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Nancy List and Ryan Shoup

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MIT Lincoln Laboratory
244 Wood Street
Lexington, MA 02420

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Incorporation of Uplink Channel State Information into an End-to-End Coded Satellite Communication System

Nancy List and Ryan Shoup
MIT Lincoln Laboratory
Lexington, MA 02420

***Abstract*—Satellite communications systems employing forward error correction (FEC) codes are simplified when the code is applied at the source's transmitter and removed at the end user's receiver (end-to-end coding), avoiding decoding and re-encoding on board the satellite. Channel capacity can be approached when channel state information from the uplink is incorporated into the soft information input to the downlink decoder. For fading channels, the channel state information is time-varying and must be updated frequently. This paper will describe techniques for both measuring and incorporating practical, bandwidth efficient uplink channel state information in an end-to-end coded satellite communications system. Link performance with and without channel state information will be compared. A technique for estimating channel state information will also be analyzed.**

I. Introduction

While most current satellite communication systems employ radio frequency (RF) links between the satellite and ground stations, recent hardware and technology advances in optical frequency links make such links candidates for future applications. The high data rates over unregulated frequencies that optical links provide, as well as their relatively low power consumption, make them attractive to replace RF links in some circumstances. However, free-space optical signals may encounter faded propagation environments that are much more extreme than those typically encountered by RF signals.

Fig. 1 shows a block diagram of a satellite communications system where coding and decoding is implemented at the user terminals ("end-to-end coding"), and the signal is simply demodulated and remodulated on board the satellite. This simplifies the payload processing and also allows a more powerful code to be implemented at the user terminals than what could be practically implemented on board the satellite [1]. To approach channel capacity in an end-to-end coded system, it is necessary to incorporate the uplink channel state information for each channel bit at the receiver. When the signal is transmitted over a fading channel, the channel state information is time-varying and must be updated frequently. Techniques for estimating the channel state on a single link are described in [3]. Since the channel state information for each channel bit transmitted on the uplink needs to be relayed to the decoder implemented at the downlink receiver in an end-to-end coded system, techniques for estimating channel state information that can be conveyed in a bandwidth efficient manner are useful in practical implementations.

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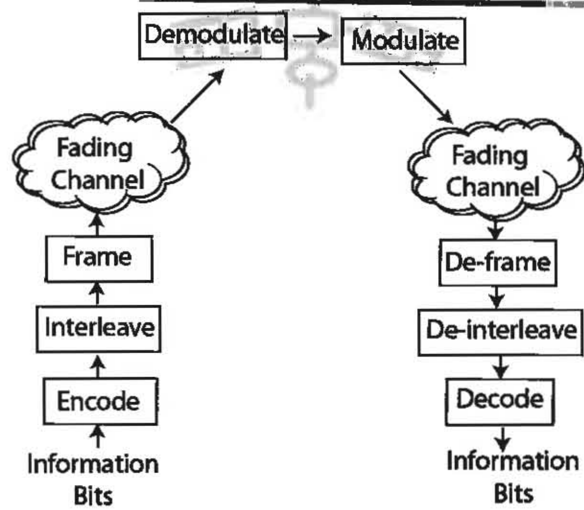

Fig. 1. Satellite communications system over fading channels with end-to-end coding and decoding.

In this paper, we describe a simple, bandwidth efficient technique for computing uplink channel state information used by the decoder in an end-to-end coded satellite communications system. We compare the performance of a system using estimated channel state information both to the performance of the system with perfect channel state information and to the channel capacity of an end-to-end coded system.

The organization of the paper is as follows. Section II describes the theoretical channel capacity of an end-to-end coded satellite communications system considering the availability of uplink and downlink channel state information and soft decision demodulation. Section III describes a simple technique for providing uplink channel state information to the downlink decoder without increasing bandwidth on the downlink. Furthermore, the technique avoids the need for hardware to measure analog signal power. This section also describes the computation of the log-likelihood inputs to the downlink decoder which incorporate the estimated uplink channel state information. Section IV compares the end-to-end coded performance using the low-complexity uplink channel state information to the performance of the system with perfect uplink channel state information. Finally, Section V concludes our work.

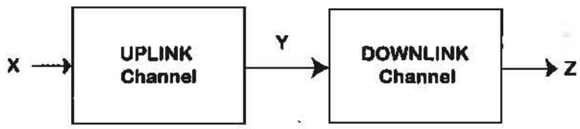

Fig. 2. Conceptual block diagram of the optical uplink. X is the input to the uplink and the end-to-end channel, Y is output of the uplink channel, and Z is the output of the downlink and end-to-end channel.

