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XXXVII Cycle

Improve the Performance in Space Missions using Convolutional Codes

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Research context and motivation

Recently, the concatenation of **convolutional codes** (CCs) with high-rate outer binary linear block codes was rediscovered, showing how the concatenation can be efficiently decoded by means of **list Viterbi algorithms** (LVAs) (Fig. 2), mimicking a similar approach used for the decoding of polar codes concatenated with outer codes.

In particular, in the short block length regime (tens to few hundreds of encoded bits), the concatenation of an **outer CRC code with an inner CC** (denoted in the following by the shorthand "CRC+CC") with moderate/small memory was shown to perform remarkably close to finite block length bounds down to low error rates with a **manageable decoding complexity**.

In Consultative Committee for Space Data Systems (**CCSDS**) telemetry synchronization and channel coding recommendation, CCs are an available option (Fig. 1 top), and they are still used by various space missions (e.g., in some European Space Agency Earth's observation satellites missions, as well as in small/cubesat missions), thanks to their simplicity and their reasonably good performance. Note that when CCs are used as the coding option of a **telemetry** (TM) link, the presence of an outer degree-16 CRC code is mandatory and inserted in the *Transfer Frame Error Control Field* (Fig. 1 bottom).

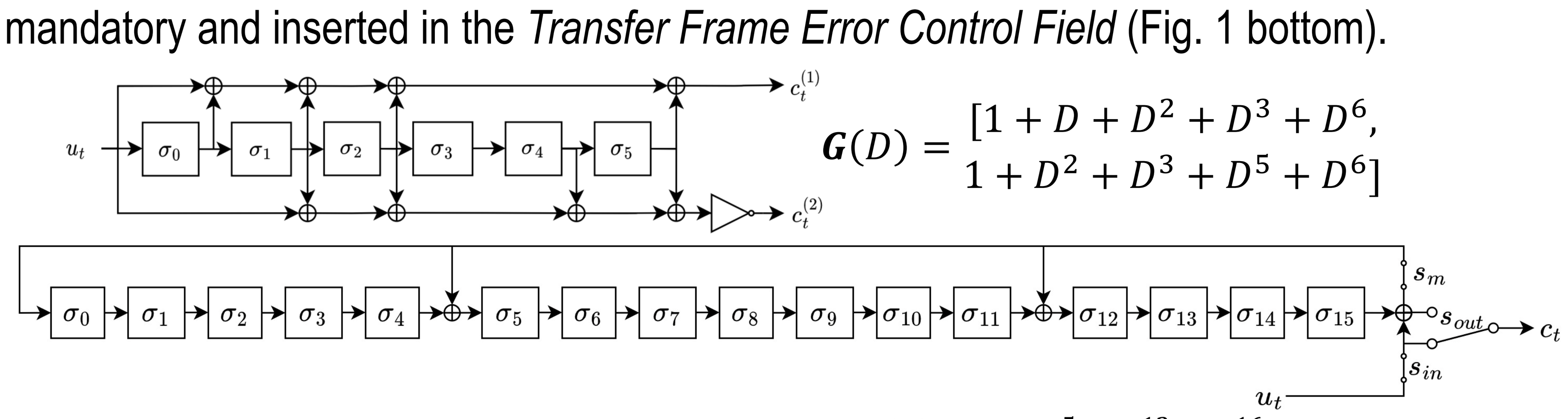

Figure 1: (top) Rate-½ convolutional encoder; **(bottom)** CRC encoder, $g(D) = 1 + D^5 + D^{12} + D^{16}$, of the CCSDS standard.

