Adaptive Coding and Modulation Experiment with NASA's Space Communication and Navigation Testbed

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National Aeronautics and Space Administration (NASA)'s Space Communication and Navigation Testbed is an advanced integrated communication payload on the International Space Station. This paper presents results from an adaptive coding and modulation (ACM) experiment over S-band using a direct-to-earth link between the SCaN Testbed and the Glenn Research Center. The testing leverages the established Digital Video Broadcasting Second Generation (DVB-S2) standard to provide various modulation and coding options, and uses the Space Data Link Protocol (Consultative Committee for Space Data Systems (CCSDS) standard) for the uplink and downlink data framing. The experiment was conducted in a challenging environment due to the multipath and shadowing caused by the International Space Station structure. Several approaches for improving the ACM system are presented, including predictive and learning techniques to accommodate signal fades. Performance of the system is evaluated as a function of end-to-end system latency (round-trip delay), and compared to the capacity of the link. Finally, improvements over standard NASA waveforms are presented.

I. Introduction

Adaptive coding and modulation (ACM) is a method to increase the overall throughput, efficiency, and reliability of a communication system by dynamically changing the modulation and forward error correction in response to the measured link conditions. When link conditions are favorable, high-order modulations and forward error correction schemes with minimal overhead are used to maximize the data transfer. Conversely in poor link conditions, robust modulation and coding are used to maintain the link, but at reduced throughput. ACM relies on a feedback path to relay channel state information back to the source. This is in contrast to a variable coding and modulation (VCM) approach, which has no feedback and uses pre-determined modulation and coding based on predicted link conditions. Previous VCM experiments[1] with the SCaN Testbed demonstrated a substantial improvement in total throughput compared to standard NASA waveforms with constant modulation and coding. This experiment is an extension to the VCM approach and seeks to further improve the reliability and efficiency of the communication link with ACM.

The second generation Digital Video Broadcasting for Satellites (DVB-S2) standard[2] is primarily used within the telecommunications industry for video broadcast and Internet services. However, it also has potential applications to spacecraft telemetry due to flexible modulation and encoding options. Within NASA, Cubesats are one possible application for DVB-S2, due to the bandwidth-limited channel and an increased desire for science data return.[3] Furthermore, the standard already includes a provision for ACM, which enables a spacecraft to automatically adapt to dynamic link conditions, such as varying path loss,

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noise, interference, pointing errors, and obstructions. The Consultative Committee for Space Data Systems (CCSDS) has recommended a method of using the DVB-S2 standard that accommodates the preferred Space Data Link Protocol for spacecraft telemetry.[4] The feedback path and protocol for relaying channel state information for ACM is not standardized by DVB-S2 or by the CCSDS standards, and is left to the mission to decide. A method of feedback which uses optional control fields in the Space Data Link Protocol is presented in this work.

This paper describes an ACM experiment using a space-based software-defined radio (SDR) transceiver on-board the Space Communication and Navigation (SCaN) Testbed on the International Space Station (ISS). Running the experiment on ISS allows the investigation of real-world link interference scenarios that arise in direct-to-ground links. Secondly, this test provides an opportunity to demonstrate how an ACM system could be integrated and operated within a typical ground station. Round-trip delay is an important consideration for the ACM feedback path, especially for a highly dynamic link. The feedback loop could either be closed at the ground station, or at the mission operations center. Careful consideration is needed when adding additional network delay to an ACM system, as the increased round-trip delay can reduce the ability to track signal fades.

The rest of this paper is organized as follows. In Section II the overall scenario is described. In Section III the key system components are explained, including the space and ground segments. Results from flight experiments with SCaN Testbed are summarized in Section IV. Next, possible approaches for improving the ACM system are presented in Section V. Finally, future work and conclusions are in Sections VI and VII.

II. Test Scenario

The National Aeronautics and Space Administration (NASA) Space Communications and Navigation (SCaN) Program is responsible for providing communications and navigation services to space flight missions throughout the solar system. The SCaN Testbed is an advanced integrated communications system and laboratory installed on the ISS, and has been operating experiments with multiple software defined radios (SDRs) since 2012.[6,7] The SDRs are reprogrammable and can run reconfigurable waveform applications.[8] Figure 1 shows the payload enclosure and the various antenna locations and each of the three software defined radios. There are five antennas around the system; three S-band, one Ka-band, and one L-band (Global Positioning System (GPS)). This experiment utilizes the Jet Propulsion Laboratory (JPL) / L3-Cincinnati Electronics SDR, and the S-band Near-Earth Network low gain antenna.

