follows in (1) and (2), respectively:

$$BER = Q\left(\sqrt{\frac{1}{\frac{K-1}{3G_p}} + \frac{N_0}{2T_bP_0}}\right) \tag{1}$$

K represents the number of users, G_p is the process gain, N_0 is the thermal noise power spectral density, T_b is the bit duration, and P_0 is the transmitted power of desired user. When considering a slow Rayleigh fading channel, it is expressed by [20]:

$$BER = Q\left(\sqrt{\frac{1}{\frac{1}{3G_p}\sum_{k=1}^{K-1}\frac{P_k}{P_0}\frac{\alpha_k^2}{\alpha_0^2} + \frac{N_0}{2T_bP_0\alpha_0^2}}}\right) \tag{2}$$

in which P_k is the power of the transmitted signal, α_0 is the path gain component from user of interest and α_k path gain component with Rayleigh distribution.

IV. RESULTS & ANALYSIS

In this section, the BER performance of our proposed test-bed is first validated and compared to the analytical results for two users. The BER performance is then tested for 1, 2, 5, and 7 users. The transmission power is 2 Watts. At the transmitter, the data is generated from a vector random source and modulated by either BPSK or QPSK to map the bits to symbols. The DS-CDMA model follows a synchronous system, therefore Walsh Hadamard codes are employed. The model uses 8 chips per symbol as the spreading code with a rectangular chip signal. The data rate employed is 500 Kbps, which results in a chip rate of 4,000 Kchips/s. The carrier frequency for the test bed is 2.4 GHz with a Doppler frequency of 3.846 kHz. Additive White Gaussian Noise (AWGN) and Rayleigh Fading channels are observed in this study. It is assumed that the receiver has perfect knowledge of the channel condition.

A. BER BPSK/QPSK Performance of DS-CDMA on AWGN and Raleigh Channel for 2 Users

In this paper, an adaptive and re-configurable inter-satellite communication for a network of small satellites is implemented with SDRs. Figure 4 shows the simulated and theoretical BER performance for a two-user case with BPSK and QPSK modulation over AWGN and Rayleigh fading. The performance of DS-CDMA in terms of bit error rate is observed in AWGN and Rayleigh Fading channels for a two-user system sending 100,000 bits on the channel. The users data are spread using two Walsh codes of length 8 that are orthogonal and have good autocorrelation properties. The signal is then modulated by Binary Phase Shift Keying (BPSK) modulation. Figure 4 demonstrates the accurate performance of the implemented test-bed in terms of BER close to the analytical results.

B. BER BPSK/QPSK Performance of DS-CDMA on AWGN and Raleigh Channel for multiple users

Figure 5 shows the simulated and theoretical BER performance for a multi-user case with only QPSK modulation over AWGN and Rayleigh fading. DS-CDMA performance effect on AWGN and Rayleigh Fading Channel for a multi user system sending 100,000 bits on the channel is observed for

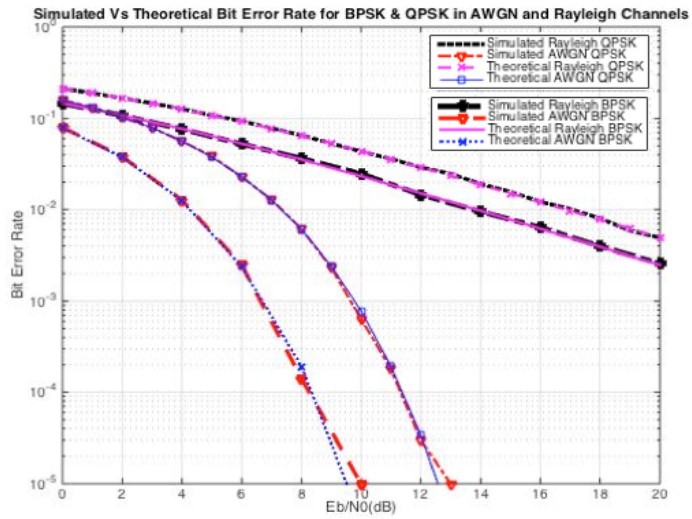

Figure 4: Performance of DS-CDMA BPSK and QPSK modulation in AWGN and Rayleigh environment

1, 2, 5, and 7 users. The results indicate that the bit error rate directly varies with the number of users, whereby increasing the number of users increases the bit error rate.

