WHITE PAPER

TSOFUN GENERALIZED CONCATENATED CODES (TGCC)

Introduction

The ultimate target of communication systems is to maximize the rate at which information can be transmitted over a channel in the presence of noise, while keeping it simple and with low power consumption.

Error-correction codes are a pivotal technology used in communication and storage systems, to enhance the affordable channel signal-to-noise ratio and increasing system's reliability. Modern coding schemes performance strives to close the gap to the theoretical achievable efficiency, the Shannon limit, with acceptable implementation complexity. This white paper provides a concise description of error-correction coding schemes developed in Tsofun, and discuss their advent-ages in comparison with currently used schemes.

Since their inception in the middle of the twen-tieth Century, coding techniques have gone through many changes. We mention here those approaches that prevailed at a certain period, namely Algebraic, Convolutional, Concatenated, Product, Turbo, Low-Density-Parity-Check (LDPC) and Polar.

Modern standards mostly use codes allowing iterative decoding: Product, Turbo and LDPC codes. Recently, Polar codes rose in a few wireless standards. Let us elaborate on the advantages and disadvantages of the leading coding schemes.

Product Codes

Advantages: low implementation complexity, possibility of parallelization and thus high throughput.

Disadvantages: inefficiency for low information rates, small minimum distance and thus error-floor, restricted rates granularity and inefficiency for short lengths.

Turbo Codes

Advantages: modest implementation complexity and high efficiency.

Disadvantages: significant error-floor, low granularity, slow convergence, heavy processing per iteration, inefficient for short block lengths and performance degradation due to puncturing (rate adjustment).

LDPC Codes

Advantages: regular design in implementation - large number of identical simple units, modest complexity, high efficiency for medium to high information rates, flexible early termination. Enabling reaching high throughputs through efficient implementation with high decoding parallelism.

Disadvantages: decreased efficiency in low information rates - the gap to the Shannon limit grows when the rate decreases; low efficiency for short code lengths; significant error-floor, essential loss in efficiency for very low output error rates (10^{-8} to 10^{-15}); increased complexity for very high information rates.

Polar Codes

Advantages; closing the gap to Shannon limit is possible by increasing the implementation complexity (flexible); error-floor free; better than LDPC codes for low rates; better than iterative schemes performance for short lengths and low information lengths.

Disadvantages: essentially sequential decoding procedure, restricting throughput; significant complexity growth when increasing list size; slow performance improvement when the code length grows, thus, necessity to drastically increase complexity (list size) for small lengths to achieve valuable performance goals.

The common weakness of all the aforementioned schemes is related to the absence of a solid theoretical analysis for their performance. Proving their performance parameters requires comprehensive simulations which in many cases are impractical for very low output error rates.

Generalized Concatenated Codes

Generalized concatenated codes (GCC) are error correction codes introduced by Blokh and Zyabolov [1] and Zinoviev [2] as generalization of Forney's concatenated codes [3]. GCC construction uses several short constituent codes, called outer-codes, that are combined into a large code by applying an inner-code on their coordinates. By employing appropriate combinations of outer-codes and nested inner-codes excellent GCC were developed [4]. Moreover, efficient decoding algorithms exist that utilize the GCC structure by performing local decoding steps on the outer-codes while using the inner-code layer for exchanging decisions between the outer-codes.

Arikan's polar codes [1] are an example of recursive GCCs. A polar code of length $N = 2^n$ bits is constructed by two outer-codes of length N/2 bits. Those outer-codes are themselves polar codes, thereby generating a recursive framework. The polar inner-code is of length two bits and defined by the mapping $\phi(u, v) = [u \oplus v, v]$, that is also called the polar code kernel.

Tsofun Generalized Concatenated Codes (TGCC)

In TGCC we push further the flexibility of the generalized concatenation construction by variation on the used kernels (inner codes), utilizing varying kernels, different lengths of outer codes, varying alphabets, etc. (refer to [6] and [7]). This allows to resolve many existing problems of generalized concatenation codes and to essentially improve the currently popular polar coding schemes [8].

Advantages of TGCC

- Convergence to the Shannon limit faster than Turbo, LDPC (as shown in Fig. 1) and Polar codes, as a function of code's length, thus, allowing for essentially lower implement-tation complexity.

