# Steps towards the Standardization of a more efficient Uplink Protocol and Code – DRAFT 55764

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**In June 2004, NASA announced a new vision for the further exploration of the Moon and Mars. The vision includes a long-term human and robotic program to explore the solar system, starting with a return to the Moon that will ultimately enable future exploration of Mars and other destinations. Inherent in this endeavor is the need to transfer the communication technology developed for lunar missions to deep space whenever possible. Furthermore, greater data throughput on the uplink will be required for future nominal operations for the Exploration missions given their highly interactive nature and the need to send files in both directions. Therefore, it is prudent for standards bodies i.e., CCSDS to develop the underlying communication recommendations necessary to deliver greater data throughput to meet future agencies' needs. This paper will examine methods for achieving greater uplink data throughput based on increased coding gains coupled with the use of CCSDS data transfer services providing low latency and reliable communications. This approach will need to be demonstrated while still maintaining compatibility with the current set of CCSDS recommendations for operations where lower rates can suffice including emergency uplink.**

## Nomenclature

*AOS* = Advanced Orbiting Systems
*ARQ* = Automatic Repeat reQuest
*BCH* = Bose, Ray-Chaudhuri, Hocquenghem (code)
*BER* = Bit Error Rate
*CRC* = Cyclic Redundancy Check
*CFDP* = CCSDS File Delivery Protocol
*dB* = Decibel
*DSN* = Deep Space Network
*EIRP* = Effective Isotropic Radiated Power
*FPGA* = Field Programmable Gate Array
*LDPC* = Low Density Parity Check (code)
*NAK* = Negative Acknowledgement
*PDU* = Protocol Data Unit
*SCPS* = Space Communication Protocol Standards
*SDST* = Small Deep Space Transponder
*SFCG* = Space Frequency Coordination Group
*SNR* = (bit) Signal to Noise Ratio
*SSNR* = Symbol Signal to Noise Ratio
*TC* = Telecommand

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## I. Introduction

THERE are several trends in robotic and human exploration that are driving the need towards higher rate uplinks. These include:

1) Use of selective repeat (ARQ) protocols e.g., CFDP
2) Available uplink margin (assuming ARQ is used)
3) Standalone antenna replacement with arrays
4) On-board applications require larger volume uplinks

### A. Use of Selective Repeat (ARQ) Protocols

Higher rate downlink missions that use Acknowledged CFDP will require higher uplink data rates. Typically for robotic missions, the telemetry data rate is much higher than the command data rate. If CFDP is used on the downlink, there is a concern that the CFDP return traffic back to the spacecraft (i.e., CFDP Finish PDU (a type of overall positive acknowledgement) and NAKs (Negative Acknowledgements) will consume too much uplink bandwidth. Even in the case of no NAKs being sent, a Finish PDU is required to be sent up from the ground for each complete file received.

This example illustrates the problem: With a downlink rate of 30 Mbps and 6Mb files, CFDP will have to transfer 5 Finish PDUs to the spacecraft per second. Each Finish PDU contains about 20 bytes (160 bits). Thus the required uplink traffic for positive acknowledgements alone is approximately 800 bits per second which is 40% of the maximum uplink traffic available at 2,000 bits per second. Moreover this bandwidth must remain dedicated to the CFDP return channel for the entire pass.

### B. Available Uplink Margin

Deep Space missions typically operate with high margins on the uplink in order to ensure a robust communications link to the spacecraft. Typically these missions operate over links that provide a BER of 10**-5 or better. For NASA's Project Constellation, a BER of 10**-7 has been proposed to support applications that require reliable transport. Consequently missions are very conservative on the uplink margin. For example the recently completed NASA Deep Impact mission operated with an uplink margin of 17 dB at encounter at maximum range from 34-m DSN stations (mean minus 3-sigma for 2 Kb/sec uplink data rate with 3 dB of additional ranging modulation)[1]. This additional margin translates into a factor of 50 greater uplink throughput, if that available coding gain can be harvested. By reducing that margin by 3dB or even 6 dB, the uplink data rate can be increased by a factor of 2 and perhaps as high as 4. The idea is to reduce the margin to the point where occasional errors (10**-3 BER) can occur. These errors result in a limited number of file segments to be retransmitted using a selective repeat protocol i.e., CFDP. As long as there is sufficient round trip light time to complete the retransmission of file segments in error, CFDP would be used. However when the round trip time is insufficient to request and receive missing file elements, then the sender would preemptively retransmit i.e., send duplicate portions of the file. Since the probability of missing the same file segment equals the square of the probabilities of losing a single segment, this loss event is small and is very unlikely to occur.