II. Channel Capacity of an End-to-End Decoded Satellite Communications Link

In an end-to-end coded satellite communications system, hard decisions on the uplink channel bits are retransmitted on the downlink. Conceptually, soft decisions on the uplink channel bits could be retransmitted on the downlink. However, this would require an expansion of the downlink bandwidth which could be used more effectively in other ways. Hard or soft decisions can be applied to the downlink channel bits before decoding.

In the absence of channel state information, the capacity of the end-to-end system is computed on the average channel bit error rate [2] for the end-to-end system, $\bar{p}$:

$$C = 1 - H(\bar{p}) \tag{1}$$

Channel capacity including channel state information is computed as

$$C = \int\int f(\rho_u) f(\rho_d) C(\rho_u, \rho_d) \partial\rho_u \partial\rho_d \tag{2}$$

where ρ_u is the state of the uplink channel and ρ_d is the state of the downlink channel.

When soft decisions from the downlink demodulator are available at the decoder in additon to channel state information, the end-to-end system capacity is expressed as:

$$C = \int\int\int f(\rho_u) f(z|\rho_d) C(\rho_u, z|\rho_d) \partial\rho_u \partial\rho_d dz \tag{3}$$

where z is the output of the downlink soft-decision demodulator in the end-to-end system as shown in Fig. 2. The function $f(z|\rho_d)$ is the distribution of the soft decision output of the downlink demodulator conditioned on the downlink channel state, ρ_d.

The uplink and downlink operating points where the end-to-end system capacity supports a rate-1/2 code with BPSK modulation and an infinite interleaver are shown in Figure 3. These "capacity" curves were computed using (1)-(3). The three curves compare the end-to-end operating points where the system is operating with either

- uplink hard decisions and downlink hard decisions, without channel state information (1); or
- uplink hard decisions, downlink hard decisions, and perfect channel state information (2); or
- uplink hard decisions, downlink soft decisions, and perfect channel state information (3).

Both the uplink and downlink channels were modelled as Rayleigh fading channels where the fading envelope, σ^2, is 1. Perfect channel state information is the fade experienced by each channel bit on both the uplink and the downlink. The asymptotes for both uplink and downlink with either hard decisions or soft decisions are shown alongside the rate-$\frac{1}{2}$ channel capacity operating points. Note that uplink soft decisions are not practically available at the downlink receiver in an end-to-end coded system, and this asymptote is shown as a point of reference for what would be achievable if decoding of the uplink were performed on board the satellite.

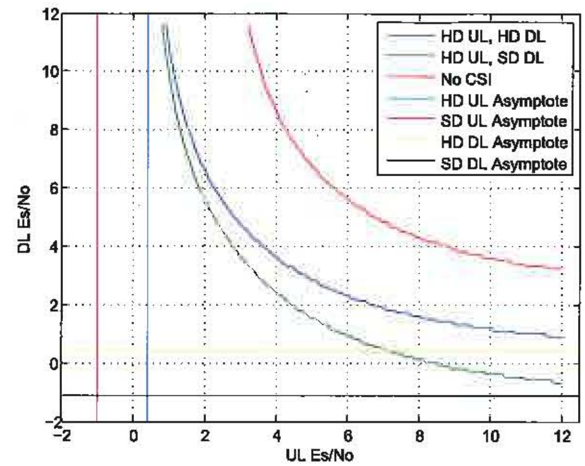

Fig. 3. Operating points where the end-to-end channel capacity over Rayleigh fading uplink and downlink channels supports a rate-1/2 code with BPSK modulation, along with hard decision and soft decision asymptotes for uplink and downlink demodulators [Note: these capacity curves are for DPSK modulation and will be replaced with capacity curves for BPSK modulation in the final draft].

III. Estimation and Application of Channel State Information

In addition to the use of a strong forward error correction (FEC) code and channel interleaving, measuring and applying the channel state information is a third means to mitigate the effects of fading. The log-likelihood ratios (LLRs) supplied to the decoder can include information regarding both the uplink and the downlink channel state experienced by each channel bit.

