SERVICE PROVIDER AGNOSTIC ADAPTIVE CODING AND MODULATION SYSTEM DESIGN

Matthew Hilts[1], Adam Gannon[1], Shadi Zogheib[1], Ethan Schweinsberg[1]

[1]*NASA Glenn Research Center, Cleveland, USA*

{matthew.d.hilts, adam.gannon, shadi.zogheib, ethan.e.schweinsberg}@nasa.gov

Keywords: ACM, SATELLITE, COMMERCIAL SERVICE PROVIDER, INTEROPERABILITY

Abstract

Commercial service providers (CSPs) are increasingly used to provide communications services to near-Earth science and exploration missions. CSPs commonly utilize modems that are designed to implement adaptive coding and modulation (ACM) in unique ways with modems from the same vendor. However, some missions cannot fly a matching vendor modem, either because the vendor only designs modems for terrestrial use, or the mission needs to fly a software defined radio. We present an ACM system design that allows missions to implement ACM on DVB-S2 compliant CSP links without needing to fly a modem from the same vendor the CSP uses. We implement and test our design in an emulated communications testbed. These tests demonstrate that our ACM system design can successfully adapt to link quality changes up to 6.12 dB/second.

1 Introduction[1]

Adaptive coding and modulation (ACM) is a method of dynamically changing the modulation and code rate (ModCod) of a communications link to maximize data throughput while maintaining a tolerable error rate. Higher order ModCods have greater spectral efficiency but require greater link quality to operate without significant error. Lower order ModCods have reduced spectral efficiency but are more robust in poor link quality conditions. Thus, as the link quality changes, an ACM system optimizes the ModCod to use the available link budget as efficiently as possible. ACM systems are closed loop and rely on a feedback mechanism to relay ModCod update information from the receiver, where link quality is measured, back to the transmitter, where the ModCod update is implemented.

The benefits of ACM have been demonstrated during data downlink from spacecraft, where link quality is dynamically changing, and unexpected interference may arise [1, 2]. Because spacecraft typically transmit more data than they receive, ACM is most commonly implemented on the downlink, although it can also be implemented on the uplink. Two commonly used space communications standards, the 2nd Generation Digital Video Broadcasting for Satellites (DVB-S2) standard [3] and the Consultative Committee for Space Data Systems (CCSDS) Flexible Advanced Coding and Modulation (FACM) standard [4], contain provisions for changing the ModCod of a link unilaterally from the transmitter. ModCod information is embedded in each frame header, allowing the receiver to adapt to ModCod changes from the transmitter on a frame-by-frame basis. This functionality allows full ACM systems to be built on top of DVB-S2 and CCSDS FACM. However, these standards do not specify the end-to-end design of an ACM system, particularly the feedback mechanism and the ModCod selection algorithm. These are left to ACM system vendors as an implementation detail.

As the number of commercially operated ground station or relay satellite networks grow, near-Earth science and exploration missions are increasingly relying on commercial service providers (CSPs) to provide communication services to their spacecraft. CSPs provide over-the-air communication with the user spacecraft and typically handle IP traffic between the user Mission Operations Center (MOC) and the user spacecraft. It is common for CSPs to use commercial DVB-S2 or CCSDS compatible modems to provide service, which typically are designed to implement ACM in unique ways with modems from the same vendor [5, 6]. This is not an issue if the user spacecraft can incorporate a modem compatible with the vendor's ACM feedback mechanism. However, vendors focused primarily on the terrestrial market do not always offer modems with size, power consumption and radiation tolerance suitable for spacecraft. Additionally, it has become increasingly desirable for some user missions to fly their own software-defined radio which can communicate with multiple CSPs during the mission lifespan [5, 7]. In this case, implementation of closed-source vendor standards for ACM is impractical. In this paper, we present an ACM system design that allows a user mission to utilize ACM with DVB-S2 compatible CSPs without needing to fly a modem from the same vendor each CSP uses. Section 2 describes our ACM system design. Section 3 describes the test environment used to evaluate our ACM system design, as well as the setup preformed for the evaluation. Section 4 presents the results of our testing and Section 5 provides concluding remarks.