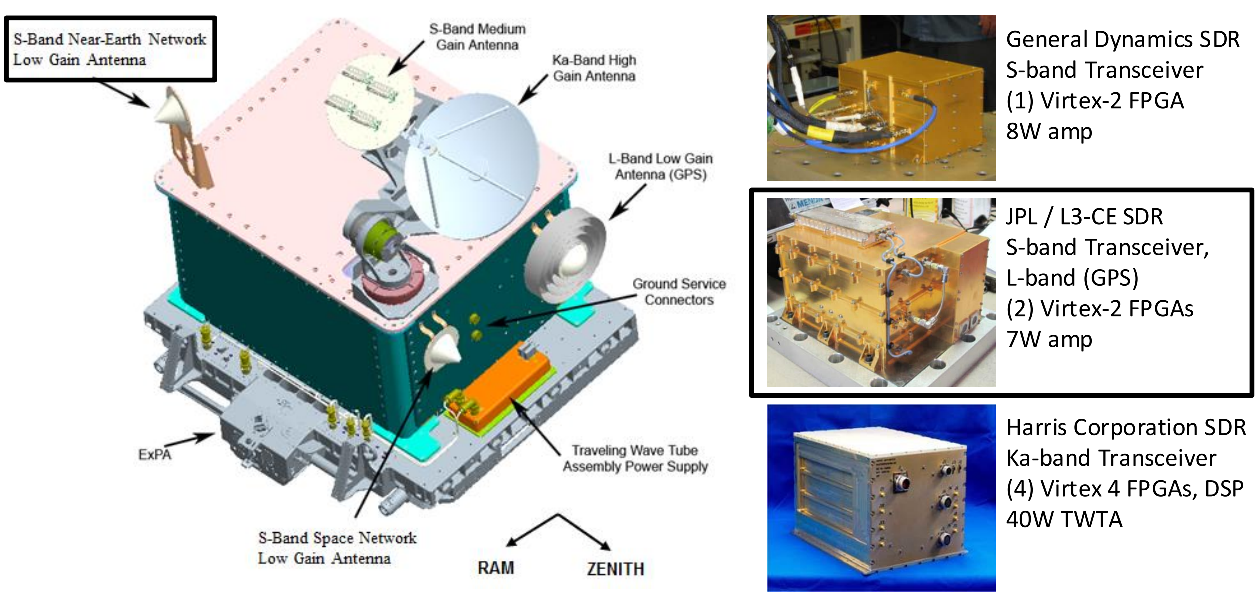

Figure 1. SCaN Testbed

For this experiment, a direct-to-Earth communications link from the SCaN Testbed to the Glenn Research Center (GRC) Ground Station (GRC-GS) was used, as Figure 2 illustrates. The GRC-GS is an experimental S-band ground station with a steerable, 2.4 m dish antenna. The JPL SDR, loaded with a DVB-S2 waveform, transmits over S-band to the ground station and the signal is received with a commercial DVB-S2 receiver. A custom decision algorithm on the ground determines the appropriate modulation and coding (MODCOD) for the given channel conditions, and provides this information to a binary phase shift keying (BPSK) transmitter for the uplink feedback path. When the SCaN Testbed is on the horizon and the path loss is the greatest a robust modulation is used, such as quadrature phase shift keying (QPSK) with a rate 1/4 code. As SCaN Testbed passes over the ground station, the signal-to-noise ratio (SNR) is maximized and permits high-order modulations to be used, such as 16- or 32-amplitude phase shift keying (APSK) with a rate 8/9 code. The SCaN Testbed flight computer controls and monitors the experiment via a separate ISS communications path through the Tracking and Data Relay Satellite System (TDRSS).

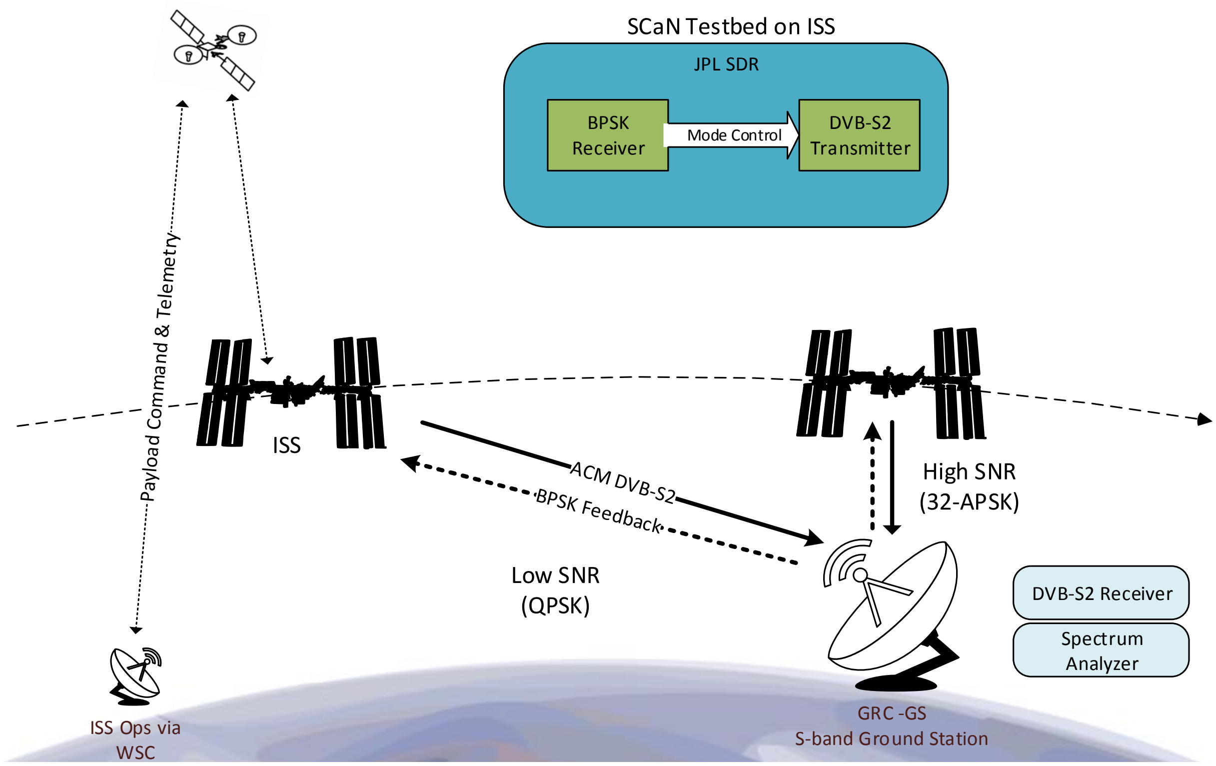

Figure 2. Test Scenario.

