Submission Title: A Study on Comparison of Polar and LDPC Codes above 100Gb/s Throughput Regime
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Re: n/a
Abstract: This talk will provide studies on the communication performance and implementation level comparison of LDPC and polar codes for above 100Gb/s throughputs. The comparison will focus on selected LDPC codes standardized in 3GPP 5G NR, IEEE 802.16 WiMAX, IEEE 802.15.3d standards, and state-of-the-art polar codes designed for ultra-high throughputs.

Purpose: Information of the Technical Advisory Group THz
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Exceeding 100 Gb/s Barrier in Wireless Communications

- **Huge available spectrum** potential above 250GHz to achieve 100Gb/s and higher throughputs.
  - 252-325 GHz bands already considered under 802.15.3d.
  - Potential bandwidth allocations: 275-450GHz in WRC 2019 (AI 1.15).

- Substantial progress in **device-level and RF** front-end.
  - THz photonics based RF front-end solutions demonstrate ~100Gb/s ([1]).
  - 300 GHz Si CMOS transceiver solutions with >100Gb/s transmitters ([2]).

- **Novel baseband algorithms and architectures** are necessary to enable ultra-high throughputs in THz domain for a wide range of practical use-cases.
  - **FEC** is the most complex and computationally intense component in the baseband chain → A key enabler and challenge for ultra-high throughput/THz communications.
State-of-the-Art FEC for High Throughput Wireless Systems

In existing wireless standards, 3GPP 5G NR, IEEE 802.15.3d and IEEE 802.11ad* present FEC classes with highest throughput requirements.

- **3GPP 5G NR (Target peak TP: 20Gb/s)**
  - Flexible QC-LDPC; 20 Gb/s with rate 8/9 is supported

- **IEEE 802.15.3d (Target peak TP: 100Gb/s)**
  - Rate 14/15 LDPC (1440,1344)
  - Rate 11/15 LDPC (1440,1056)

- **IEEE 802.11ad (Target peak TP: 7Gb/s)**
  - Rate (1/2, 5/8, 3/4, 13/16) LDPC with code-word length 672

* 802.11ay amendment (Draft 3.0 stage) targets >20 Gb/s, in addition includes Rate (1/2, 5/8, 3/4, 13/16) LDPC-1344. The decoder architectures are based on 11ad LDPC-672 codes.
Motivation

▪ The feasibility of already standardized and/or state-of-the-art FEC should be assessed for practical THz use-cases, in particular for 100Gb/s and above throughput regimes.

▪ It is most essential to identify both communications (e.g. FER) and implementation (e.g. throughput, power, area) performances to have a fair comparison among the codes.

▪ In this contribution, we consider selected codes from 3GPP 5G NR, WiMAX, and 802.15.3d* standards as well as polar codes designed for the target ultra-high throughputs.

* In this contribution, only communications performance of 802.15.3d codes is provided.
Study 1: 5G NR Polar Codes versus LDPC Codes - Implementation Performance

- Length=1024, Rate=1/2, 3GPP 5G NR Polar (eMBB control channel) and LDPC Codes (eMBB data channel)\(^3\).
- Polar codes with successive cancellation decoder, LDPC with Min-Sum decoder (4 & 7 iterations).

![Graph showing FER vs Eb/N0 for different codes](image)

FER \(10^{-7}\) @ 400 Gbit/s
Study 1: 5G NR Polar Codes versus LDPC Codes - Implementation Performance

- Length=1024, Rate=1/2, 3GPP 5G NR Polar (eMBB control channel) and LDPC Codes (eMBB data channel)[3].
- Worst case PVT timing 28nm technology, target frequency 400MHz.
- Fully “unrolled decoder architectures” for both codes @ 400Gbit/s (200Gbit/s coded throughput).

<table>
<thead>
<tr>
<th>Place &amp; Route</th>
<th>Polar SC</th>
<th>LDPC Min-Sum I=7</th>
<th>LDPC Min-Sum I=4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (MHz)</td>
<td>402</td>
<td>339</td>
<td>400</td>
</tr>
<tr>
<td>Throughput (Gbps)</td>
<td>411.2</td>
<td>347.6</td>
<td>409.6</td>
</tr>
<tr>
<td>Area (mm²)</td>
<td>1.4349</td>
<td>6.9455</td>
<td>3.8562</td>
</tr>
<tr>
<td>Area Efficiency (Gbps/mm²)</td>
<td>287</td>
<td>50</td>
<td>106</td>
</tr>
<tr>
<td>Utilization %</td>
<td>75</td>
<td>70</td>
<td>70</td>
</tr>
<tr>
<td>Power Total (W)</td>
<td>1.264</td>
<td>8.083</td>
<td>5.051</td>
</tr>
<tr>
<td>Power Clock (W)</td>
<td>0.222</td>
<td>1.352</td>
<td>0.887</td>
</tr>
<tr>
<td>Power Registers (W)</td>
<td>0.178</td>
<td>1.019</td>
<td>0.687</td>
</tr>
<tr>
<td>Power Comb (W)</td>
<td>0.864</td>
<td>5.713</td>
<td>3.477</td>
</tr>
<tr>
<td>Energy Efficiency (pJ/bit)</td>
<td>3.07</td>
<td>23.25</td>
<td>12.33</td>
</tr>
<tr>
<td>Power Density (W/mm²)</td>
<td>0.88</td>
<td>1.16</td>
<td>1.31</td>
</tr>
</tbody>
</table>
Study 1: 5G NR Polar Codes versus LDPC Codes - Implementation Performance

- Length=1024, Rate=1/2, 3GPP 5G NR Polar (eMBB control channel) and LDPC Codes (eMBB data channel)\[^3\].