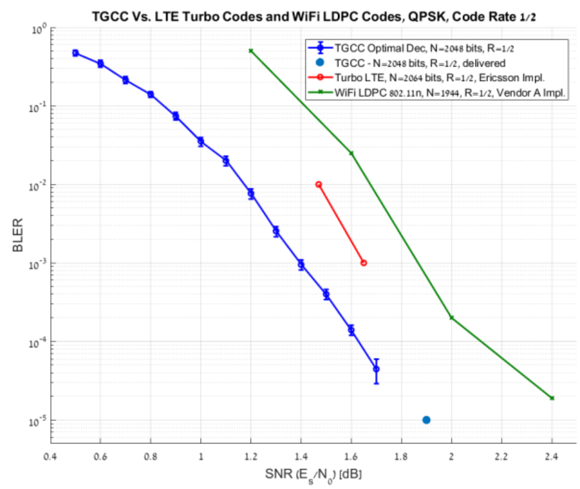

Fig. 1: TGCC advantage over Turbo (4G/LTE) and LDPC (802.11ac Wi-Fi) codes

- Supporting essentially higher throughput, through parallelization of the decoding process.
- Free of error floor, unlike codes with iterative decoding (e.g. LDPC).
- Provable low output error rates performance, based on simple inner codes design.
- Very high information rate granularity, enabling simple implementation of the systems supporting a large set of codes.
- High performance for short code lengths.

- High performance with modest implementation complexity for very low output error rates.
- High performance with modest implementation complexity for low information rates, with the ability to provide outstanding performance at very low SNR levels. Unlike in LDPC codes, the Shannon limit gap does not grow when the information rate decrease, thus allowing using higher constellations along with low rate TGCC codes.
- Allowing trade-offs between complexity and performance.

Applications in which TGCC is superior to other codes

Satellite Communications

Recently adopted DVB-S2X standard uses LDPC codes of lengths 16K and 64K. The required output error rates are very low. TGCC codes allow improving spectrum efficiency of the codes from the standard by ~10% in the SNR interval from 10dB to -10dB, and by 25% and more for lower SNR levels, while keeping implementation complexity similar to standard LDPC schemes.

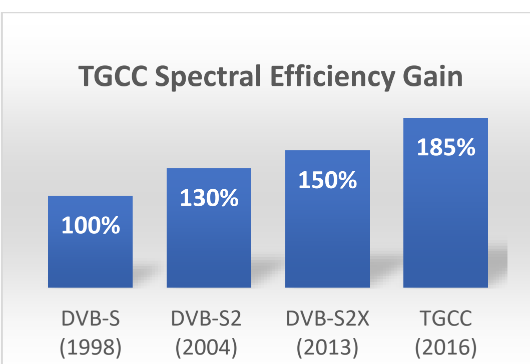

Fig. 2: TGCC Spectral Efficiency gain in Satellite Communication

5G Polar Codes

The approaches developed for TGCC enables a significant improvement in implementation of the 3GPP-adopted 5G standard Polar coding schemes (UL and DL), with improved FER (with List 32, as shown in Fig 4), smaller decoding latency (as shown in Fig. 5), 30% less complexity and reduction of the power consumption (as shown in Fig. 6), compared to the best solutions available in the market.

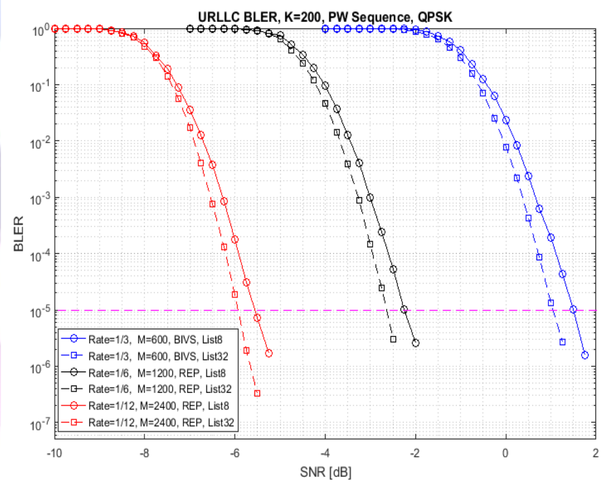

Fig. 4: Tsofun 5G implementation gain (0.5dB without adding complexity)

