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

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

* 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

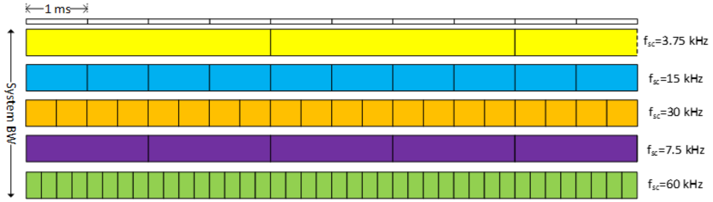
Support of higher & wider frequency band

- 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)

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

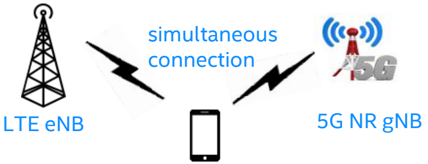
Scalable numerology

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



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

Code	Data rate	Area	Throughput/Area
LTE turbo code	1.67 Gbps	2.004 mm^2 @45nm	0.81
802.11n LDPC code	3 Gbps	0.81 mm^2 @45nm	3.70

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)

Code	Peak Data rate (Gbps)	Area (sq.mm)	Throughput/Area (Gbps/sq.mm)
Turbo	1. 7	2.00 @45nm	0.81
LDPC	3	0.81 @45nm	3.70
Polar SC**	1.9	0.69 @65nm	2.70

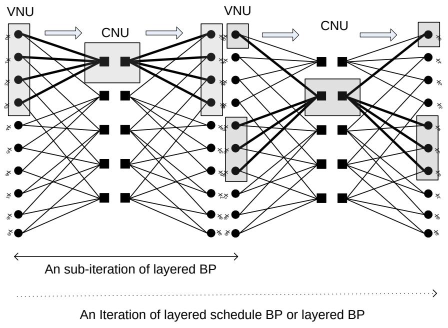
Turbo is LTE turbo,
LDPC is 802.11n WiFi LDPC
Note ** : Polar SC decoder has inferior performance compared to Turbo/LDPC, List decoding improves Polar code performance

- 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

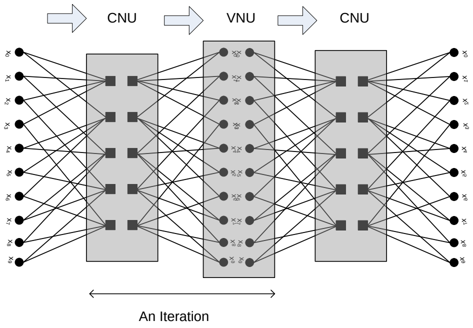
LDPC Key Benefits

- 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)

Layered BP



Flooding BP



Acknowledgement: Motorola, “LDPC Decoding for 802.22 Draft Standard”, 2007

Key LDPC features

- Flexible LDPC design – code rates/block lengths
- An LDPC code is defined by a parity check matrix H, (H. 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)

1	0	1	0	0	0	1	1	0	0	0	0	0
0	1	0	0	1	0	0	1	1	0	0	0	0
0	0	1	0	0	1	1	0	1	1	0	0	0
1	0	0	1	0	0	0	0	0	1	1	0	0
0	1	0	0	1	0	0	0	0	0	1	1	0
0	0	0	1	0	1	1	0	0	0	0	1	0
1	0	1	0	1	0	0	0	0	0	0	0	1