2 ACM System Design

We present a service provider agnostic ACM system design, which allows a user spacecraft to implement ACM on downlinks with DVB-S2 compliant CSPs, without needing to fly a modem from the same vendor as the CSP. We achieve this by employing an IP traffic feedback mechanism and leveraging the DVB-S2 standard's provision allowing the transmitter to unilaterally change the ModCod of the link. Besides DVB-S2 compatibility, our system design requires that the CSP provide real time and low latency link quality metrics to the user mission on request. A stand-alone server implements a ModCod selection algorithm and creates ModCod update messages for each received link quality metric. These ModCod update messages are multiplexed into the existing IP data stream from the user MOC to the CSP, where they are forwarded to the user spacecraft for implementation. An important element of our design is that it does not require any user hardware to be installed at CSP facilities. Additionally, although the technical implementation of the design presented in this paper relies on the DVB-S2 standard, the high-level design could be implemented with any standard that allows the transmitter to unilaterally change the ModCod of the link.

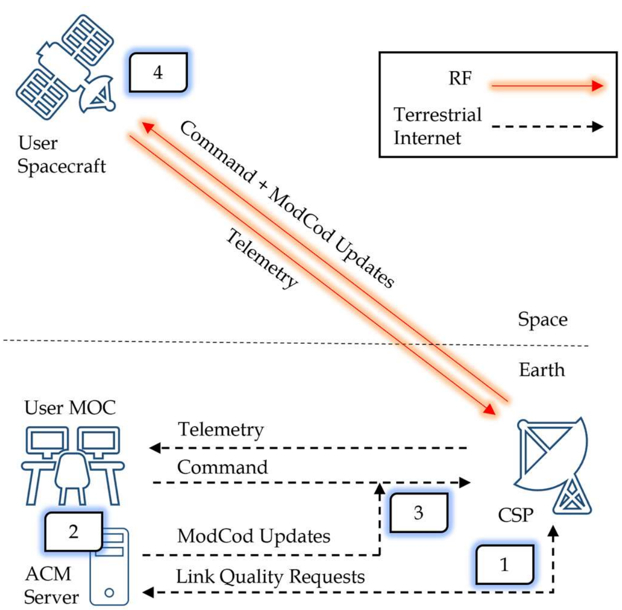

Fig. 1 Service provider agnostic ACM system design

Our ACM system design consists of two major components: a ModCod selection server and a ModCod update receiver. The ModCod selection server is connected to the terrestrial internet and runs a ModCod selection algorithm. The ModCod update receiver operates on the user spacecraft and implements the ModCod changes it receives from the ModCod selection server. These two components are described in greater detail in Sections 2.1 and 2.3. The flow of our ACM system design is numbered and described below and illustrated in Figure 1.

1. The ModCod selection server requests and receives a link quality metric from the CSP via the Internet.

2. The ModCod selection server calculates the optimal ModCod for the received link quality.

3. The ModCod selection server sends the selected ModCod to the user spacecraft via CSP-handled IP traffic.

4. The ModCod update receiver receives the ModCod selection and implements it on the link.

2.1 ModCod Selection Server

The ModCod selection server is connected to the terrestrial Internet and can be located at either the user MOC or at a remote location. The default configuration is for one ModCod selection server to support one user mission, but it would be possible to have multiple missions serviced by one ModCod selection server. When the user spacecraft begins downlink with a CSP, the ModCod selection server requests a link quality metric from the CSP at a regular interval (e.g., once per second). In our ACM system design, the metric requested is the link's symbol energy to noise power spectral density ratio (E_S/N_0). Once the link quality metric is received, the ModCod selection server runs a ModCod selection algorithm, described in Section 2.2, to determine the optimal ModCod for the current link quality. Then, when the optimal ModCod is determined, the ModCod selection server creates a ModCod update message, which will be sent to the ModCod update receiver. The structure of this message is shown below in Table 1. Bytes 0 and 1 are used by the ModCod update receiver to verify the message is a ModCod update message. Byte 2 contains the selected ModCod's DVB-S2 index number. Bytes 3-10 and 11-18 contain the timestamps of when the ModCod update packet was formed, and when the link quality used to make the ModCod selection was requested, respectfully. These timestamps are used to evaluate the latency performance of the system, as described in Section 4.2.

