



5G NR Channel Coding

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Next Generation & Standards (NGS)

Acknowledgements

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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

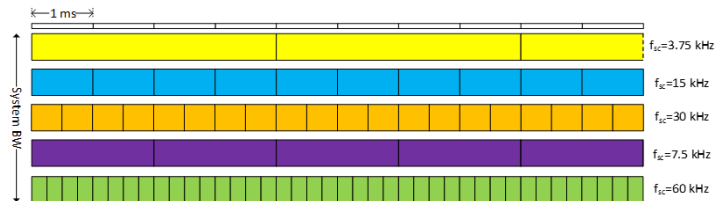
- Rel-15 supports up to 52.6GHz (sub-1GHz, sub-6GHz, above 6GHz)
 - Much wider BW available in 24.5-39GHz bands, e.g., ~1GHz
- Support of wider BW per component carrier
 - up to 400 MHz in Rel-15 (note: LTE supports up to 20MHz per CC)

Wide bandwidth per component carrier

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

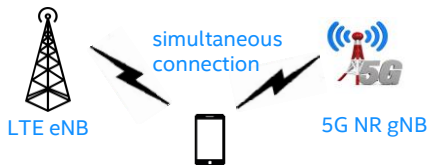
Scalable numerology

- 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,

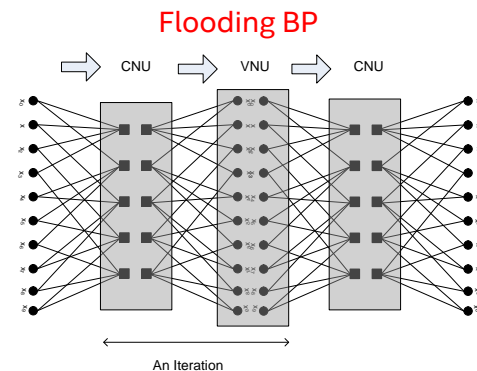
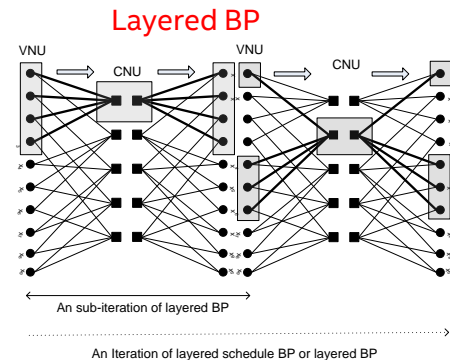
LDPC is 802.11n WiFi LDPC

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)



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 , ($H \cdot x^T = 0$)
- ❑ 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 $8/9 \sim 2/3$ coding rate and small to larger block sizes
 - ❑ BG2 covers $2/3 \sim 1/5$ 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