In addition to the varying path loss, this scenario also provides for a highly dynamic link due to shadowing/obstruction losses, and multipath effects from the complex ISS structure. Antenna pointing losses due to elevation angle restrictions also impact the link. These effects are described in more detail in Ref. 1, 11. ACM techniques will be evaluated as a method of counteracting these impairments.

III. System Description

A. DVB-S2 Downlink Waveform

The DVB-S2 standard defines a set of modulation and coding options, designated MODCODs, which include QPSK, 8-PSK, 16-APSK, and 32-APSK. The forward error correction consists of a Bose-Chaudhuri-Hocquenghem (BCH) outer code and a Low Density Parity Check (LDPC) inner code, with code rates between 1/4 to 9/10. A key feature of the DVB-S2 standard which is different than most communication systems used by NASA is the inclusion of a Physical Layer (PL) frame structure. The PL header is $\pi/2$-BPSK modulated and is used to identify the MODCOD of the frame, which can vary between each subsequent frame. The receiver reads the PL header and configures the demodulator and decoder appropriately.

Changes between different MODCODs are done on a frame by frame basis with no loss of data. In contrast to Variable Coding and Modulation (VCM), the ACM waveform accepts real-time configuration changes from the feedback channel receiver in addition to the SDR's general purpose processor (GPP). Figure 3 shows the functional components that comprise the downlink waveform and its various inputs.

Table 1 summarizes the waveform capabilities that were developed for the JPL SDR. Only the DVB-S2 short frames, which have n=16200 bits per frame, are implemented in this experiment. Short frames were selected to minimize complexity and to reduce latency. DVB-S2 pilots were enabled for improved acquisition and tracking performance. See Ref. 1 for additional details on the waveform application.

Table 1. Waveform Summary

Module	Description
Data Source	External, or PRBS-23
Baud Rates	0.1 - 6.125 Mbaud
Framing	CCSDS 732.0-B-2
Randomization	CCSDS 131.0-B-2
Forward Error Correction	BCH+LDPC, Effective rates 0.18 to 0.87 (Short Frames)
Modulation	QPSK, 8-PSK, 16-APSK, 32-APSK
Pulse-shape Filter	Square-Root Raised Cosine, $\alpha = 0.2, 0.25, 0.35$
	Memory-less (Look-up Table and Symbol Position)

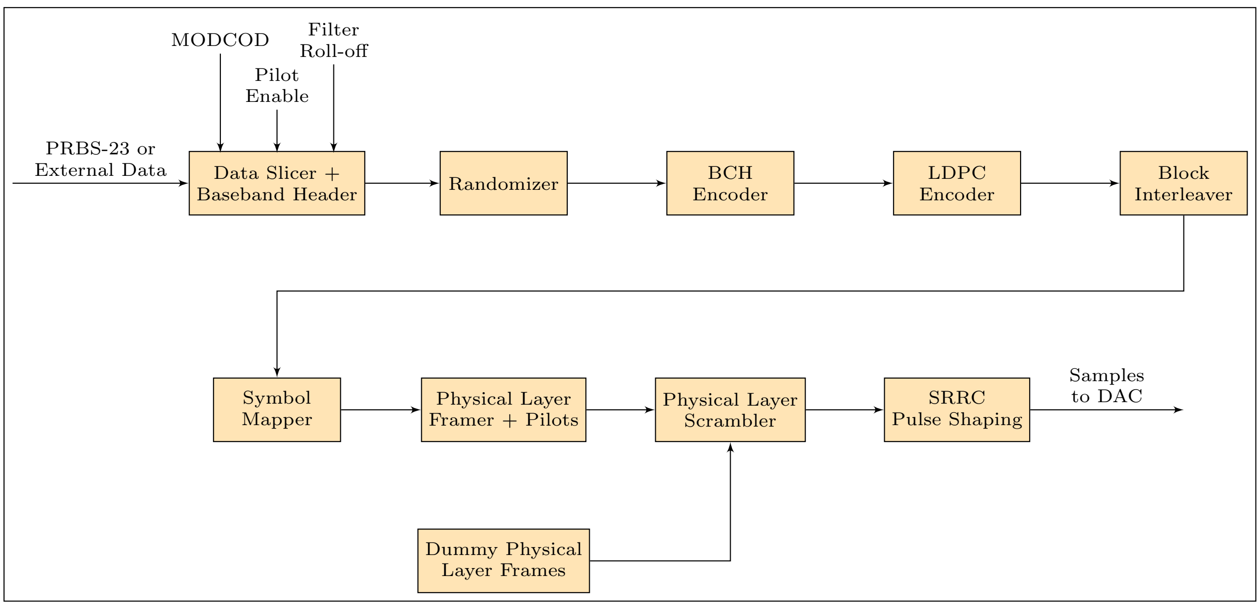

Figure 3. DVB-S2 Waveform Processing Functions

The GRC-developed waveform and the JPL SDR platform are compliant with the Space Telecommunications Radio System (STRS) standard, an open architecture standard for SDRs.[12] The waveform application is available for future mission re-use via the STRS waveform repository.[13]