Table 1 ModCod update message structure

Message Bytes	Information
0	ModCod selection server ID
1	ModCod update message ID
2	Selected DVB-S2 ModCod Index
3-10	Timestamp when message was sent
11-18	Timestamp of link quality request
19	CRC check

Once the ModCod update message is formed, the ModCod selection server places it inside an IP packet with IP destination address of the spacecraft and UDP port number of the ModCod update receiver. This IP packet is then delivered to the spacecraft by the CSP, where the ModCod update is implemented.

2.2 ModCod Selection Algorithm

The ModCod selection algorithm determines the optimal ModCod for the link, given the current link quality. The ModCod selection algorithm is run on the ModCod selection server, rather than on a modem at a CSP ground station, which grants the user greater control over the algorithm design and parameters than would otherwise be available. For example, the user could choose to implement an algorithm that factors in a greater or lesser amount of link margin or uses machine learning and predictive algorithms [1]. Additionally, if the user spacecraft's modem hardware cannot operate with certain DVB-S2 ModCods, the algorithm can be tailored to exclude those ModCods from its allowable selections.

In this paper, we present and demonstrate a simple ModCod selection algorithm based on the DVB-S2 standard Quasi Error Free (QEF) performance table [3]. The DVB-S2 QEF performance table assigns a minimum required E_S/N_0 to each of the 27 DVB-S2 ModCods to operate with a packet error rate of less than 1 in 10,000,000 packets. Our ModCod selection algorithm takes the current link E_S/N_0, desired link margin and DVB-S2 QEF performance table as inputs, and outputs the DVB-S2 index of the optimal ModCod for the link. Table 2 below describes the steps of the algorithm for one ModCod calculation.

Table 2 A simple ModCod selection algorithm

Inputs: *Current* E_S/N_0*, link margin, DVB-S2 Quasi Error Free Performance Table (QEF)*
1. ***Available*** $\boldsymbol{E_S/N_0}$ ← *Current* E_S/N_0 *– link margin*
2. ***Available ModCods*** ← *QEF filtered to remove all ModCods requiring higher than available* E_S/N_0
3. **Selected ModCod** ← *Available ModCod with the greatest spectral efficiency*
Output: *selected ModCod*

The desired link margin input ensures that the selected ModCod will be able to continue operating error free if the link quality drops by less than the margin. This input plays an important role in the rate of link quality change an ACM system can handle, which will be discussed in detail in Section 4.2.

2.3 ModCod Update Receiver

The ModCod update receiver operates on the spacecraft's flight computer. It consists of two processes: one responsible for receiving and validating ModCod update commands and the other for implementing the new ModCod. These processes run in parallel to reduce the overall latency of receiving and applying ModCod updates. The high-level operation of the ModCod update receiver's operation on the spacecraft flight computer is shown in Figure 2. As in section 2.1, ModCod update UDP/IP packets are addressed to the ModCod update receiver's port number. Once a message arrives, the ModCod update receiver checks it for expected length, and verifies it is uncorrupted via a cyclic redundancy check. Next, it inspects bytes 0 and 1 of the message to verify that (1) the message is for the ModCod update receiver and (2) that the received message is indeed a ModCod update message. If the packet is verified, the ModCod update receiver extracts the DVB-S2 ModCod index value from byte 2.

Next, the achievable data rate for the new ModCod is calculated. We assume there is no closed-loop flow control between the spacecraft networking module, which handles the storing and forwarding of data, and the radio. Thus, our design handles synchronizing the egress rate of the networking module with the transmit capabilities of the radio. If the networking module's egress rate is too high, the radio's data buffer will overflow. If the egress rate is too low, the link will not be fully utilized.