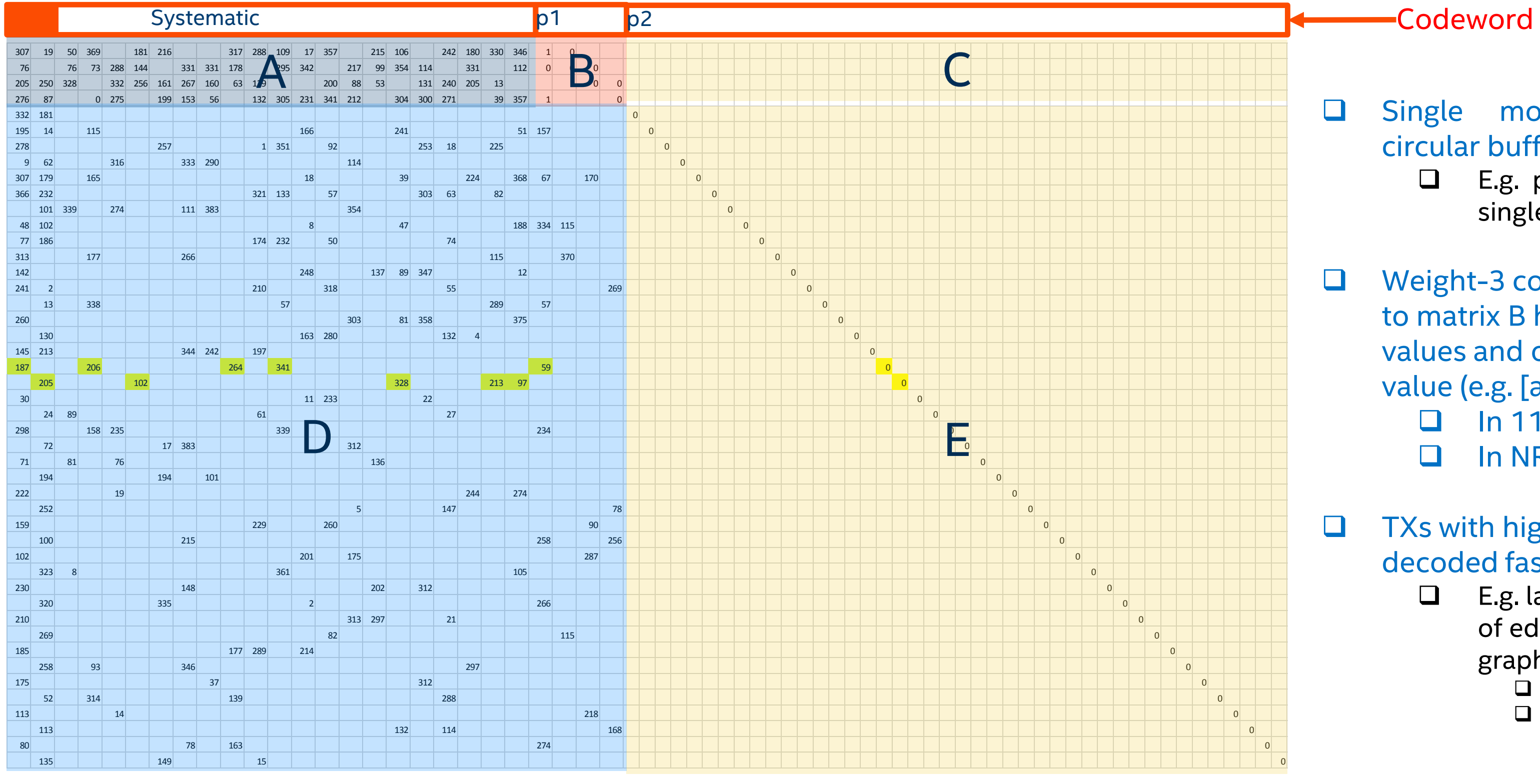
Shift size z=32

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

24	-	0	-	-	-	1	0	-	-	-	-	-
-	14	-	-	6	-	-	0	0	-	-	-	-
-	-	2	-	-	9	0	-	0	0	-	-	-
23	-	-	8	-	-	-	-	-	0	0	-	-
-	15	-	-	3	-	-	-	-	-	0	0	-
-	-	-	13	-	5	1	-	-	-	-	0	-
16	-	10	-	14	-	-	-	-	-	-	-	0

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

Example : LDPC Matrix



- Single mother CW supports circular buffer operation
  - E.g. p1 = 11n-like, p2 = 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

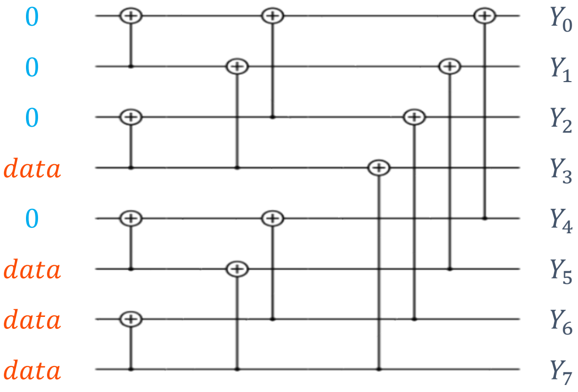
Example BG1 : k=8448, 46 x68, R-1/3, z=384, yellow highlight shows example row-orthogonality

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)