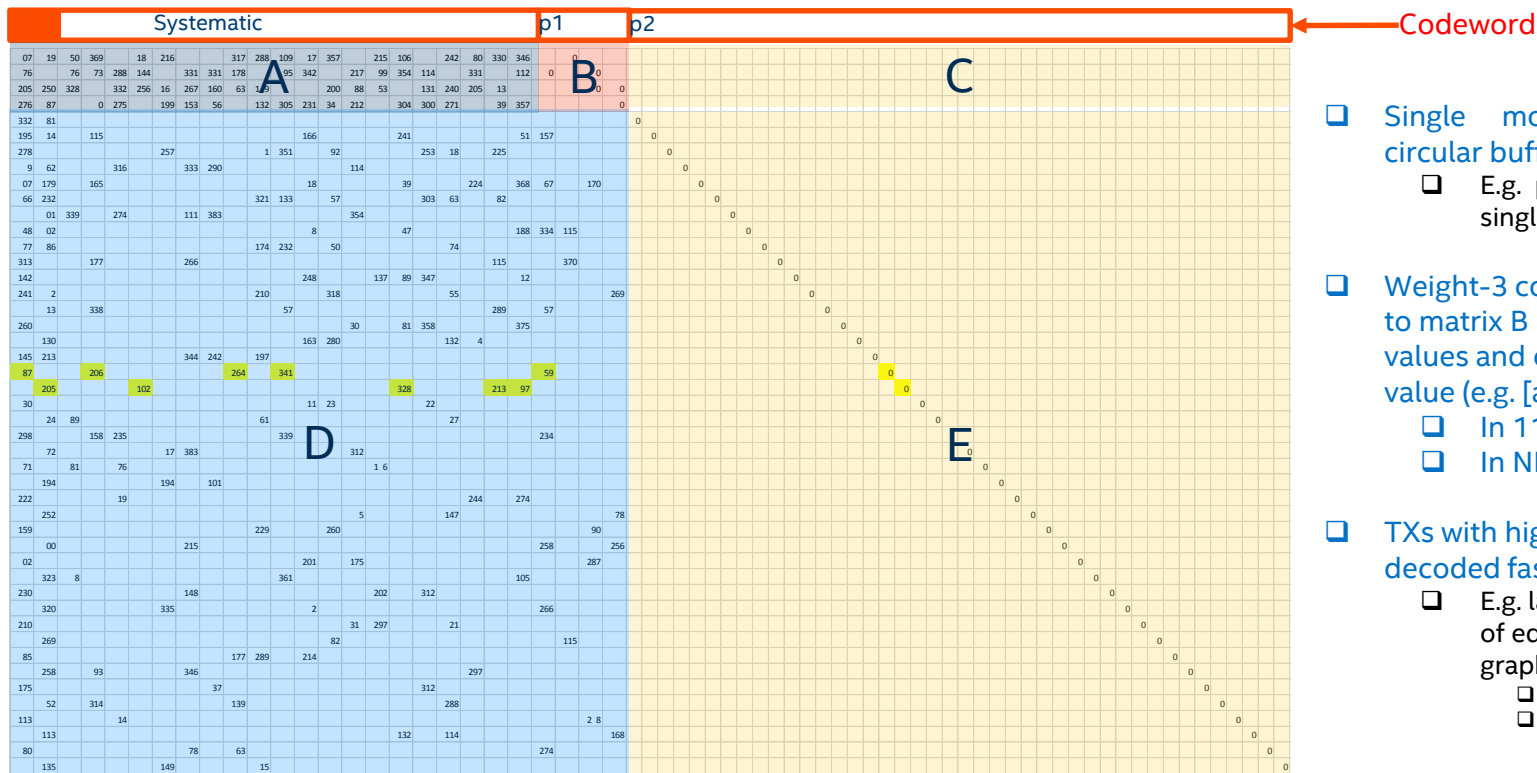
Shift size $z=32$

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 32×32 Identity matrix shifted to the right by x
 - ❑ Each “-” is replaced with a 32×32 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

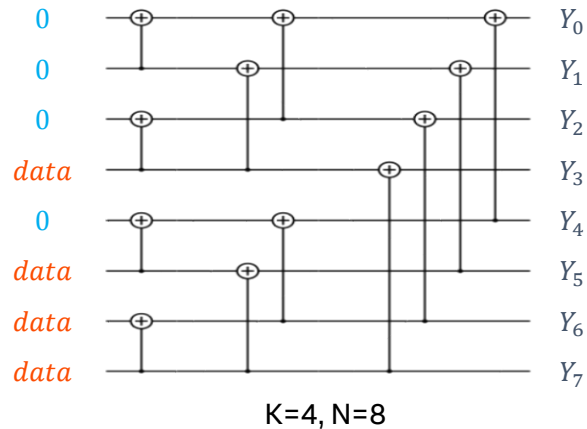
Example BG1 : k=8448, 46 x68, R-1/3, z=384, yellow highlight shows example row-orthogonality

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)