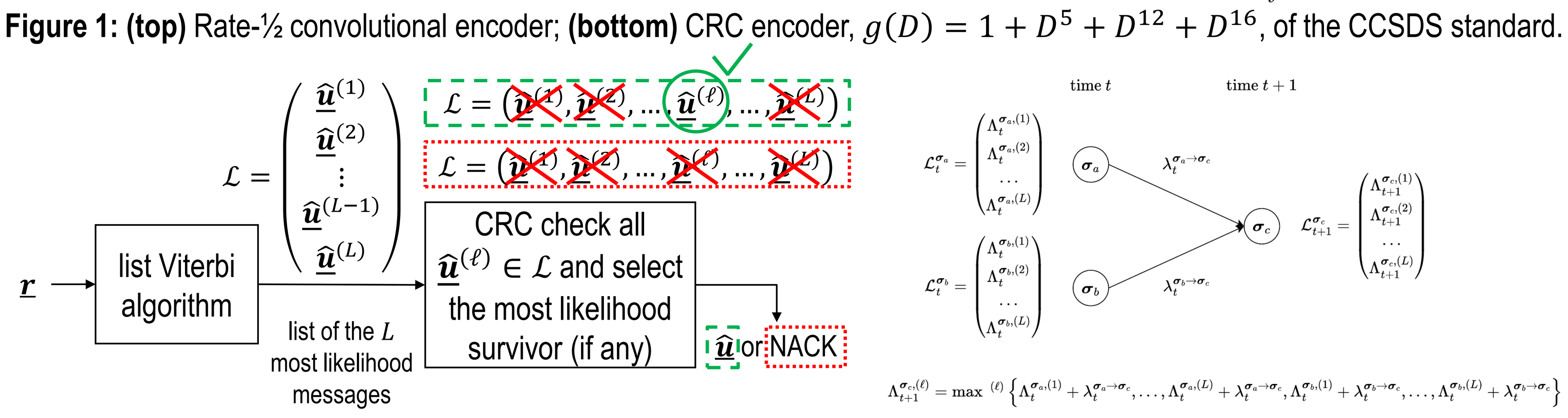

Figure 2: (left) joint CRC+CC decoding via LVAs; **(right)** construction of the list at a generic trellis state using the parallel-LVA

Addressed research questions/problems

- **Quantify the possible theoretical performance gain** of the CCSDS TM CCs, when the CRC is jointly decoded with the CCs over the additive white Gaussian (AWGN) channel with binary-phase shift Keying (BPSK) modulated signals.
- **Evaluate the real performance gain of the joint CRC+CC code decoding by means of LVAs**.
- **Create a fast software solution to jointly decode CRC+CC** codes, which can be integrated in software defined radio systems, and which can support any CRC+CC codes (*i.e.,* the tail-biting terminated CCs with their CRC options used in the 4G standard) and which can boost the study of CRC+CC codes for future applications and standards.

Adopted methodologies

- Analysis of the finite state machine of the CRC+CC codes for the construction of their trellis graph representation and computation of the spectrum of the same codes using algorithms which run over their trellis (*i.e.,* FAST, BEAST, …).
- Computation of upper bounds on the maximum likelihood decoding performance of CRC+CC codes with algorithms which use the spectrum of the CRC+CC codes (*i.e.,* union bound, Divsalar's bound,…).
- Use of Monte-Carlo simulations to evaluate the error rate performances of LVAs as channel decoders, so to estimate practical coding gains of the joint decoding of CRC+CC codes for various list sizes.
- Use of *Intel intrinsics* to take advantage of CPU hardware accelerators in the simulations.

Submitted and published works

- Schiavone, R. , Garello, R. and Liva, G., "*Application of List Viterbi Algorithms to Improve the Performance in Space Missions using Convolutional Codes*", 9th ESA International Workshop on Tracking, Telemetry and Command Systems for Space Applications, Noordwijk, 2022 *[submitted]*
- Schiavone, R., Galati, F. and Zuluaga, M., "*Sparsifying Binary Networks*", The 37th AAAI Conference on Artificial Intelligence, Washington, 2023 *[submitted]*

Novel contributions

- We developed a **technique to construct the trellis of CRC+CC codes**, which allows us to compute the spectrum of the codes and to evaluate a **theoretical upper bound on the error rate of the same codes.**
- We showed that the joint decoding of the CCSDS CRC+CC code can provide up to **3 dB coding gain**, with respect to the Viterbi decoding of "only" the inner CC (Fig. 3 left).
- We developed a **fast fully-software Viterbi decoder** in C for modern **CPUs**, using *Advanced Vector Extension* (AVX) *Single Instruction Multiple Data* (SIMD) sets, which runs at **44 Mbps/core** (full-precision), supporting multiprocessing environments and reaching nearly **~1 Gbps on an Intel Xeon** Scalable Processors Gold 6130. Then, we quantized the decoder, reaching up to **~100 Mbps/core** (Fig. 3 middle).