The general expression for the LLR on the uplink fading channel shown in Figure 2 is given by:

$$LLR(y) = \log \frac{f_{Y|X}(y|1)}{f_{Y|X}(y|0)} \tag{4}$$

In the case of hard-decision payload decoding, the uplink becomes a binary-symmetric channel, and the input to the decoder on the payload becomes a LLR calculated using the cross-over probability on the uplink, p_u, which is determined according to the state of the fading channel over which a particular channel bit was transmitted:

$$LLR(y) = \pm\log \frac{(1 - p_u)}{p_u} \tag{5}$$

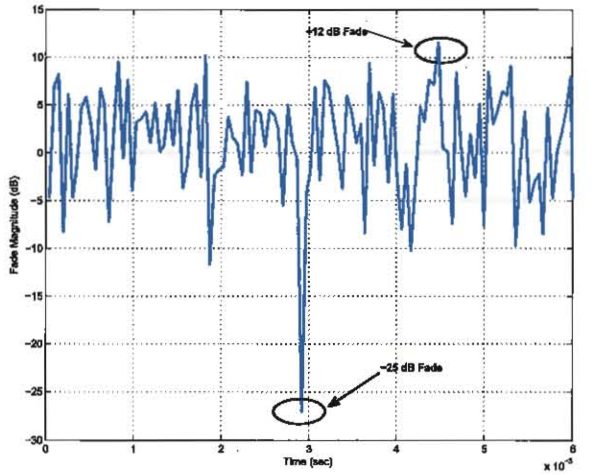

Fig. 4. Sequence of channel fades from Rayleigh fading channel model ($\sigma = 1$) used in analysis and simulations.

In the absence of payload decoding, the uplink channel state information should be used to form the LLRs that are input to the decoder on the ground. In the case of hard-decision end-to-end decoding, the input to the decoder is a LLR calculated using the cross-over probability, p_u, of the uplink channel experienced by a particular channel bit, along with the cross-over probability, p_d, of the same channel bit on the downlink:

$$LLR(z) = \log \frac{f_{Z|X}(z|1)}{f_{Z|X}(z|0)} \tag{6}$$

$$= \pm \log \frac{(1-p_u)(1-p_d) + p_u p_d}{(1-p_u)p_d + p_u(1-p_d)} \tag{7}$$

Because of payload complexity and downlink channel throughput, we do not consider either soft-decision payload decoding or ground-based soft-decision decoding. However, it is feasible to consider soft information from an analog-to-digital converter (A/D) in the ground-based receiver along with the uplink channel state information for each channel bit to calculate a more refined LLR input to the end-to-end decoder:

$$LLR(z) = \log \frac{f_{Z|X}(z|1)}{f_{Z|X}(z|0)} \tag{8}$$

$$LR'(z) = \frac{f_{Z|Y}(z|1)}{f_{Z|Y}(z|0)} \tag{9}$$

$$LLR(z) = \log \frac{(1-p_{ul}) f_{Z|Y}(z|1) + p_{ul} f_{Z|Y}(z|0)}{p_{ul} f_{Z|Y}(z|1) + (1-p_{ul}) f_{Z|Y}(z|0)} \tag{10}$$

$$LLR(z) = \log \frac{(1-p_{ul}) LR'(z) + p_{ul}}{1 - p_{ul} + p_{ul} LR'(z)} \tag{11}$$

Biasing the LLR inputs to the decoder by including the uplink channel state information becomes increasingly important as the uplink fading channel deteriorates with increasing atmospheric turbulence. Fig. 4 shows a sequence of channel fades that were generated by a model of a Rayleigh fading channel where the fading envelope, σ^2, is 1. The distribution of fades from this channel model shows that frames will reguarly

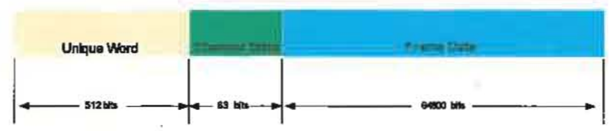

Fig. 5. Physical layer frame structure for use in fading channel.

experience both deep attenuation (> 25 dB) and high gain (> 12 dB) with regularity. Having information about the state of the channel over which a particular frame was transmitted will improve the performance of the end-to-end coded system as shown by the capacity curves in Fig. 3. It is also desirable to estimate the uplink channel information in a manner that is both simple and bandwidth efficient.

The physical layer framing structure can be used to estimate the channel state information. The requirements for the frame structure are that the frame itself be short enough such that it can be transmitted within the coherence time of the fading channel (i.e., each frame experiences a single channel fade), and that the frame is appended with a known sequence (or unique word) from which an estimation of the channel state can be made. The requirements for the physical layer frame on the downlink are the same as for the uplink frame, with the addition of some minimal overhead for the transmission of the uplink channel state information.