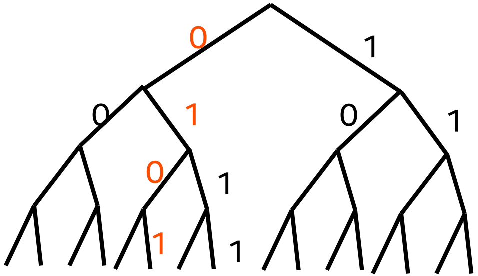
Polar code overview – encoding/decoding

- ❑ **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**



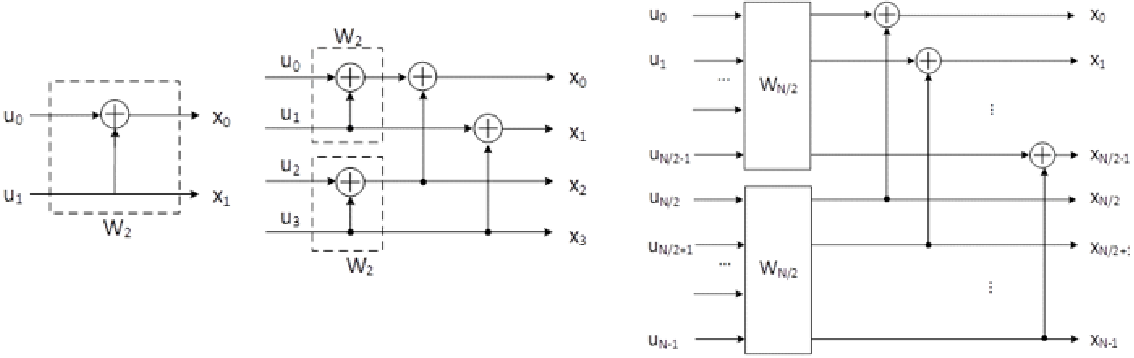
K=4, N=8

- ❑ **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**



Polar Code description

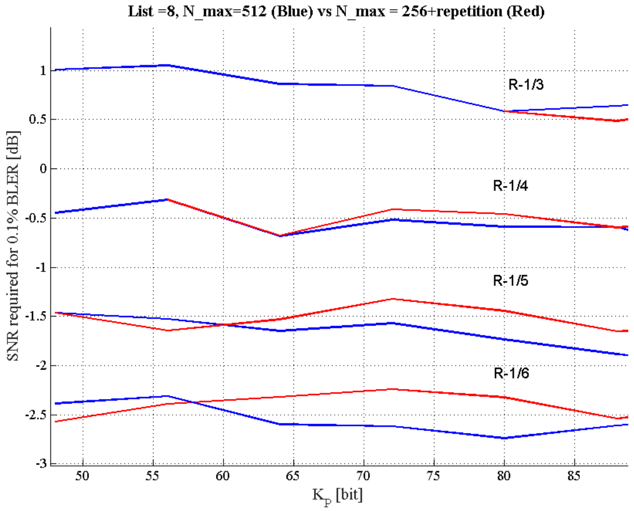
- In NR Polar Code discussion, polar codes will be described without bit reversal in the encoder, i.e.:



- The output of the polar encoder is: $x_0^{N-1} = u_0^{N-1} G_N$
- 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, $N_{max,DCI} = 512$
  - For UL, $N_{max,UCI} = 1024$
    - Optimising code design for K up to 200 is also being considered

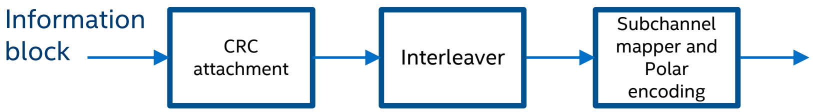


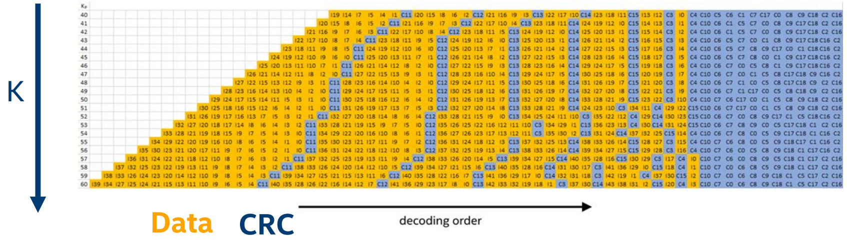
From R1- 1702713, using bit-reverse shortening based rate-matching

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

Example of distributed CRC





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

Intel Communication and Devices Group