5G NR Channel Coding

Ajit Nimbalker

Next Generation & Standards (NGS)
Acknowledgements

Dmitry Dikarev
Fatemeh Hamidi-Sepehr
Gregory Ermolaev
Seunghee Han
Eddy Kwon
# 3GPP 5G Requirements (TR 38.913)

**Key requirements (to be met by either or both of LTE-evolution and New Radio)**

- Extreme peak rates
- Ultra-high network capacity
- Uniform user experience
- Massive connectivity
- Ultra-reliable and low-latency communication (URLLC)
- Improved cost & energy efficiency

<table>
<thead>
<tr>
<th></th>
<th>5G</th>
<th>LTE-Advanced (4.5G)</th>
<th>LTE (4G)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Peak data rate</strong></td>
<td>20 Gbps for DL, 10 Gbps for UL</td>
<td>1 Gbps for DL, 500 Mbps for UL</td>
<td>100Mbps for DL, 50Mbps for UL</td>
</tr>
<tr>
<td><strong>Peak Spectral Efficiency</strong></td>
<td>30 bps/Hz for DL and 15 bps/Hz for UL</td>
<td>30 bps/Hz for DL and 15 bps/Hz for UL</td>
<td>5 bps/Hz for DL, 2.5 bps/Hz for UL</td>
</tr>
<tr>
<td><strong>Control Plane Latency (IDLE-&gt;ACTIVE)</strong></td>
<td>10 ms</td>
<td>50 ms</td>
<td>100ms</td>
</tr>
<tr>
<td><strong>User Plane Latency</strong> *</td>
<td>eMBB: 4 ms for DL, 4 ms for UL. URLLC: 0.5 ms for DL, 0.5 ms for UL</td>
<td>Lower than LTE</td>
<td>5ms in unload condition</td>
</tr>
<tr>
<td><strong>Reliability</strong></td>
<td>Support up to 10^-5 packet error rate within 1ms</td>
<td>Not defined</td>
<td>Not defined</td>
</tr>
<tr>
<td><strong>Connection density</strong></td>
<td>1 Million device/km^2 in urban environment</td>
<td>300 UEs/cell per 5MHz</td>
<td>200 UEs/cell per 5MHz</td>
</tr>
<tr>
<td><strong>Target mobility</strong></td>
<td>500km/h</td>
<td>up to 350km/h (or perhaps even up to 500km/h depending on the frequency band)</td>
<td>Optimized for 0 to 15km/h Support with high perf for 15 to 120 km/h Support up to 350km/h</td>
</tr>
</tbody>
</table>

* The time it takes to successfully deliver an application layer packet/message from the radio protocol layer 2/3 SDU ingress point to the radio protocol layer 2/3 SDU egress point via the radio interface in both uplink and downlink directions.
Some Key Features of Rel-15 5G NR

**Support of higher & wider frequency band**
- Rel-15 supports up to 52.6GHz (sub-1GHz, sub-6GHz, above 6GHz)
  - Much wider BW available in 24.5-39GHz bands, e.g., ~1GHz
- Support of wider BW per component carrier
  - up to 400 MHz in Rel-15 (note: LTE supports up to 20MHz per CC)

**Scalable numerology**
- Support multiple numerologies (subcarrier spacing, CP, slot length) with scaling (LTE: 15kHz subcarrier spacing for MBB)

**Wide bandwidth per component carrier**
Support up to 400 MHz per component carrier in Rel-15

**LTE-NR Dual connectivity**
- UE is simultaneously connected to LTE and NR base stations
- LTE provides coverage layer ensuring signalling reliability, while NR provides high data rates.
- Reducing service interruption by quick fall back to LTE when there is blockage in NR link or UE goes out of NR coverage

**Advanced Channel Coding Schemes**
- LDPC for data and Polar code for control
  - Efficient support of very high peak rates and lower latency
  - Better performance esp., for small packets.
- TBD for URLLC and mMTC

<table>
<thead>
<tr>
<th>Code</th>
<th>Data rate</th>
<th>Area</th>
<th>Throughput/Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>LTE turbo code</td>
<td>1.67 Gbps</td>
<td>2.004 mm²@45nm</td>
<td>0.81</td>
</tr>
<tr>
<td>802.11n LDPC code</td>
<td>3 Gbps</td>
<td>0.81 mm²@45nm</td>
<td>3.70</td>
</tr>
</tbody>
</table>
EMBB Data channel

- Target ~20 Gbps peak rate on DL (10 Gbps on UL) and low latencies
- Candidate considered in 3GPP
  - LDPC
  - Turbo code
  - Polar Code
  - Dual-Code solution (e.g. LDPC for large block sizes +Polar code for small block sizes)
- Coding schemes for URLLC, etc. is TBD in RAN1
State of the art implementations (e.g. IEEE)

<table>
<thead>
<tr>
<th>Code</th>
<th>Peak Data rate (Gbps)</th>
<th>Area (sq.mm)</th>
<th>Throughput/Area (Gbps/sq.mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbo</td>
<td>1.7</td>
<td>2.00 @45nm</td>
<td>0.81</td>
</tr>
<tr>
<td>LDPC</td>
<td>3</td>
<td>0.81 @45nm</td>
<td>3.70</td>
</tr>
<tr>
<td>Polar SC**</td>
<td>1.9</td>
<td>0.69 @65nm</td>
<td>2.70</td>
</tr>
</tbody>
</table>

Turbo is LTE turbo, LDPC is 802.11n WiFi LDPC
Note **: Polar SC decoder has inferior performance compared to Turbo/LDPC, List decoding improves Polar code performance