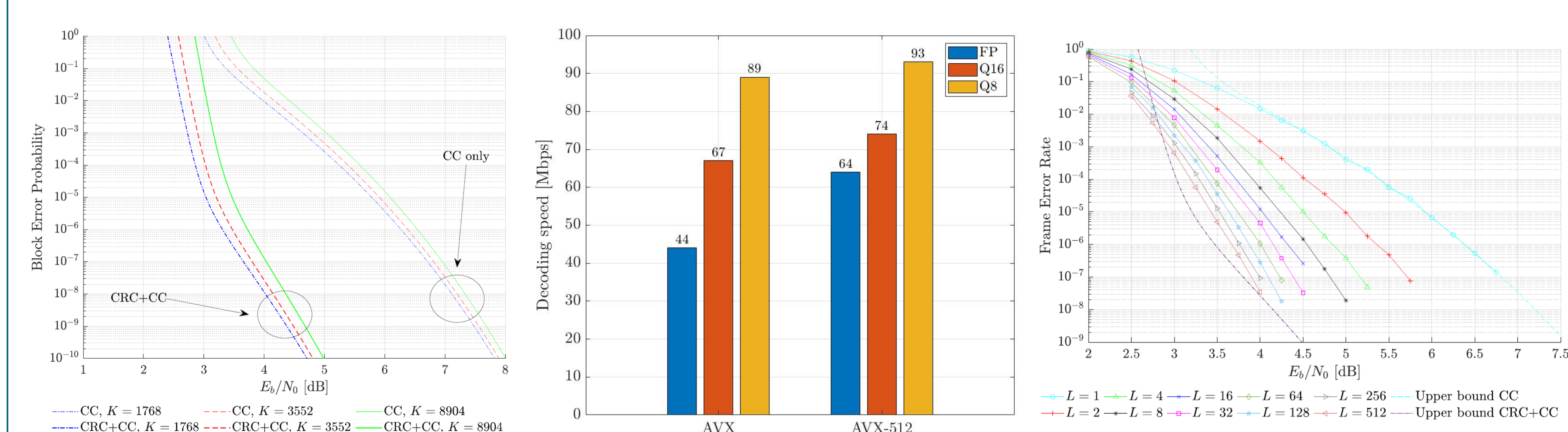

Figure 3: (left) upper bounds on the block error probability of the CCSDS TM CRC+CC codes and CC codes for different SNR values and frame lengths K; **(middle)** decoding speed of Viterbi algorithm on a single core of an Intel Xeon Silver 4210 for various SIMD sets and quantization levels; **(right)** Monte-Carlo simulations of the decoding of the CRC+CC code via LVAs with K=3552 bits and various list sizes.

- We run extensive Monte-Carlo simulations, below frame error rates of 10^{-7} for the CCSDS CRC+CC codes decoded with various list sizes, up to list of size 512 (Fig. 3 right).
- We showed that **it is possible to reach the 3 dB coding gain with manageable decoding complexity** using iterative list Viterbi algorithms, without penalizing the throughput, while penalizing the decoding latency of few decoded messages (Fig. 4).

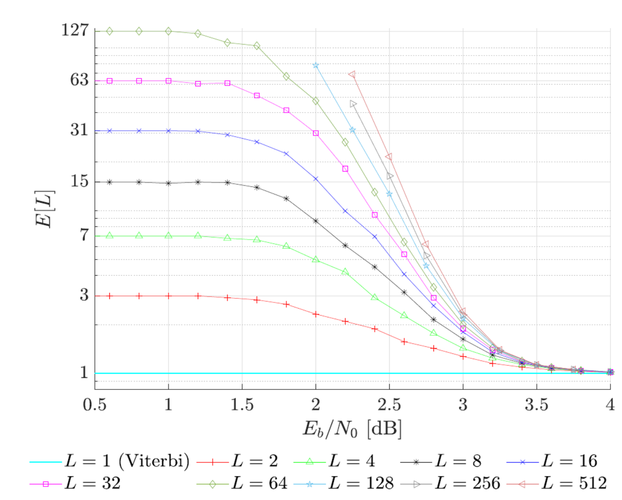

Figure 4: Expected list size using an iterative parallel-LVA, as measure of average decoding complexity when K=3552 bits and various maximum list sizes

Future work

- Study both theoretically and via simulations the penalization of the undetected error rates of list decoders with respect to the Viterbi decoding of the inner CC.
- Find theoretical upper bounds for the list decoding performance.
- Extend the capabilities of the fully-software decoder with the support of any CRC code and any CC code of rate-1/*n* (both tail-biting and zero-tail terminated).
- Analyze the performance of CRC+CC codes over fading channels which are of interest for cellular networks, and with new likelihood decoding metrics for list decoding over fading channels, like the tail-biting terminated CC code of the 4G standard.
- Search for new CRC+CC codes with better spectrum properties than the ones already in use or recommended in various standards and systems.

List of attended classes

- 01UNMRT – Aspetti algebrici della crittografia (2022, 6 credits)
- 01TSGKG – The Monte Carlo method (2022, 6 credits)
- 02SFURV – Programmazione scientifica avanzata in matlab (2022, 6 credits)
- 01ROOKG – Introduction to Belief Propagation (2022, 2 credits)
- 01DOCRV – The Hitchhiker's Guide to the Academic Galaxy… (2022, 4 credits)
- 01SWPRV – Time management (2022, 1 credits)
- 02LWHRV – Communication (2022, 1 credits)
- 01UNXRV – Thinking out of the box (2022, 1 credits)
- 01RISRV – Public speaking (2022, 1 credits)
- "Online Ladybird Guide to Spacecraft Communications Training Course 2022", European Space Agency (2022, 40h)