### C. Standalone Antenna Replacement with Arrays

The DSN is planning to replace its aging larger standalone antennas with downlink arrays which will support multiple spacecraft telemetry links within the same aperture. An array is efficient for supporting telemetry but its utility for uplink is yet to be proven and will certainly be limited to supporting a single spacecraft leaving the remainder unsupported. Thus initially array operations will require uplinks to be shared during their telemetry passes which will result in significantly shorter command passes.

### D. On-board Applications require larger volume Uplinks

Today's spacecraft are storehouses for application software which include software for Field Programmable Gate Arrays (FPGAs) which are rapidly replacing unique hardware systems. State of the art on-board telecommunication systems are deploying "software radios" implemented in FPGAs that can be easily reprogrammed in flight. Moreover, changes to flight software applications occasionally requires the uplink to deliver very large volumes of data due to reprogramming. Lastly, emerging requirements from the NASA Exploration Program include the need for relay of high rate video data for manned missions.

## II. Uplink Constraints

This section examines the constraints placed upon a solution to the needs above. Since we desire a solution integrating the physical, coding and link layers, let's start by examining the constraints upon each layer individually.

### A. Physical Layer

The physical layer limitations are:

1) Current State of the Art deep space transponders are rate limited
2) Use of frequencies and bandwidths within SFCG guidelines

The current operational deep space transponder i.e., Small Deep Space Transponder (SDST) has limited performance. It provides a maximum uplink of 2 Kb/sec and has limited bit synchronization capabilities. It is not possible to lower the operational symbol to noise ratio (SSNR) by the use of complex codes without significantly improving the receiver. Improving the receiver will be expensive and at this time cost prohibitive in these times of constrained budgets.

The use of frequencies and their associated bandwidth and channel allocations requires coordination with the SFCG. SFCG is currently developing a recommendation on the use of frequency bands for lunar missions. Furthermore, while for deep space applications the band 34/32 GHz allows easy accommodation of such high rates, for lunar missions the X-band may not be usable (to be assessed). An alternative operating band is 40 GHz. The move to such this band represents a huge technological development effort. Another alternative could be the 22 GHz band if space science is granted an Earth-space allocation in the future.

### B. Coding Layer

The Coding layer limitations are:

1) On uplink coding due to short code block size for emergency operations for acquisition
2) On uplink coding due to the need for high carrier power for emergency operations
3) To chose an uplink code with a low flight implementation complexity
4) To provide a means to detect extremely low undetected frame error rates

Coding performance varies significantly with the constraint on the information block size. Ideally, one would use an infinitely sized code block in order to approach the capacity of the channel. Clearly such lengths would not be practical. The current CCSDS telecommand recommendation provides a data payload of up to 1019 bytes in the telecommand frame. The CCSDS Proximity-1 recommendation accommodates up to 2043 bytes of payload space. For emergency uplinks, block sizes must be very short (around 100 bits) to limit message duration in order to increase the probability of reception in most likely a degraded spacecraft configuration.

Another limitation on uplink coding is due to the need for high carrier power for emergency operations. Current emergency uplinks require a large percentage of the total uplink power to be dedicated to the carrier in order to simplify the initial acquisition process. Allocating more power to the carrier means there is less uplink power dedicated to the data, which reduces the benefit of any gain the code provides.

More complex uplink coding provides "coding gain" which reduces the required EIRP, while preserving the required very low undetected error rate. However in so doing, it significantly reduces the symbol SNR requiring improved receiver performance along with the expense of a decoder on the spacecraft. Current state of the art advanced coding algorithms can be implemented in a single FPGA up to rates as high as 50 Mb/sec.

Since future candidate uplink codes (see section 3) can produce burst errors, a powerful error detection code is required to validate the correctness of the frame.

a. The Proximity link protocol utilizes a variable length frame format with the standard and powerful 32 bit CRC. This protocol uses an optional CC(7,1/2) convolutional code for use in proximity environments. This mandatory CRC provides an undetected BER of $\sim 10^{-11}$.

b. The AOS frame format is fixed in length and uses the standard 16 bit CRC for validation. This optional CRC provides an undetected BER of $\sim 10^{-5}$.
c. The TC frame format is variable in length and also uses the same standard 16 bit CRC for validation, whose use is optional.