- List decoding of Polar code is an active area of R&D
- Performance of all three schemes comparable at least at large block sizes
- LDPC can deliver superior throughput and reduced latency
LDPC Key Benefits

- Flexible and tailored design
- Hardware friendly and parallelizable encoding/decoding
- Base graph construction, and selection of shift sizes (or lift sizes)
- Row-orthogonality to further reduce latency and increase throughputs

- Flexible decoder implementations based on layered belief propagation
- Faster information flow
- Scope for differentiation (Single Block, Multi-Block, etc)
- Finer iteration control (e.g. Stop decoding after any CNU)

Key LDPC features

- Flexible LDPC design – code rates/block lengths
- An LDPC code is defined by a parity check matrix $H$, $(H \cdot x^T = 0)$
- $H$ is derived from
  - Base graph (BG) smaller BG => lower latency
  - Shift size (Z) larger Z => higher throughput
  - Shift coefficients
- Encoding based on dual-diagonal structure (similar to 11n) and Single parity-check (SPC) based extension for lower rate
- LTE-like circular buffer rate-matching for IR-HARQ and LBRM
- Two base graphs
  - BG1 covers 8/9~2/3 coding rate and small to larger block sizes
  - BG2 covers 2/3~1/5 coding rate and very small to medium block sizes
    - Smaller BG2 => better decoding latency

Example: Base graph $r$-6/13 ($k_b = 6$, $n_b = 13$)

Shift size $z=32$

Shift Coefficients for $z=32$ ($k = z \cdot k_b$, $n = z \cdot n_b$)

- PCM for ($k = 192$, $n = 416$) obtained from shift coefficient matrix by replacing
  - Each non-negative entry ($x$) with a $32 \times 32$ Identity matrix shifted to the right by $x$
  - Each "-" is replaced with a $32 \times 32$ all zero-matrix
Example : LDPC Matrix

- **Systematic**
  - **p1**
  - **p2**

- **Codeword**

- **Single mother CW supports circular buffer operation**
  - E.g. \( p_1 = 11n \)-like, \( p_2 = \) single parity-check

- **Weight-3 column corresponding to matrix B has two paired shift values and one unpaired shift value (e.g. \([a \ b \ a]\)).**
  - In 11n LDPC, \( b = 0 \) always
  - In NR, \( b \) is not always 0

- **TXs with higher rate can be decoded faster**
  - E.g. latency proportional to # of edges in the "partial" base graph used for decoding
  - Rate-1/3 has 317 edges
  - Rate-22/24 has 76 edges

**Example BG1 :** \( k=8448, 46 \times 68, R=1/3, z=384 \), yellow highlight shows example row-orthogonality
EMBB Control Channel

- For DL control, need to support several blind decodes, reduced power consumption, lower decoding latency, etc
- Payload is typically 12~128 bits
- Candidates considered in 3GPP
  - Tail-biting convolutional code
  - Polar Code
  - and LDPC, Turbo, Reed-Muller, Repetition and Simplex
- 3GPP agreed on Polar code for UL and DL control information (except for very short block sizes)
Polar code overview – encoding/decoding

- Encoding using a recursive structure for code size $N=2^n$
  - Place data in $K$ input positions and freeze the remaining input positions to 0
  - Reliability sequence identifies the locations of the data bits and frozen bits
  - Flexible information sizes/code rates

- Decoding based on Successive Cancellation
  - SC decoding: Track the best path
  - List decoding: Track $L$ best paths and pick a “best” path at the end
    - E.g. Pick based on CRC (i.e. CA-Polar)
    - E.g. Pick based on path metric (possibly less CRC checks)
  - List size $L$ and code size $N$ affect complexity/latency
  - Simplified SCL algorithms to reduce latency

K=4, N=8

Diagram showing the encoding process with data inputs and corresponding $Y_i$ values.
Polar Code description

- In NR Polar Code discussion, polar codes will be described without bit reversal in the encoder, i.e.:

\[ x_0^{N-1} = u_0^{N-1} G_N \]

- \( G_N \) is the generator matrix of size \( N \)
  - \( G_2 = \begin{bmatrix} 1 & 0 \\ 1 & 1 \end{bmatrix} \)
  - \( G_N = F \otimes^n \) for any \( N = 2^n, n \geq 1 \), where
    - \( F = \begin{bmatrix} 1 & 0 \\ 1 & 1 \end{bmatrix} \), and \( F \otimes^n \) is the \( n \)-th Kronecker power of matrix \( F \)
Maximum Code size (N)

- Mother code length $N$ is limited to reduce latency and complexity
- For DL Control and PBCH, $N_{\text{max},\text{DCI}} = 512$
- For UL, $N_{\text{max},\text{UCI}} = 1024$
  - Optimising code design for $K$ up to 200 is also being considered

From R1-1702713, using bit-reverse shortening based rate-matching
Polar code construction with interleaver (DL)

- One potential candidate is Distributed CRC based design
  - CRC distribution (via interleaver) could be beneficial for early termination (ET)
  - A post-CRC interleaver can distribute information and CRC bits such that partial CRC checks can be performed during list decoding
  - Paths failing partial CRC could be pruned away, leading to early termination (ET) of decoding
  - Interleaver design is closely tied to the CRC generator polynomial
  - Select CRC polynomial so as to achieve better ET gains and maintain same False Alarm Rate

- CRC polynomial and interleaver design is under discussion in 3GPP RAN1
Concluding remarks

- 3GPP NR is envisioned to deliver superior data rates at lower latencies
  - Support of higher and wider frequency band
  - Scalable numerology
  - LTE-NR dual connectivity
  - Advanced channel coding

- Advanced channel coding schemes adopted in NR to facilitate implementations that can efficiently support NR data rates and latencies