B. BPSK Feedback Waveform

The Glenn Goddard TDRSS (GGT) Waveform was previously developed for the JPL SDR and is available via the STRS repository.[13] This experiment exclusively uses the 155.346 kbps mode with rate 1/2 convolutional code. The ACM feedback commands are implemented using the frame structure defined in the AOS Space Data Link Protocol.[10] The Operational Control Field (OCF) of the Transfer Frame (TF) trailer is used to send the MODCOD, pilot enable, and pulse shape filtering settings from the ground system to the flight SDR. Figure 4 shows the formatting for the OCF usage.

On-orbit, the received commands are sent to the DVB-S2 transmitter if, and only if, the Frame Error Control Field's error detection syndrome is zero. Once new operational parameters are received, they are

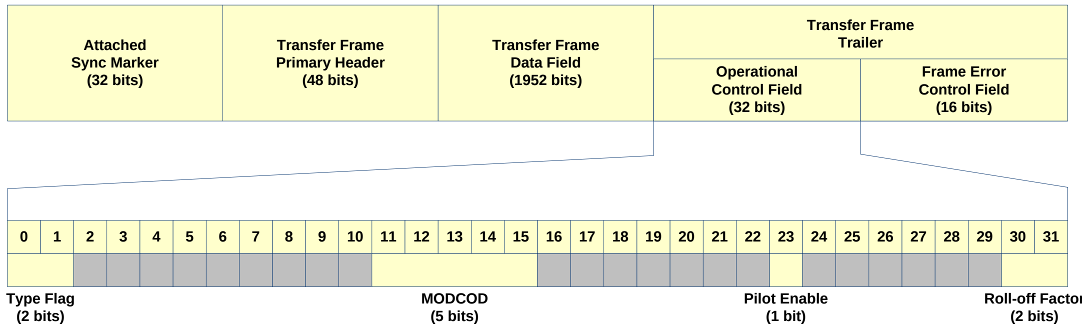

Figure 4. OCF Field for Feedback.

applied to the next available PL frame. Since the bitrate is 155.346 kbps and the AOS frame length is 2080 bits, the effective update rate of the feedback channel is approximately 75 Hz. Additionally, since only 1952 bits of each frame are available for user data, this protocol has a framing overhead of approximately 6.2 percent. Lastly, the pulse shape filter roll-off (RO) is determined as a function of symbol rate. Since the allowed licensed bandwidth is fixed at 5 MHz, higher symbol rates must use a smaller pulse shape filter parameter ($\alpha = 0.2$).

C. Ground System and Adaptive Algorithm

In changing from VCM to ACM testing, the realtime MODCOD control moves from predetermined scripts executing in the JPL SDR on-orbit to a ground-based adaptive algorithm that determines transitions dynamically. As shown in Figure 5, the ground hardware components required for running ACM operations comprise of a ViaSat HI-BEAM DVB-S2 modem, a DekTec DTA-2137C PCI Express receiver card, a Windows-based workstation for all software applications, and a Field Programmable Gate Array (FPGA)-based development board with a BPSK transmitter waveform for the uplink. Ideally only one commercial DVB-S2 receiver would be needed, but a comparison of their performance was desired.

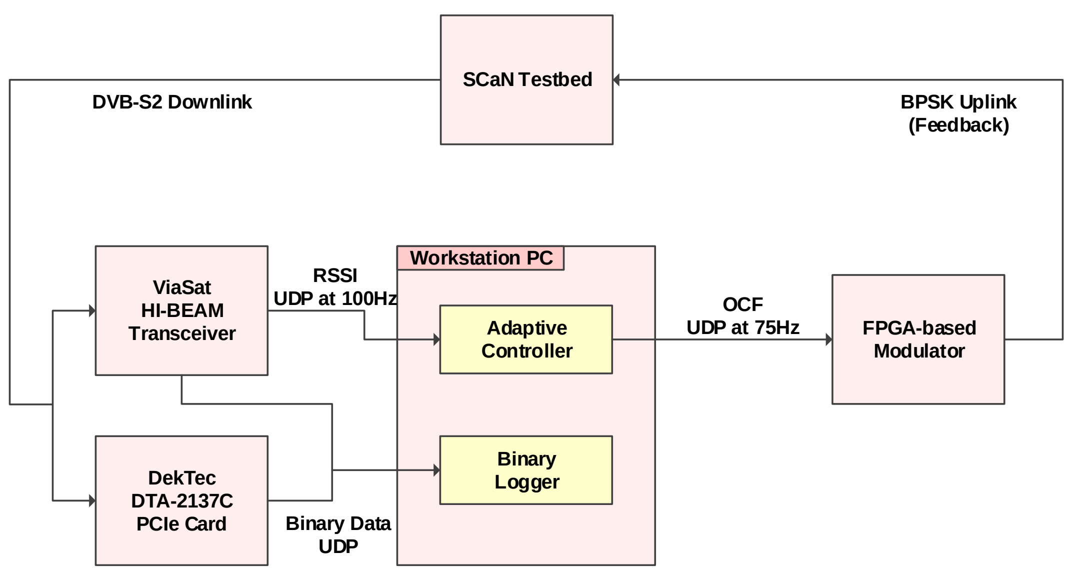

Figure 5. Adaptive Controller.