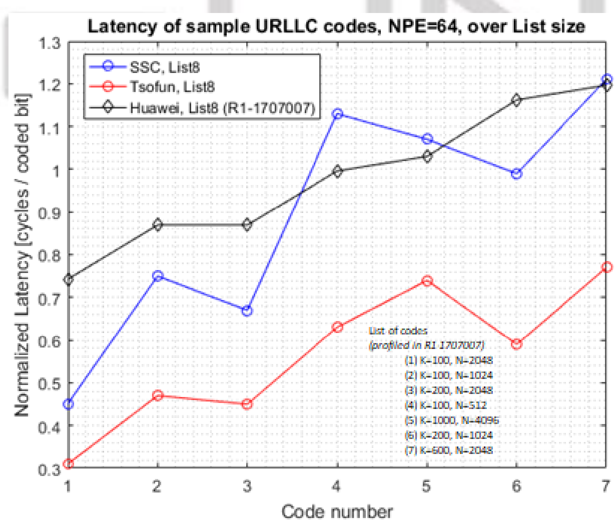

Fig. 5: Tsofun 5G implementation outperforms competition in Latency

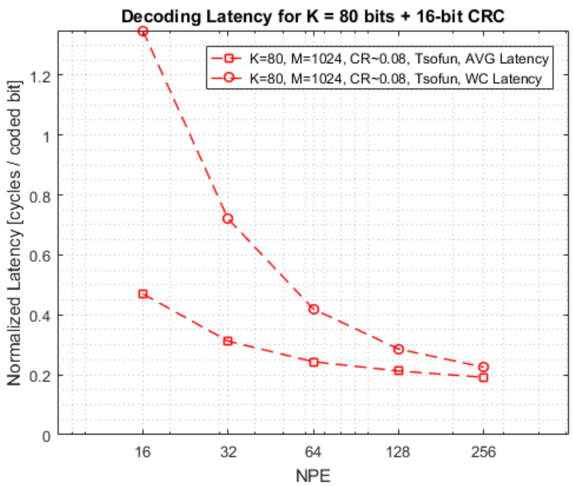

Fig. 6: Tsofun 5G implementation saves power and complexity

Optical Communications

Challenging conditions of 100 / 200 / 400Gbps fast optical network with their very low output error rates, push for designing highly efficient parallel coding schemes. TGCC achieves more than 11 dB net coding gain (NCG) at 10^{-15} BER, as shown in Fig. 3, with modest implementation complexity, prevailing the best performing competing schemes in the market.

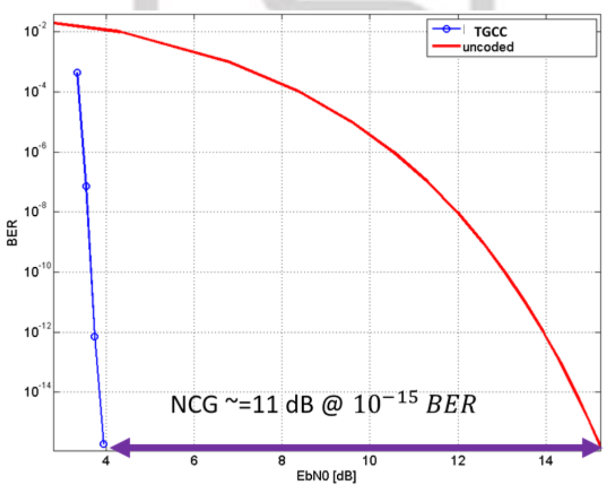

Fig. 3: TGCC Net Coding Gain in Fast Optical Networks

Flash Memory Controllers

TGCC outperforms state-of-the-art solutions in power consumption, throughput and capacity. It tolerates 20% more errors before switching to Soft Bits decoding (high power and high latency error correction mode), and tolerates 50% more input errors before decoding, in high power and high latency error correction mode, while providing equal or higher throughput at smaller silicon IP size.

Low SNR communication systems

TGCC is implemented in several proprietary Low SNR systems, providing improved performance without increasing the implementation complexity. Some low SNR scenarios include:

- Unmanned military/defense systems
- Space Data Links
- Maritime Communication
- Terrestrial Communication
- Automotive Communication
- Connected Cars
- IoT & M2M
- Agricultural Systems
- Public Safety
- Disaster Recovery

Summary

This white paper provided a concise description of the novel Tsofun Generalized Concatenated Codes (TGCC) and discussed its superiority over today's most advanced coding schemes (Turbo and LDPC) in Satellite, 5G, Optical, Flash and various low SNR communication systems.

TGCC supports higher throughput, it is free of error floor, not sensitive to SNR estimation errors, has low output error-rates' performance and very high information rate granularity. It enables achieving high coding performance for short code lengths, very low output error rates and low information rates, while providing outstanding performance at very low SNR levels.

Based on the TGCC codes, Tsofun also implemented the 3GPP-adopted 5G standard Polar codes (UL and DL), with shorter decoding latency, higher throughput and lower power consumption, compared to the best available solutions in the market.

References

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