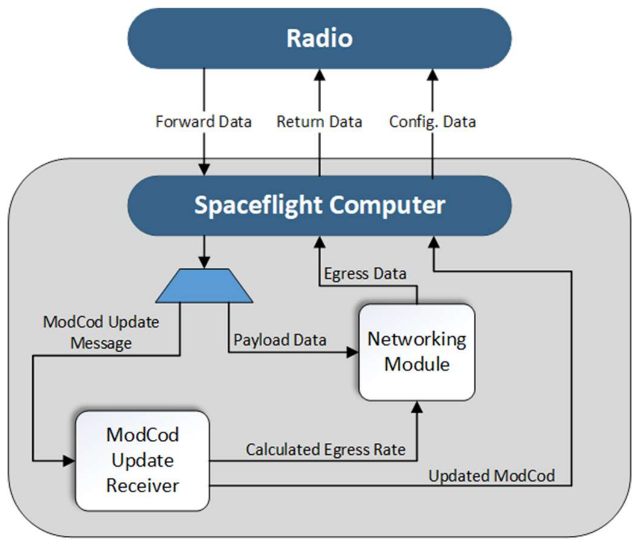

Fig. 2 High-level diagram of the ModCod update process

Once the new achievable data rate has been calculated, the ModCod update receiver determines if it is higher or lower than the current data egress rate. If it is higher, then the ModCod update receiver sends a command to the spacecraft radio to update the ModCod, and then sends a command to the networking module to update the data egress rate. If it is lower, then the data egress rate is updated first, to prevent buffer overflow in the radio. After the new ModCod is implemented, the latency of the system from link quality request to ModCod implementation is calculated using bytes 11-18 in the ModCod update message.

3 Testbed Design and Test Configuration

Our ACM system design is evaluated in the Cognitive Ground Testbed (CGT) at NASA's Glenn Research Center [8]. The CGT is a communications testbed designed to emulate the physical and network layers of the near-Earth communications environment with high fidelity. Section 3.1 describes the high-level design of the CGT. Section 3.2 describes the modifications made to the CGT to evaluate our ACM system and Section 3.3 describes the evaluation test configuration.

3.1 CGT Design

The CGT emulates the near-Earth communications environment by emulating user spacecraft, RF channels, service providers and user MOCs. A high-level schematic of the CGT is shown below in Figure 3.

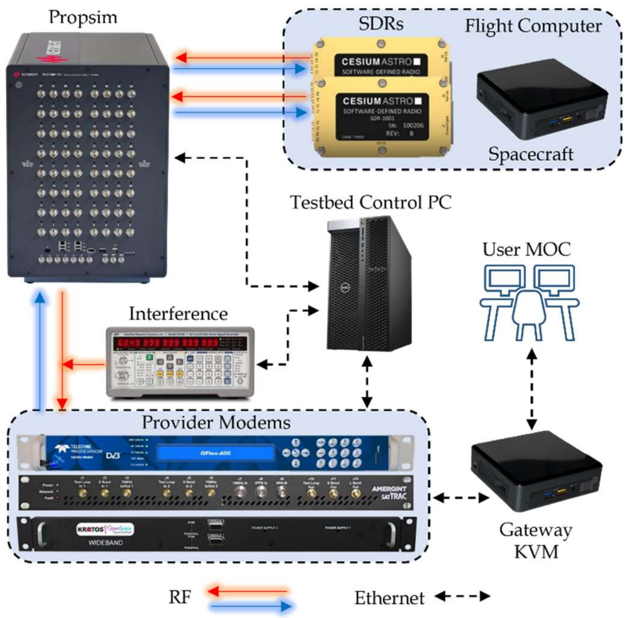

Fig. 3 Cognitive Ground Testbed

User spacecraft are emulated by combining engineering models of smallsat form-factor software defined radios with single-board computers. Service providers, both commercial and governmental, are emulated through representative modems which are compliant with provider accurate waveforms. The orbits of each of the user spacecraft and provider relay satellites, as well as the locations of provider ground stations, are loaded into an orbital mechanics simulation, which is used to drive a Keysight Propsim channel emulator. The Propsim creates an RF channel with realistic impairments based on the orbital mechanics simulation, including delay, doppler and free space path loss. RF interference is added by a separate signal generator. Two virtual machines are used to emulate a gateway and the user MOC, respectively. The gateway is used to run link switching software which enables seamless network connection of the user MOC to the user spacecraft over each of the providers [9]. The CGT can be loaded with test scenarios, which contain spacecraft and relay satellite orbits, ground station locations, terminal RF parameters and spacecraft data generation schemes.