The ViaSat and DekTec receivers are run simultaneously on the DVB-S2 return signal, and both baseband frame streams are recorded for post-event playback and analysis. The ViaSat's Received Signal Strength Indicator (RSSI), sourced at 100 Hz over User Datagram Protocol (UDP) packets, is the sole input to the adaptive algorithm. Specifically, the adaptive algorithm software uses a modem characterization file that contains Es/N_0 thresholds above which the system operates in a quasi-error-free state (i.e., code word error rate of 1e-5). Each incoming RSSI value is compared against the thresholds (plus additional configurable margin), and the highest available MODCOD is selected so as to maximize spectral efficiency and maintain positive link margin. Finally, the rolloff factor and use of pilots can be configured pre-event, but are held static for the duration of the test.

Once the real-time parameters are determined, an OCF is created for each command using the selected MODCOD, in addition to roll-off and pilot settings. The OCF is then sent at 75 Hz as a UDP packet to the BPSK transmitter for ACM feedback, where it is appended to the simulated mission uplink data stream. Note that the feedback path closes at the ground station to eliminate any additional network delays to the mission operations center. The transfer frame (without OCF) could still originate externally without impacting the round-trip delay. Additionally, each ACM command is logged to a file for post event analysis.

D. Event Automation Software

The ground software components, which were all implemented in C or C++, required for operating an ACM event are comprised of a master coordination application, DekTec controller and data logger, ViaSat data logger, ACM algorithm, and real-time metric grapher. To simplify the process for running flight events and to eliminate preparation time, the experimenter uses a master coordination application, pictured in Figure 6, to automatically start, configure, and stop all of the ground applications at user-defined times for the test event. Note this is a significant improvement from the VCM process reported on in Ref. 1. After an initial pass through a MATLAB® script that aims to maximize throughput using projected event data, one of four symbol rates is selected: 1, 2, 3, or 4.55Msym/s.

Next, the experimenter selects the optimal symbol rate in the graphical user interface, along with any additional system margin that is desired – integer values between 0 and 9 dB. Additionally, the software that interfaces with the DekTec card does real-time AOS deframing and bit error rate testing, which gives the experimenter an indication of the status of the system and the current channel dynamics. Once starting the application, all subprograms are opened two minutes before the flight event, and are exited one minute after the flight event. Lastly, the metric graphing application provides a real-time visual representation of MODCOD, measured Es/No, and available margin that are provided by the ACM controller application (Figure 7).

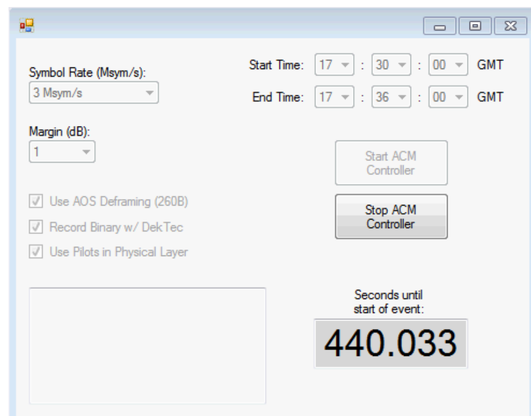

Figure 6. Event Coordination Application

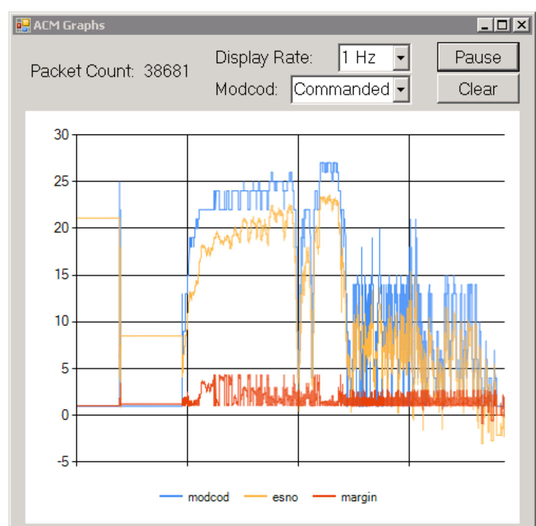

Figure 7. Real-time ACM Controller Plot.

IV. On-orbit Test Results

The following sections present the results of on-orbit testing with the SCaN Testbed. Testing was conducted in multiple phases, due to the cyclic nature of ground station contacts (events) which occur during first shift operations at the GRC control center. A subset consisting of 12 events were chosen for detailed analysis, after eliminating events with poor signal-to-noise ratio or excessive obstructions. Results include system round-trip delay measurements and effects, bit-error rate performance, and total throughput comparisons.