In the uplink receiver, the field containing the unique word is compared to the reference unique word. The number of channel bit errors in the received unique word are used to compute a channel bit error rate on that frame. The unique word must be long enough to make a good estimate of the channel bit error rate. This measurement is converted to a seven bit sequence via a look-up table shown in Fig. I. The seven bit representation of the uplink channel state is encoded with a (63,7) BCH code for transmission in the downlink physical layer frame. The 64800 bit physical layer frame payload contains one DVB-S2 rate-1/2 codeblock [4]. It is assumed that the entire physical layer frame can be transmitted during one channel coherence time at the data rate for the system. On the downlink, the field containing the unique word is refreshed so that the downlink channel state can be estimated independently of the uplink channel. The (63,7) BCH encoded uplink channel state information is contained in a 63 bit field of the downlink physical layer frame as shown in Fig. 5. In Section IV, the end-to-end system performance using channel state information from a 512 bit reference sequence is compared to a system with perfect channel state information.

IV. Performance Comparison

Performance of an end-to-end coded system using a rate-$\frac{1}{2}$ DVB-S2 and BPSK modulation operating over a Rayleigh fading uplink and downlink ($\sigma = 1$) with various types of demodulation (hard or soft decision) and channel state information (perfect, estimated, or none) is shown in Figs. 6-9. These figures all show the operating points where "error-free" performance (coded bit error rate $< 10^{-7}$) is achieved, and

TABLE I
CHANNEL STATE INFORMATION VALUE BASED ON CORRELATION RESULTS.

Number Correlated ≥	Number Correlated ≤	Channel State Value
511	512	1111111
509	510	1111110
507	508	1111101
⋮	⋮	⋮
259	260	0000010
257	258	0000001
0	256	0000000

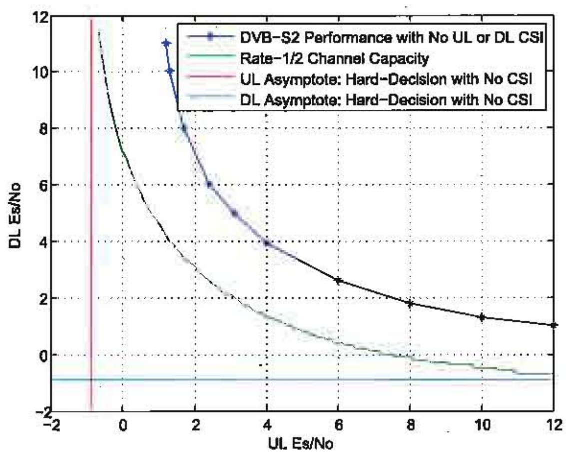

Fig. 6. DVB-S2 rate-1/2 code, hard decision downlink demodulator, no channel state information (CSI).

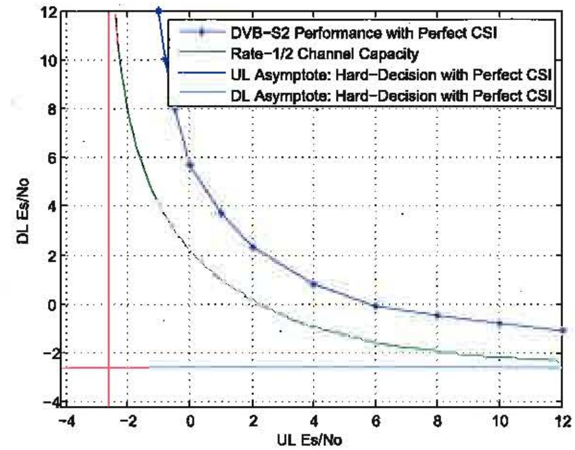

Fig. 7. DVB-S2 rate-1/2 code, hard decision downlink demodulator, perfect channel state information (CSI).