3.2 CGT Modifications for ACM System Design

To implement our ACM system design, several modifications are made to the CGT. A provider interface emulator is added to the Testbed Control PC and provides a network-based interface for a user to query and receive E_S/N_0 metrics from each of the provider modems. This emulates a CSP providing on-demand link quality metrics to a user mission over the Internet. A ModCod selection server is added to the gateway and is connected to the CSP interface emulator via a local network connection. When a link is active, the ModCod selection server requests E_S/N_0 metrics once per second from the CSP interface emulator and runs the algorithm presented in Section 2.2 to select the optimal ModCod. Once a ModCod is selected, the ModCod selection server sends a ModCod update packet to the spacecraft, as in Section 2.1. The packet is sent from the gateway to the representative service provider modem, which then transmits it via the RF channel to the spacecraft. A ModCod update receiver is run on the spacecraft flight computer and waits for ModCod update packets to arrive at its bound receiving port. Once a ModCod update packet arrives, the ModCod update receiver forwards the ModCod change to the software defined radio, calculates the new achievable rate, and updates the data egress rate of the flight computer, as in Section 2.3.

To calculate the achievable data rate, the ModCod update receiver performs the following steps. First, the baseband data rate is calculated by multiplying the symbol rate by the spectral efficiency of the selected ModCod, a value pulled from Annex D defined in [10]. Then, the Generic Stream Encapsulation (GSE) rate for DVB-S2 is calculated by using (1), which adjusts the baseband rate to account for baseband and GSE headers. Lastly, the IP rate is calculated. If the radio is using High Efficiency Mode (HEM), then the IP rate is simply equal to the GSE rate. If the radio is not using HEM, then the IP rate is calculated with (2), where the lengths indicate bytes.

$$\boldsymbol{rate_{gse} = rate_{BB} \cdot \left(\frac{\#\ gse\ symbols/frame}{\#\ baseband\ symbols/frame}\right)} \quad [1]$$

$$\boldsymbol{rate_{ip} = rate_{gse} \cdot \left(\frac{length_{ip}}{length_{gse\ user\ data}}\right)} \quad [2]$$

The spacecraft's networking module utilizes the Licklider Transmission Protocol (LTP) over UDP to ensure reliable transmission. It supports real-time adjustments of the UDP egress rate on command. This UDP rate excludes IP and Ethernet headers, which are added before the data reaches the radio. Therefore, a buffer as a percentage is applied to the IP rate mentioned above before updating the final egress rate, to account for this additional network overhead.

3.3 Test Configuration

The CGT is configured to emulate a scenario in which a user spacecraft in low-Earth orbit communicates direct-to-Earth (DTE) with a single CSP. The ModCod selection algorithm in the gateway is configured to solve with 3 dB of desired link margin. During the test, the metrics in Table 3 are collected for post-test analysis. Because the CGT utilizes LTP at the application layer for ensuring reliable transmission, the spacecraft data egress rate reflects only the data that has been acknowledged by the user MOC. Thus, in our testing we measure the end-to-end, successful data rate from the user spacecraft to user MOC. Table 4 shows the relevant orbital and RF parameters used in the test scenario.

Table 3 CGT metrics

Metric	Location Collected
Spacecraft data egress rate	Spacecraft flight computer
Link E_S/N_0	CSP interface emulator
Link ModCod index	Provider modem
ACM system latency	Gateway KVM

Table 4 Test Scenario Parameters

Parameter	Value
Spacecraft Apogee	422 km
Spacecraft Perigee	413 km
Spacecraft EIRP	2 dBW
CSP Ground Station G/T	16 dB/K
Link Frequency	2.25 GHz
Link Symbol Rate	10 MBaud

The maximum bit rate the DVB-S2 standard can achieve at 10 MBaud is about 42.5 Mbps. However, the CGT is limited to about 26 Mbps. Therefore, we configure the spacecraft egress rate calculation to add a 40% buffer to the calculated IP rate, per Section 3.2. This limits the maximum data rate to about 25.5 Mbps and ensures that the changes in data rate based on the selected ModCod will be clearly demonstrated during the test.

4 Test Execution and Results

The CGT is configured per Section 3.3 and two contacts are emulated, with interference being added midway through the second contact. During each contact, data generated on the user spacecraft is transmitted through the channel emulator to the CSP representative modem, which then forwards the data through the gateway to the user MOC. Sections 4.1 and 4.2 discuss the data throughput and latency results of the test, respectively.