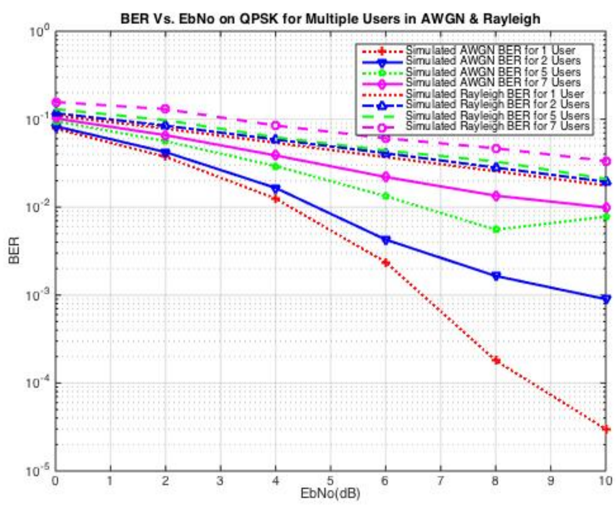

Figure 5: Performance of DS-CDMA QPSK modulation in AWGN and Rayleigh environment for multiple users

V. CONCLUSION

The performance of DS-CDMA as the best multiple access technique for simultaneous transmissions in a cluster of small satellites is analyzed and validated in this test-bed for various number of users and different communication channels. This package can be adapted in different missions with most desirable communications properties as the despreading module has the ability to change the acquisition threshold and users have the ability to enable manual or auto choosers for the tracking/acquisition of the signal. The results show the promising performance of this testbed in terms of the BER comparing to the theoretical ones.

VI. ACKNOWLEDGMENT

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REFERENCES

[1] M. Maheshwarappa and C. Bridges, "Software Defined Radios for Small Satellites," in *Adaptive Hardware and Systems (AHS), 2014 NASA/ESA Conference on*, July 2014, pp. 172–179.

[2] Mission Design Division Staff, "Small Spacecraft Technology State of the Art," NASA Ames Research Center, Tech. Rep.

[3] Aviation Week. [Online]. Available: http://aviationweek.com/awin/boeing-unveils-air-launched-space-access-concept

[4] Cooltools. [Online]. Available: http://kk.org/cooltools/archives/7419

[5] R. Radhakrishnan, W. W. Edmonson, F. Afghah, J. Chenou, R. M. Rodriguez-Osorio, and Q. A. Zeng, "Optimal Multiple Access Protocol for Inter-satellite Communication in Small Satellite Systems," in *The 4S Symposium, 2014*.

[6] ESA Navipedia. [Online]. Available: http://www.navipedia.net/index.php/Satellite_Formation_Flying

[7] P. P. Sundaramoorthy, E. Gil, and C. J. M. Verhoeven, "Systematic Identification of Applications for a Cluster of Femto-satellites," in *61st International Astronautical Congress, 2010*.

[8] W. Edmonson, S. Gebreyohannes, A. Dillion, R. Radhakrishnan, J. Chenou, A. Esterline, and F. Afghah, "Systems engineering of inter-satellite communications for distributed systems of small satellites," in *Systems Conference (SysCon), 2015 9th Annual IEEE International*, April 2015, pp. 705–710.

[9] R. Sun, J. Guo, E. Gill, and D. Maessen, "Potential and Limitations of CDMA Networks for Combined Inter-satellite Communication and Relative Navigation," *International Journal on Advances in Telecommunications*, vol. 5, no. 1 and 2, pp. 21–32, 2012.

[10] I. Seskar and N. B. Mandayam, "Software-defined radio architectures for interference cancellation in ds-cdma systems," *Personal Communications, IEEE*, vol. 6, no. 4, pp. 26–34, Aug 1999.

[11] F. Afghah, A. Razi, and A. Abedi, "Stochastic game theoretical model for packet forwarding in relay networks," *Springer Telecommunication Systems Journal, Special Issue on Mobile Computing and Networking Technologies*, vol. 52, no. 4, pp. 1877–1893, 2013.

[12] ——, "Throughput optimization in relay networks using markovian game theory," in *Wireless Communications and Networking Conference (WCNC), 2011 IEEE*, March 2011, pp. 1080–1085.

[13] D. P. Agarwal and Q. A. Zeng, *Introduction to Wireless and Mobile Systems*. USA: Thomson Learning, 2010.

[14] R. Radhakishnan, Q. A. Zeng, and W. W. Edmonson, "Inter-satellite Communications for Small Satellite Systems," *International Journal of Interdisciplinary Telecommunications and Networking*, vol. 5, no. 3, pp. 11–24, 2013.

[15] R. Radhakishnan, W. W. Edmonson, and Q. A. Zeng, "The Performance Evaluation of Distributed Inter-satellite Communication Protocols for Cube Satellite Systems ," in *The 4th Design, Development and Research Conference, Capetown, South Africa, 2014*.

[16] A. Curiel and et al., "Introduction to FORMOSAT-7/COSMIC-2 Mission," in *Small satellite constellations: Strength in numbers, 27th Small Satellite Conference, 2013*.

[17] SWIFT. [Online]. Available: http://www.tethers.com/SpecSheets/Brochure_SWIFT-RelNav

[18] M. Wolf, *High-Performance Embedded Computing, Second Edition: Applications in Cyber-Physical Systems and Mobile Computing*. Elsevier Inc.

[19] J. Zheng and A. Jamalipour, *Wireless Sensor Networks; A Networking Perspective*. New Jersey, USA: A John wiley and Sons, inc., 2009.

[20] E. Falletti, F. Vipiana, and R. Cigno, "On SIR and BER Approximation in DS-CDMA System," Contratto CSP-Omnitel UMTS, Tech. Rep.