A. Round-trip Delay

The round-trip delay of the ACM system (i.e., the amount of time between the adaptive algorithm software making a waveform configuration change and observing the desired change in the demodulated output of the DVB-S2 ground receivers) is an important parameter in determining the performance of the closed-loop system. Reduction of the system delay allows for the system gain margin to be decreased, as worsening signal-to-noise ratios can be more quickly rectified.

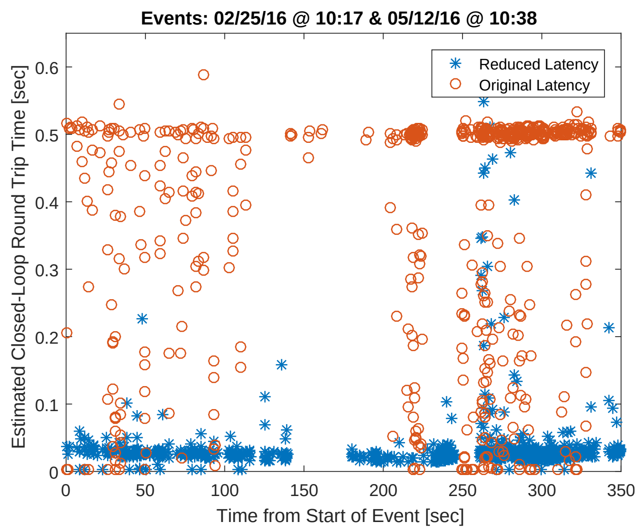

Figure 8. In-situ delay measurements.

Figure 8 shows round-trip delay measurements observed in-situ at the physical layer during two different rounds of flight events. It was determined that the initial version of the ground modulator caused end-to-end system delays in excess of 500 ms. This, in addition with the rapidly fluctuating channel conditions, made the system unable to maintain the desired link margin of 2 dB. See Figure 9 for a comparison of the two events. After moving to an FPGA-based solution for the ground modulator, the round-trip delay was reduced to approximately 40ms, and the system could be reliably operated at 1dB margin. The delay was estimated by analyzing log files of the sent MODCOD, and comparing those to the received MODCOD log. Since waveform configuration commands are not individually identifiable, round-trip time estimates can only be computed when changes are made in at least one of the OCF parameters, hence the sparseness of Figure 8's traces. This measurement method of the round-trip delay is prone to erroneous values based on a number of factors, however the overall trend is still apparent.

B. Bit-Error and Frame-Error Rate Performance

The bit-error rate and number of dropped AOS frames were analyzed by post-processing the recorded binary files from each event (Table 2). Overall, the BER has improved by several orders of magnitude over the typical 1e−5 performance of the VCM results.[1] The link operates completely error-free while there is line-of-sight, and only incurs bit-errors during severe multipath or shadow fades, when the adaptive controller is no longer effective. For example, in Figure 9, the transition to the backlobe of the antenna occurs $\sim$ 250 s into the event. After this time, poor performance is expected.

The DekTec receiver, as configured, has a issue with transitioning between MODCODs with different modulation types (8-PSK to 16-APSK, for example).[1] When the modulation type changes, there was a burst of 200 lost frames observed. This error was not observed with the ViaSat receiver.

Table 2. BER Performance

Run Number	BER
1	1.28e-06
2	2.41e-07
3	1.79e-06
4	2.23e-06
5	2.51e-08
6	7.67e-07
7	4.09e-07
8	5.34e-07
9	1.76e-06
10	1.50e-06
11	1.37e-06
12	1.68e-06

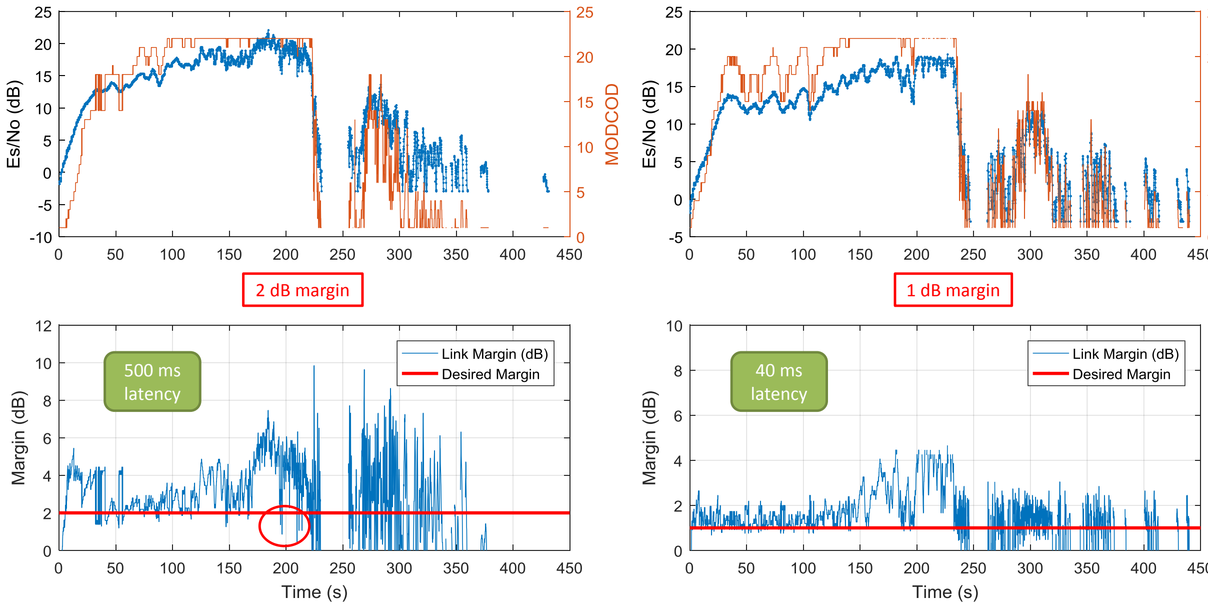

Figure 9. Link margin versus time comparison of two similar events with 500 ms delay (left) and 40 ms delay (right). The red circle in the lower left plot highlight regions of the event where the system was unable to maintain the desired link margin due to excessive delay.