4.1 Data Throughput Results

Figure 4 shows the results of the first contact, in which the link experiences changing quality due only to the orbital mechanics of the scenario. Throughout the contact, our ACM system successfully adapts the ModCod and data rate of the link to use the link budget most efficiently, while still maintaining an error-free link. Additionally, the measured data rate over the link matches the rate calculated by the ModCod update receiver for each ModCod, as shown in Figure 4(a). Figure 5 shows the results of the second contact, with artificial interference added midway through. Our ACM system adapts to the resulting drop in link E_S/N_0 by lowering the ModCod of the link and adjusting the data egress rate accordingly. However, the link experiences errors momentarily when the interference is first added, shown by the data rate dropout at 13:17:15 in Figure 5(a). This is because the instantaneous rate of change of the link quality when the interference is added is greater than our system can handle, which will be discussed further in Section 4.2.

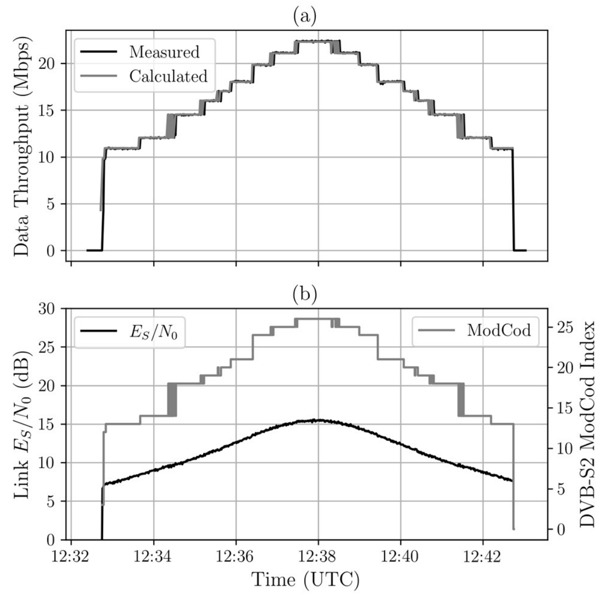

Fig. 4 (a) Data throughput, (b) available E_S/N_0 and selected ModCod for the first emulated contact

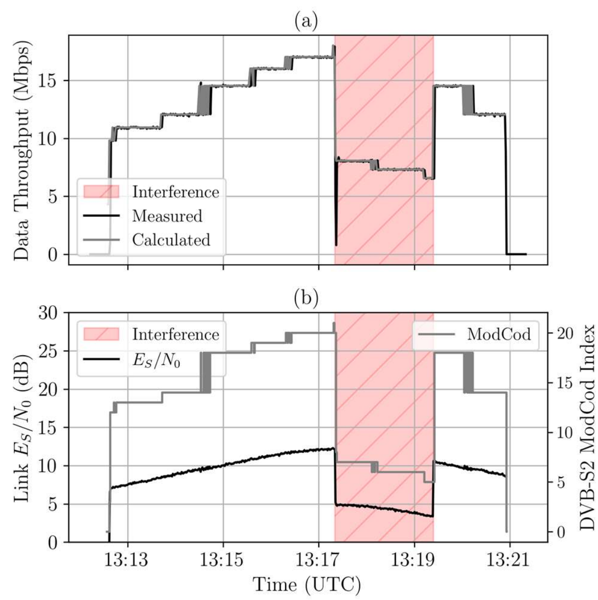

Fig. 5 (a) Data throughput, (b) available E_S/N_0 and selected ModCod for the second emulated contact

4.2 Latency Results

Latency is a key performance metric of any ACM system, as it directly determines the rate of link quality change an ACM system can handle. The latency period of an ACM system is defined as the time between when the link quality is measured, and when the selected ModCod is applied on the spacecraft. If the link quality increases in the latency period, the link will remain error free, albeit at a lower data rate than theoretically is possible. However, if the link quality decreases in the latency period, there is potential for errors in the link, which occur if the applied ModCod requires a higher link quality than exists. In this case, the link will experience errors until the next ModCod update is applied.