<table>
<thead>
<tr>
<th></th>
<th>Polar decoder</th>
<th>LDPC decoder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area</td>
<td>1.4 mm(^2)</td>
<td>6.9 mm(^2)</td>
</tr>
<tr>
<td>Power</td>
<td>1.2 W</td>
<td>8 Watt</td>
</tr>
</tbody>
</table>
Study 2: Polar Codes versus WiMAX LDPC Codes - Communications Performance

- Length=1024, Rate=5/6 Polar Codes generated with:
  i. 6.5dB density evolution (DE)
  ii. 2dB Gaussian Approximation (GA)
- Length=1056, Rate=5/6 LDPC codes with min-sum (2 iterations)

![Graph showing FER vs Eb/N0 for LDPC/Polar codes]

FER $10^{-7}$ @400 Gbit/s
Study 2: Polar Codes versus WiMAX LDPC Codes - Implementation Performance

- Rate=5/6, Length=1024 Polar (DE 6.5dB), Length=1056 LDPC Codes[4].
- Worst case PVT timing 28nm technology, target frequency 400MHz.
- Fully “unrolled decoder architectures” for both codes @ 400Gbit/s (333Gbit/s coded throughput).

<table>
<thead>
<tr>
<th>Place &amp; Route</th>
<th>Polar GA</th>
<th>Polar DE</th>
<th>LDPC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (MHz)</td>
<td>402</td>
<td>402</td>
<td>400</td>
</tr>
<tr>
<td>Throughput (Gbps)</td>
<td>411.2</td>
<td>411.2</td>
<td>409.6</td>
</tr>
<tr>
<td>Area (mm²)</td>
<td>1.2135</td>
<td>1.3816</td>
<td>1.6736</td>
</tr>
<tr>
<td>Area Efficiency (Gbps/mm²)</td>
<td>339</td>
<td>298</td>
<td>245</td>
</tr>
<tr>
<td>Utilization %</td>
<td>73</td>
<td>75</td>
<td>70</td>
</tr>
<tr>
<td>Power Total (W)</td>
<td>0.892</td>
<td>1.147</td>
<td>2.037</td>
</tr>
<tr>
<td>Power Clock (W)</td>
<td>0.196</td>
<td>0.228</td>
<td>0.371</td>
</tr>
<tr>
<td>Power Registers (W)</td>
<td>0.161</td>
<td>0.192</td>
<td>0.262</td>
</tr>
<tr>
<td>Power Comb (W)</td>
<td>0.536</td>
<td>0.727</td>
<td>1.404</td>
</tr>
<tr>
<td>Energy Efficiency (pJ/bit)</td>
<td>2.17</td>
<td>2.79</td>
<td>4.97</td>
</tr>
<tr>
<td>Power Density (W/mm²)</td>
<td>0.74</td>
<td>0.83</td>
<td>1.22</td>
</tr>
</tbody>
</table>
Study 2: Polar Codes versus WiMAX LDPC Codes - Implementation Performance

- Rate=5/6, Length=1024 Polar (DE 6.5dB), Rate=5/6, Length=1056 LDPC Codes[^4]

Polar decoder DE
1.4 mm² @ 1.1 W
>1dB gain @ FER 10⁻⁷

LDPC decoder
1.7 mm² @ 2.0 Watt
Study 3: Polar Codes versus 802.15.3d LDPC Codes - Communications Performance

- **FEC classes evaluated:**
  - **802.15.3d LDPC:** Length-1440, Rate=11/15\[^5\]. I=50 iterations.
  - **Polar codes:** Length(L) = 2048, 4096, Rate=11/15. List-size=1,2 (CRC=8bits). Density (D) evolution based code design.

**Observation:**
- Polar code L=4096, List-size=1 and Polar code L=2048, List-size=2 are able to compete with LDPC codes at SNRs greater than 6dB.
- LDPC code experiences degraded performance at high SNRs (>6dB), a critical range for THz use-cases.

**Modulation:** QPSK
**AWGN channel** (BH/FH use-case in 802.15.3d study)
Conclusion

- A thorough investigation of FEC both in terms of communications and implementation performances is necessary for practical THz use-cases.

- The study demonstrates under the same technology (28nm), (frequency, quantization) constraints, and 400Gb/s throughput:
  - 5G NR polar codes with SC (Length=1024, Rate=1/2) outperforms 5G NR LDPC codes with min-sum decoder (Length=1024, Rate=1/2, iter=4,7) both in terms of implementation and communications performances (at least <10\(^{-7}\) FER).
  - Polar codes with SC (Length=1024, Rate=5/6, DE 6.5dB) outperforms WiMAX LDPC codes with min-sum decoder (Length=1056, Rate=5/6, iter=2) both in terms of implementation and communications performances.
  - In terms of communications performance only, Polar codes with Length=4096, List-size=1 and Polar code Length=2048, List-size=2 demonstrate better performance for SNR>6dB.
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REFERENCES