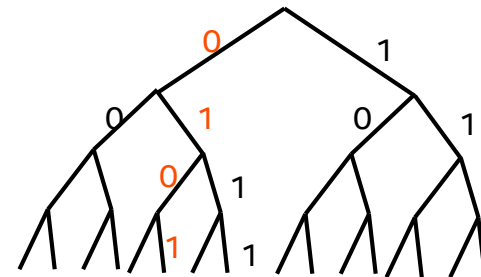
Polar code overview – encoding/decoding

- ❑ 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



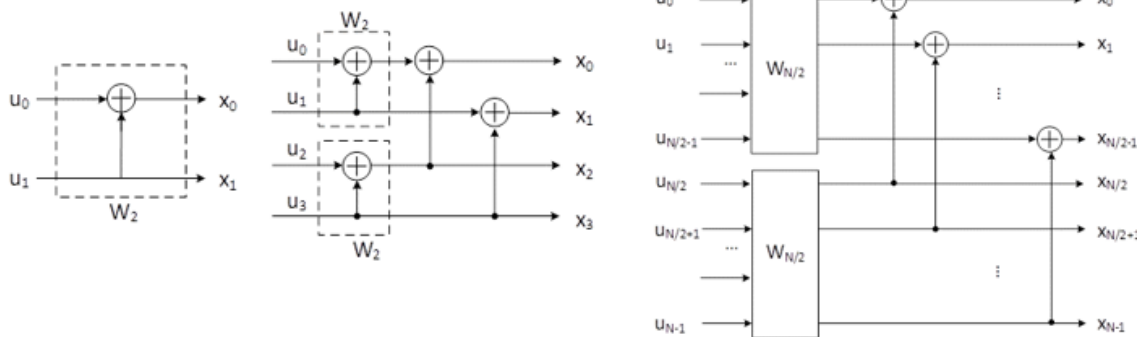
- ❑ Decoding based on Successive Cancellation

- ❑ 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

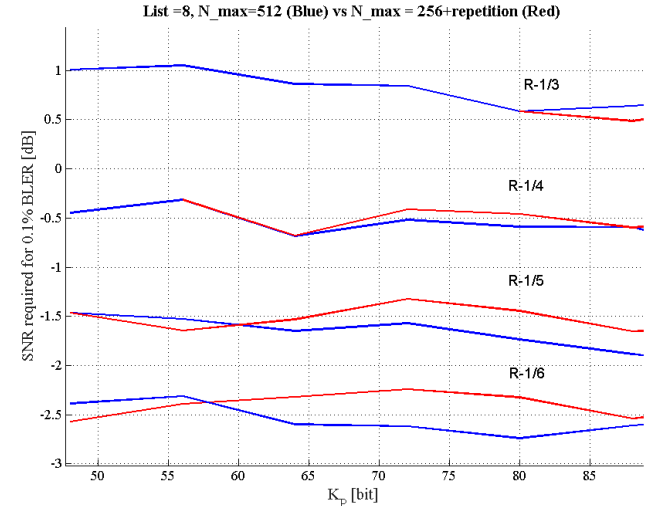
- In NR Polar Code discussion, polar codes will be described without bit reversal in the encoder, i.e.:



- 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

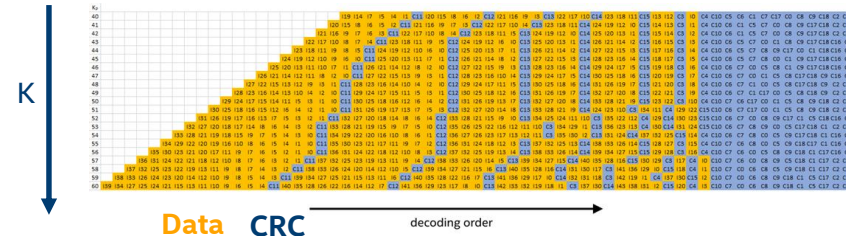
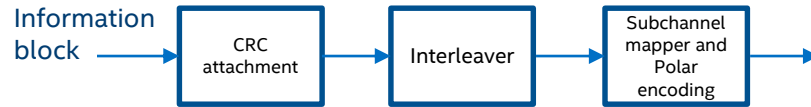


From R1- 1702713, using bit-reverse shortening based rate-matching

Polar code construction with interleaver (DL)

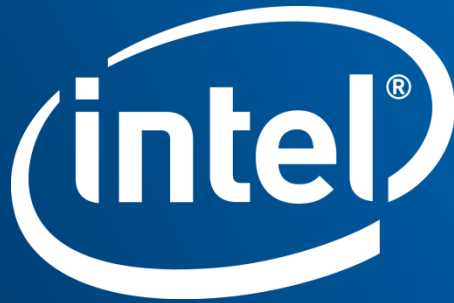
- One potential candidate is Distributed CRC based design
 - CRC distribution (via interleaver) could be beneficial for early termination (ET)
 - A post-CRC interleaver can distribute information and CRC bits such that partial CRC checks can be performed during list decoding
 - Paths failing partial 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