### C. Link Layer

The Link Layer limitations are:

1) Additional requirements for carrying voice and video along with data
2) Potential need to multiplex data types
3) Maximum frame length limits code block length

Robotic spacecraft at lunar distances will need to relay voice and video along with data. The CCSDS AOS protocol provides an insert zone within the AOS frame for carrying either voice or video as well as data within the payload portion of the frame. By its very nature, voice communication is more tolerant of errors, therefore the BER for voice can be lower than for data communications. However, this requirement competes with the low BER required for reliable data communications driven by the perceived need of running IP over TBD reliable transport and application layer protocols.

Like all of the CCSDS link layer protocols including Telecommand, AOS provides a rich set of data multiplexing capabilities. Currently IP, SCPS-NP, CCSDS Space Packets, and the CCSDS encapsulation packets (for IPv6, CFDP PDUs and future protocols) can be multiplexed onto the same or separate virtual channel(s). Multiplexing of packet types provides greater flexibility to the on-board applications e.g., it's unclear at this time that all on-board data transfer from lunar orbit can be accommodated by IP.

The maximum frame size of the AOS frame is currently 16,384 bits. This limitation is due to the size of the first header point, which is an 11 bit field, which points to the first complete packet within the payload of the frame. It provides for a maximum frame size of $2^{11}$bytes or equivalently 16,384 bits. For Telecommand (TC), the maximum frame size is currently 8,192 bits. This limitation is due to the size of the frame length field, which is a 10 bit field, in the transfer frame header. Although there is provision in these protocols to extend the frame length beyond the current limit, the current proposed coding block lengths of the advanced codes do not exceed it.

## III. Recommendations

The following three application profiles in Figure 1 to the right provide an integrated channel coding and link layer protocol approach to the goals expressed in the abstract, namely to provide high throughput on the uplink for nominal operations but be backward compatible for emergencies. These application profiles are described in the paragraphs below. Emergency communication for Human missions is very contentious at this time and will not be discussed.

**Figure 1. Uplink Application Profiles.**

| Mission Class/Key Metrics | A) Robotic Emergency | B) Robotic Nominal | C) Human Missions |
|---|---|---|---|
| Data Rate | 7.8125 bit/sec | 250 bps to 2Mbps | 20 Mb/sec |
| Block Size | ~100 bits | 1024 or 16,384 bits | 16,384 bits |
| Code | BCH or BCH+CC (3,1/2) | Rate ½ LDPC | Rate ½ LDPC |
| Coding Gain | 1 to ~3.8 dB | 8.8 to 9.7 dB | 9.7 dB |
| Link Protocol | TC | **AOS** | AOS |

### A. Robotic Missions – Emergency Uplink

The fundamental approach to emergency uplink for robotic spacecraft centers upon the use of small sized frames to increase the probability of reception in an assumed degraded spacecraft state. Depending upon the sophistication of the spacecraft, the spacecraft may be tumbling therefore limiting the time the ground can see the spacecraft antenna. In such cases, it is often prudent to send short frames (~100 bits) composed of short codeblocks to the spacecraft. The CCSDS TC protocol provides an asynchronous data link consisting of variable length transfer frames each of which "rubberbands" to the size of the command message or messages transferred. The TC protocol uses the (63,56) BCH code and an optional 16-bit CRC for error detection over the TC frame.

The present BCH code applied to the uplink for deep space utilizes the Single Error Correction (SEC) and Double Error Detection (DED) mode and provides a bit signal to noise ratio (SNR) of about 9.5 dB at a $10^{-6}$ bit error rate (see Figure 2) with a symbol SNR of about 6.8 dB. Alternatives to the current BCH code to enhance link performance for the uplink are:

1) Concatenated BCH and rate 1/2 constraint length 3 Convolutional Code i.e., BCH + CC(3,1/2) with interleaver
2) Standard CCSDS Convolution rate ½ constraint length 7 convolutional code i.e., CC(7,1/2)