When link quality is changing at a constant, negative rate, the maximum rate of change an ACM system can handle over one latency period is described by (3):

$$\boldsymbol{Rate} = \frac{\boldsymbol{Quality_{selection}} - \boldsymbol{Quality_{error}}}{\boldsymbol{T_l}} \quad [3]$$

Where $\boldsymbol{Quality_{selection}}$ is the link quality used to select the new ModCod, $\boldsymbol{Quality_{error}}$ is the link quality at which the selected ModCod will experience errors, and $\boldsymbol{T_l}$ is the latency period. When a link margin is factored into the ModCod selection algorithm, the difference between $\boldsymbol{Quality_{selection}}$ and $\boldsymbol{Quality_{error}}$ is guaranteed to be at *least* the link margin. Thus, the minimum rate of change an ACM system is *guaranteed* to be able to handle is:

$$\boldsymbol{Rate} = \frac{\boldsymbol{link\ margin}}{\boldsymbol{T_l}} \quad [4]$$

Thus, to improve the rate of change an ACM system can handle, the link margin factored into ModCod selection can be increased, or the latency period can be decreased. Increasing the link margin can be undesirable, as it entails using less spectrally efficient ModCods on the link than would theoretically be possible. Vendor designed ACM systems can achieve extremely low latency by placing all ACM system components inside the transmitter and receiver modems and using an in-band signalling feedback mechanism. Our ACM system design requires data processing external to these modems, and thus is fundamentally disadvantaged in terms of latency. Therefore, it is important to evaluate the latency performance of our ACM system design, and to verify that our design can meet real-world performance requirements.

Figure 6 shows the latency of our ACM system during the first contact. The total system latency varies significantly with time, from as low as 0.2 seconds to as high as 1.4 seconds. Most of this variance can be attributed to the latency of querying the link E_S/N_0, as Figure 6(b) shows more clearly. The latency of calculating the optimal ModCod, transmitting it to the user spacecraft, and implementing it on the link remains relatively constant, at about 0.2 seconds. The reason that the E_S/N_0 query varies so much is because the CSP representative modem used in our test has a user interface that is not optimized for rapid polling of link metrics. We do not anticipate this will be a problem for real-world use of our ACM system design, because (1) CSPs that provide link metrics are incentivized to provide them with the lowest latency possible and (2) modems used by CSPs have demonstrated metric reporting latencies down to 10ms [1]. Thus, our subsequent performance calculations are conservative.

The average latency of our ACM system design over the first contact is 0.24 seconds, and the latency at two standard deviations above the mean is 0.49 seconds. Using (4) with a 3dB link margin and assuming 0.49 seconds as our system's latency, we calculate that our ACM system design, as configured in the CGT, can handle absolute rates of change less than 6.12 dB/second. Because this value is calculated based on the latency two standard deviations above the mean, our calculation will hold 97.5% of the time. As discussed above, we expect the system latency to be lower and more stable in real-world scenarios.

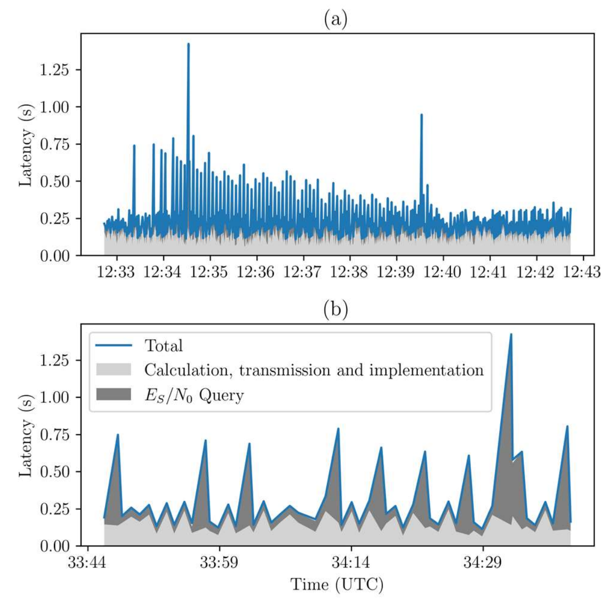

Fig. 6 (a) ACM system latency over the first emulated contact and (b) a zoomed in subsection of the latency

In satellite communications, two typical sources of time-varying link quality reduction are changing free-space path loss due to spacecraft motion and rain fade. During both contacts, the link is subjected to normal free space path loss for a low-Earth orbit spacecraft communicating DTE. This results in E_S/N_0 changes with an absolute value of less than 0.4 dB/second, as shown below in Figure 7.