C. Throughput Gain

One metric for comparing event performance is the total throughput (bits) of the link. A software simulation was run for each event to estimate the throughput of a standard NASA waveform (QPSK, rate 1/2 convolutional code w/Reed Solomon) based on the measured signal-to-noise ratio profile. The throughput gain is determined by dividing the actual ACM received total throughput compared to the estimated throughput from the standard NASA waveform. On average, ACM has shown a 1.6 dB improvement in throughput compared to the VCM system, and performed within 0.25 dB of the ideal (no delay) case. In addition, ACM provided a 4.34 dB improvement as compared to the standard NASA waveform.

Table 3. Summary of Test Results

Run Number	ACM vs VCM (dB)	ACM vs Ideal (dB)	ACM vs NASA Std. (dB)
1	2.36	-0.14	3.42
2	0.63	-0.15	4.95
3	0.26	-0.25	3.52
4	1.50	-0.43	4.12
5	0.81	-0.12	5.42
6	0.48	-0.26	4.98
7	1.08	-0.27	3.78
8	2.52	-0.14	3.85
9	2.20	-0.33	3.83
10	1.30	-0.22	4.71
11	1.34	-0.21	4.70
12	3.62	-0.21	4.29
Average	1.62	-0.23	4.34

V. Improving Performance with Predictive / Learning Algorithms

The relatively simple Es/N_0 threshold-based adaptive controller is likely sufficient for a wide range of applications. However, the severe multipath and shadow fading conditions which occur with this scenario can still disrupt the link, even with the adaptive feedback loop. This scenario provides an interesting opportunity to explore predictive and/or learning algorithms which could estimate the state of the channel in the future (accounting for round-trip delay), and factor in prior experience (such as the location of an obstruction). If the system had knowledge of its expected environment it could modify link parameters (such as MODCOD) accordingly, to reduce margin in clear sky conditions or increase system margin during fading conditions, or transmit idle data until a momentary obstruction passes.

Towards this goal, a software simulation was used to evaluate various algorithms: 1) Baseline ACM 2) Hysteresis 3) Adaptive Fade Margin 4) Neural Network. The baseline ACM algorithm is a model of the current threshold-based approach with flight test results described in this paper - the MODCOD is selected based on the instantaneous reading of the SNR. Hysteresis is a simple approach which prevents rapid MODCOD transitions by defining two thresholds (up threshold, down threshold). With hysteresis, the controller will wait for additional margin before transitioning states. Hysteresis algorithms have been previously applied to DVB-S2 systems as a fade mitigation technique.[14,15] The adaptive fade margin algorithm determines an appropriate margin proportional to the worst case slope (dB/s) of the SNR in a given window of time. A neural network approach requires a training set of data from multiple events to model the system and predict future values. For this analysis a nonlinear auto-regressive model was used to represent the system. The learning process is based on the Levenberg-Marquardt method,[16] which is an iterative technique which locates the minimum of a function that is expressed as the sum of squares of nonlinear functions.

Preliminary results are shown in Table 4 for the four approaches, comparing the total throughput for an example SNR profile (left plot of Figure 11). No significant change in total throughput was observed, however, the adaptive margin and neural network algorithms did reduce the time spent below the target link margin. Note that all cases are biased by the poor performance of the antenna back-lobe after ∼225 seconds into the event. The improvement with the neural network approach can also be seen in Figure 10, noting the reduction in link margins below the red line 1 dB target during the front-lobe portion of the event (time 0 to ∼225).

Table 4. Simulation Results

Algorithm	Total Bits	Seconds Below Target Margin	% Relative to ACM
ACM	2.57e9	11.94 (s)	-
Hysteresis	2.49e9	10.45 (s)	87.5%
Adaptive Margin	2.46e9	4.35 (s)	36.4%
Neural Network	2.49e9	5.31 (s)	44.5%