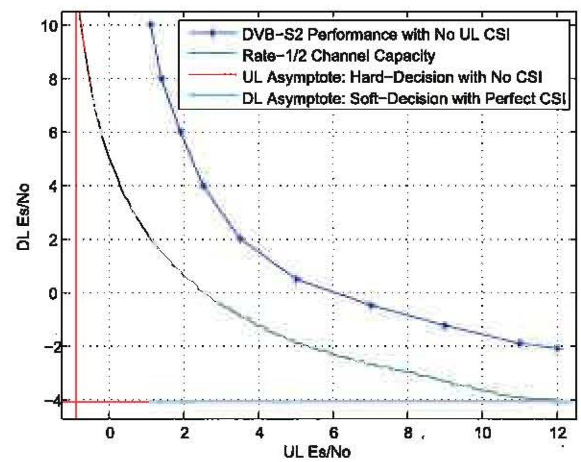

Fig. 8. DVB-S2 rate-1/2 code, soft decision downlink demodulator, perfect downlink channel state information (CSI), no uplink CSI.

compare these operating curves to the points where the end-to-end system capacity supports a rate-$\frac{1}{2}$ code in each particular system configuration. The performance curves were simulated using a DVB-S2 rate-$\frac{1}{2}$ code [4]. An "infinite interleaver" was assumed in these simulations which allowed each channel bit to experience an independent fade on both the uplink and the downlink.

The error-free performance of a DVB-S2 rate-$\frac{1}{2}$ code where both the uplink and downlink demodulator produce hard decisions is shown in Fig. 6, compared to the channel capacity from (1). Channel state information is not available for either the uplink or the downlink in this configuration.

Fig. 7 shows the error-free performance of a DVB-S2 rate-$\frac{1}{2}$ code where both the uplink and downlink demodulator produce hard decisions. This is compared to the channel capacity for this configuration computed as in (2). For this configuration, perfect uplink and downlink channel state information was available. The decoder then biased the LLR inputs as in (7).

The error-free performance of a DVB-S2 rate-$\frac{1}{2}$ code where both the uplink demodulator produces hard decisions and the downlink demodulator produces soft decisions is shown in Fig. 8. This is compared to the channel capacity for this configuration computed as in (3). Perfect downlink channel state information, without uplink channel state information, was available to the decoder. The decoder then biased the LLR inputs as in (10).

Fig. 9 shows the shows the error-free performance of a DVB-S2 rate-$\frac{1}{2}$ code where both the uplink demodulator produces hard decisions and the downlink demodulator produces soft decisions. This performance is compared to the channel capacity for the same configuration as computed as in (3) [Note: capacity curve to be provided in final draft]. For this example, the performance where perfect uplink and downlink channel state information was available to the decoder (LLRs computed as in (11)) is compared to the performance when the channel state information was estimated from the physical layer frame unique word as described in Section III. Performance using estimated channel state information is nearly identical to performance with perfect channel state information.

V. CONCLUSION

To approach channel capacity in an end-to-end coded system, it is necessary to incorporate the uplink channel state

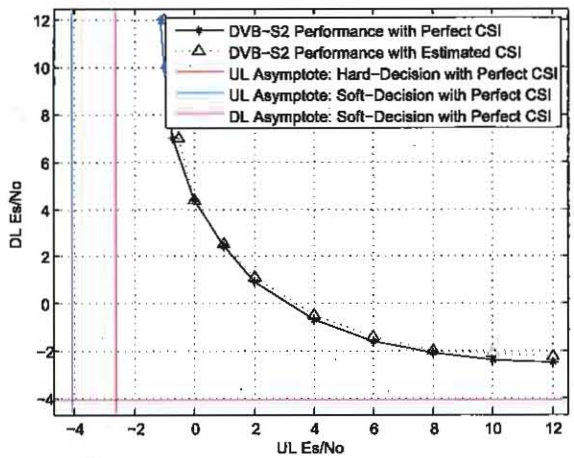

Fig. 9. DVB-S2 rate-1/2 code, soft decision downlink demodulator, perfect channel state information (CSI).

information for each channel bit at the receiver. Capacity analysis in Section II as well as simulated performance shown in Section IV with rate-$\frac{1}{2}$ DVB-S2 curves shows that biasing decoder inputs based on the state of the uplink fading channel improves overall coded performance by approximately 2dB when the channel is uplink limited.

Since the channel state information for a fading channel is time-varying and must be updated frequently, the bandwidth efficient technique for estimating uplink channel state information described in Section III is useful in practical implementations. Performance simulations of this technique of estimating channel state information from a reference sequence (unique word) transmitted in the physical layer frame header shows that it is nearly identical to performance with perfect channel state information where the fade experienced by each channel bit in the fading channel is known at the decoder.

[Note: Figures will be modified to black-and-white for final draft.]

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