In the first alternative, the approach is to improve the channel performance by up to ~3.8 dB by using the CC(3,1/2) as the inner code but keep the current BCH code for error detection. The optional 16-bit CRC could be used in the emergency frame configuration but there is a high overhead of ~16% to pay due to the small ~100 bit block size. The CC (3, ½) would lower the required bit SNR to about 6.5 dB but would require two symbol per bit thus reducing the symbol SNR to 3.5 dB which is a very significant difference from the 6.8 dB available for symbol synchronization with the currently BCH code. Note that the convolutional code is a streaming code and is thus compatible with the variable length Telecommand (TC) frame protocol presently used for uplink. Although available for the CC(7, ½) code, there are no space qualified encoder/decoder chips available for the reduced constraint length 3 convolutional code. Therefore the development costs could be rather high and the risk large. Moreover, the better performance may not be justified by the steep increase in complexity in comparison to the BCH encoder/decoder. Another consideration is the addition of an interleaver in order to disperse the burst errors that result from the decoding process. The average size burst is typically one-half the coding constraint length, which is 1.5 bits, which is close to the error detection capability of the BCH outer code.

In the second alternative, the approach is to improve the channel performance even more, by up to ~5 dB by using the standard CC(7,1/2) code. Upon decoding, the average burst error length is 3 bits, which would overcome the error detection capability of the BCH code and obviate its usefulness. The advantage is that there are space qualified chips available so that the development costs should be rather low and the risk small.

### B. Robotic Missions – Nominal Uplink

In order to take advantage of the large coding gains available from advanced block codes i.e., LDPC, the most efficient way of doing this is to make the code block synchronous to the transfer frame. The CCSDS AOS protocol provides a synchronous data link and a fixed length frame of up to 16,384 bits. This protocol is quite different from the asynchronous data link and the Physical Layer Operations Procedures (PLOPs) provided by the TC protocol. In this case, a synchronous uplink would be maintained between the ground and the spacecraft. When the ground had no command data to uplink to the spacecraft it would fill the data link with AOS fill transfer frames instead of idle data. Therefore, the spacecraft would need to remain in frame synchronization with the ground continuously or drop synchronization and reacquire it in order to receive commands.

The second application profile involves routine command, sequencing, and file uploading to the spacecraft during non-emergency operations. The basic approach taken is to maximize data throughput for higher rate applications by utilizing the available coding gain of advanced codes while still meeting the data latency and undetected error rate requirements. The specific approach taken is based upon the type of data transmitted. Lunar robotic spacecraft will need to handle voice as well as data in support of manned missions. Voice can tolerate a higher BER but requires a shorter latency than data. Therefore, for voice a shorter LDPC block length of 1024 bits is used. For data, a block size up to the maximum AOS transmission unit of 16,384 is used. But the LDPC codes are block codes and thus add a different wrinkle into the uplink process. One problem is how to detect LDPC block errors, another is the requirement to perform code block synchronization and decoding prior to command frame synchronization. Lower rate LDPC e.g., rate ½ codes could be used but they would have a significant effect in lowering the signal strength for symbol synchronization as expressed in Section 2 Uplink Constraints. The LDPC decoder is currently in development and its complexity at this time is unknown. The code block length affects the performance of the code and the complexity of the decoder. The larger the code block the better the performance, but the more complex the decoder implementation.

This application profile requires that the spacecraft fly an LDPC decoder most likely implemented into a single FPGA. However the increase in coding gain provided by these LDPC codes provides the ability to support these higher rates.

### C. Human Missions – Nominal Uplink

We advocate the use of LDPC rate ½, block length 16384 bit code with a 16 bit CRC for error detection. However, this application profile requires a very fast on-board LDPC decoder capable of handling 20 Mbps uplinks, which are under development but are not currently available for flight operations.

## IV. Conclusion

The major conclusions are: 1. Uplink coding provides substantial benefits at the cost of a manageable increase in complexity by adding an on board decoder implemented within a single FPGA . State of the Art Uplink coding is a very cost effective way to improve uplink throughput performance. 2. Use of the CCSDS AOS synchronous data link protocol provides a very efficient way of sending voice, video, and data along with the ability to multiplex packet types onto the physical channel and support LDPC block codes of various lengths. 3. Emergency needs can be met by the existing TC protocol with the BCH code and CRC. If higher rates are required, the TC frame can be used with a CC code and interleaver to minimize burst errors.

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## References

[1]Taylor, J., Hansen, D., "Deep Impact Flyby and Impactor Telecommunications," *DESCANSO Design and Performance Summary Series*, Article 9, September 2005, pp. 59, 60.