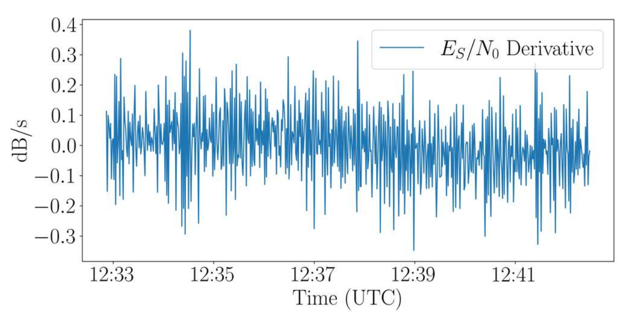

Fig. 7 Derivative of the E_S/N_0 over the first contact.

Rain fade typically results in greater rates of link quality change, and thus it is important to evaluate how our system would perform in a rain fade scenario. In our CGT testing, the S-Band links we emulate would not degrade in the presence of rain. However, we can compare the minimum rate of link quality change our system is able to handle with simulated rain fade slopes for a mission using higher frequencies that are susceptible to rain fade. For a spacecraft at 200km altitude operating links DTE at 27.5 GHz, the link quality slope will not exceed 3 dB/second 99% of the time [11]. This is well under the 6.12 dB/second link quality slope our ACM system design can handle.

5 Conclusion

Our ACM system design allows user missions to utilize ACM on DVB-S2 compliant CSP links, without flying a modem from the same vendor the CSP uses. This allows missions to benefit from ACM that would otherwise be unable to. Though vendor-specific ACM methods generally have lower latency than our ACM system design, we have shown that our system can successfully adapt the link ModCod to meet the typical changes in link quality experienced by a spacecraft without introducing errors. One other benefit our design provides is that it allows a user mission to continue to implement ACM with a CSP if the CSP changes the modem vendor they use to provide service, provided the CSP still uses the DVB-S2 standard.

6 Acknowledgements

This work was performed under the Cognitive Communications project, funded by NASA's Space Communications and Navigation (SCaN) program. We extend special thanks to Lucas Shalkhauser for his work implementing DVB-S2 waveforms on the CGT and Vladimir Linetsky for assisting in the construction and operation of the CGT.

References

[1] Downey, J., Mortensen, D., Evans, E., Briones, J., Tollis, N.: 'Adaptive Coding and Modulation Experiment with NASA's Space Communication and Navigation Testbed'. 34th Int. Communications Satellite Systems Conf., Cleveland, United States, October 2016

[2] Downey, J., Evans, M., Tollis, N.: 'DVB-S2 Experiment over NASA's Space Network', 2017

[3] EN 302 307 v1.2.1: '2nd Generation Digital Video Broadcasting for Satellites', 2014

[4] CCSDS 131.2-B-2: 'Flexible Advanced Coding and Modulation Scheme for High Rate Telemetry Applications', 2023

[5] Piasecki, M., Downey, J., Pham, N., Nessel, J., Gannon, A., Zeleznikar, D., Kock, M.: 'Development and Demonstration of a Wideband RF User Terminal for Roaming between Ka-Band Relay Satellite Networks'. 38th International Communications Satellite Systems Conference, Arlington, United States, September 2021, pp 7

[6] Miller, R.: 'Adaptive Coding and Modulation (ACM) in the CDM-625 Advanced Satellite Modem' (Comtech EF Data Corporation, 2009), pp. 5

[7] Heckler, G. *et al*: 'NASA's Progress Toward Commercial Space Communications – SATCOM Demonstrations and Wideband Multilingual Terminal Development'. 39th International Communications Satellite Systems Conference, Stresa, Italy, October 2022

[8] Downey, J., Gannon, A., Smith, A., Koch, M., Dudukovich, R.: 'Emulated Spacecraft Communication Testbed for Evaluating Cognitive Networking Technology'. Cognitive Communications for Aerospace Applications Workshop, Cleveland, United States, June 2023

[9] Gannon, A. *et al*: 'Automated end-to-end spacecraft connectivity across diverse links'. Proc. 29th Ka and Broadband Communications Conference, Seattle, United States, September 2024

[10] CCSDS 131.3-B-2: 'CCSDS Space Link Protocols over ETSI DVB-S2 Standard', 2022.

[11] Liu, W., Michelson, D.: 'Fade Slope Analysis of Ka-Band Earth-LEO Satellite Links Using a Synthetic Rain Field Model'. IEEE Transactions on Vehicular Technology, 2009, 58, (8), pp 4013-4022