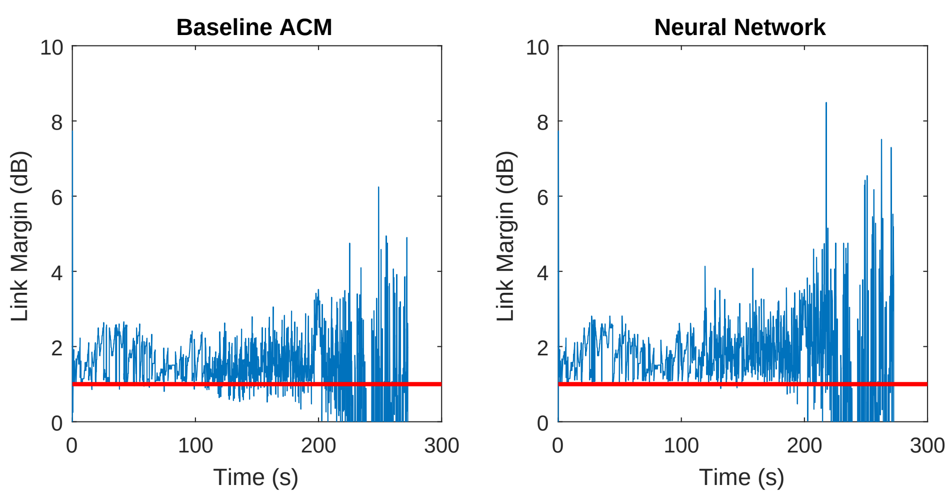

Figure 10. Link Margin over Time for Baseline ACM and Neural Network Algorithm

The SNR (Es/N_0) and corresponding adaptive fade margin plot is shown in Figure 11. Note that the fade margin is low for the majority of the event, and then increases in proportion to the received signal variation.

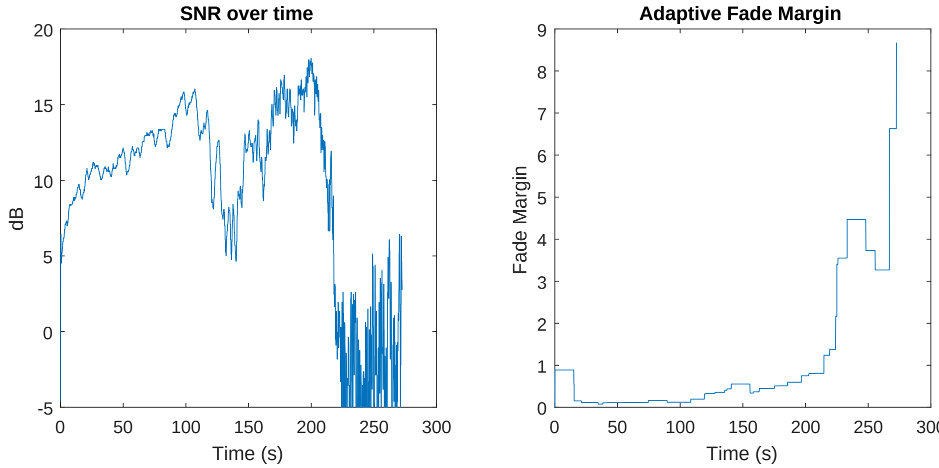

Figure 11. SNR and Adaptive Fade Margin

VI. Conclusions

This paper demonstrated the significant performance gains from applying ACM techniques to an experimental NASA space communication system. The ACM approach was effective for this direct-to-Earth scenario, given the dynamic environment, multi-path, and shadowing losses. On-orbit test results have demonstrated > 4dB improvement in total user information throughput over standard NASA waveforms (constant coding and modulation). A method of relaying channel feedback via the CCSDS Space Data Link Protocol has been presented, and may have applications to future missions. Software simulations indicate that further performance gains with the ACM system are possible by applying link prediction algorithms, and will be further investigated and evaluated with on-orbit testing.

As reported here, round-trip delay can be critical to an ACM system's performance. Therefore, VCM techniques may be better suited for deep space missions, or whenever the round-trip delay is greater than the link variation's periodicity. However, wherever possible ACM approaches are preferred because they can maximize data throughput and minimize operational burden.

NASA can benefit from utilizing either VCM or ACM for communication links whenever possible. Radio adaptability, be it autonomous or scheduled, can help all missions operate more reliably, return more science data, and improve NASAs spectrum and SCaN network utilization.

VII. Forward Work

Adaptive point-to-point links are a critical building block for NASAs future intelligent communications systems, providing cognitive applications with variables to control. The Cognitive Communications Systems Project at NASA GRC is developing technologies to address a variety of future mission needs, including throughput optimization, network scheduling, interference mitigation, power optimization, and spectrum sharing. Cognitive engine algorithms targeting interference mitigation are being developed and tested. This algorithm type may be helpful with mitigating other mission anomalies as well.

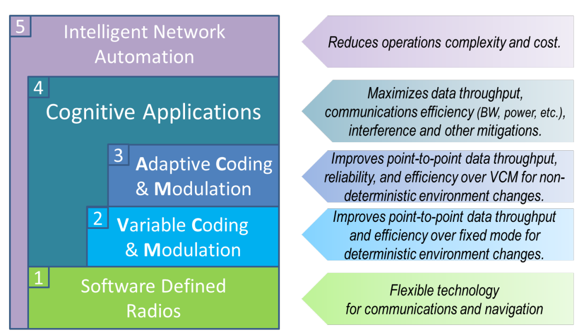

Figure 12. Cognitive Communication System

With the SDR waveform application now aware of its environment, there is opportunity for this information to be used network-wide on decisions at a higher level. For example, network routing through relay satellites versus direct-to-ground links can be done more intelligently for a mission with a large quantity of time sensitive data to downlink. For these mission scenarios protocols for cross-layer optimization are being investigated, in collaboration with emerging standards.

The adaptive coding and modulation waveform demonstrated in this paper is certainly an advancement for point-to-point links at the physical and data link layer. However, it is just as importantly an asset for future cognitive applications being developed.

Acknowledgments

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