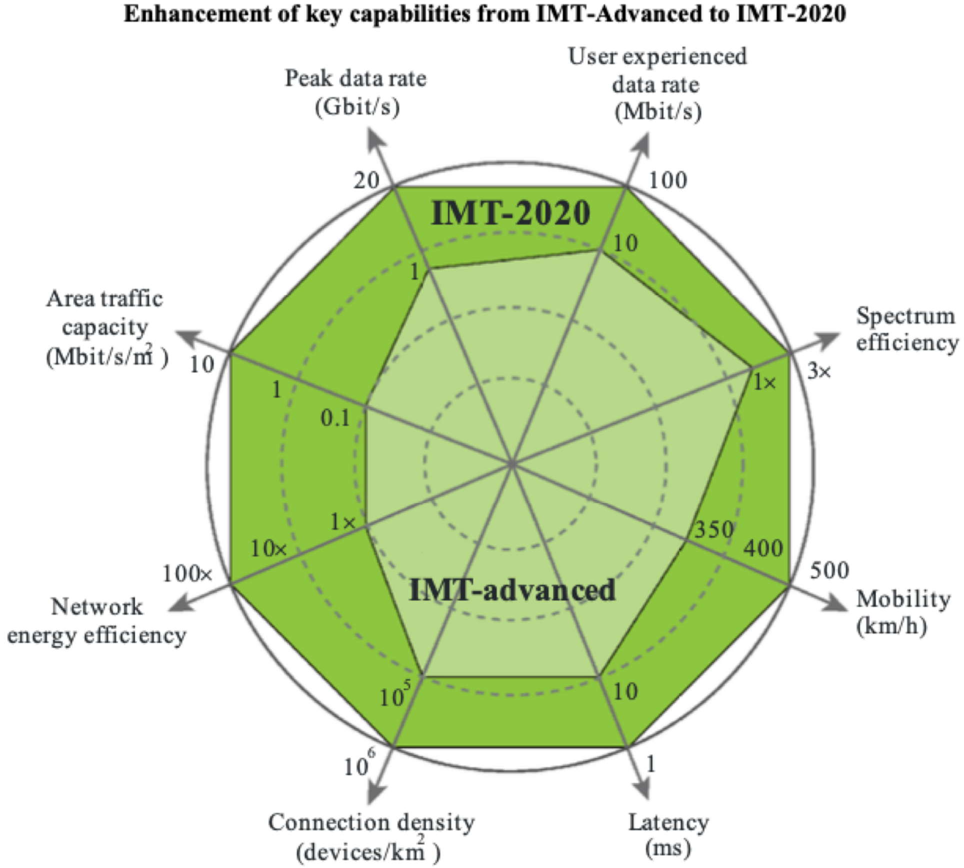
Part 9 Technique for 5G and Beyond

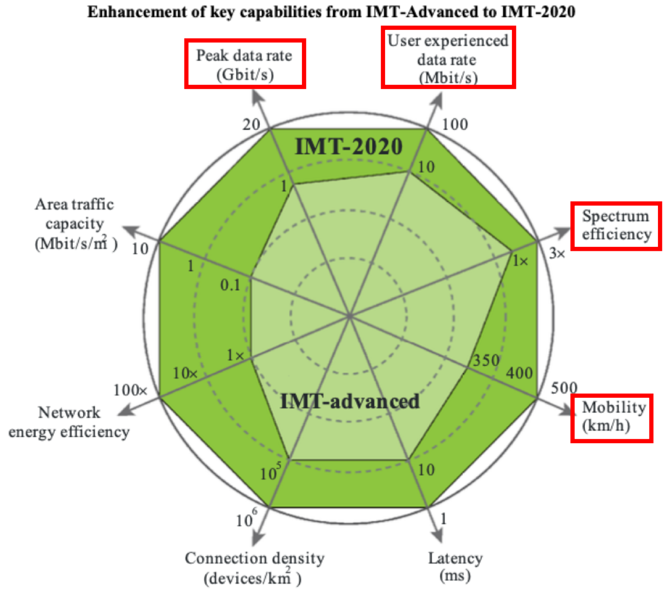
Definition of 5G



Recommendation ITU-R M.2083-0, “IMT Vision – Framework and overall objectives of the future development of IMT for 2020 and beyond,” p. 14, September 2015.

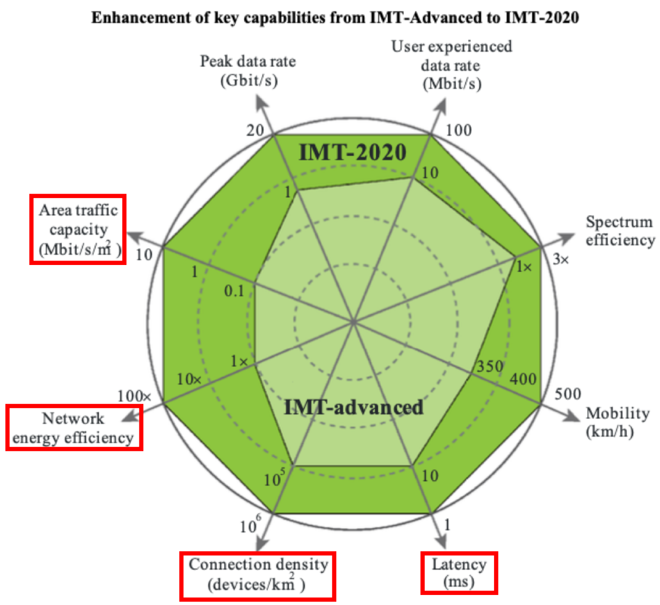
Definition of 5G

- **Peak data rate**:
  - max rate per user under ideal conditions
  - 10 Gbps for mobiles, and 20 Gbps under certain conditions
- **User experienced data rate**:
  - 95% rate across the coverage area per user
  - 100 Mbps in urban/suburban areas, and 1 Gbps hotspot
- **Spectrum efficiency**:
  - Throughput per Hz per cell
- **Mobility**:
  - max speed at which seamless handover and QoS is guaranteed



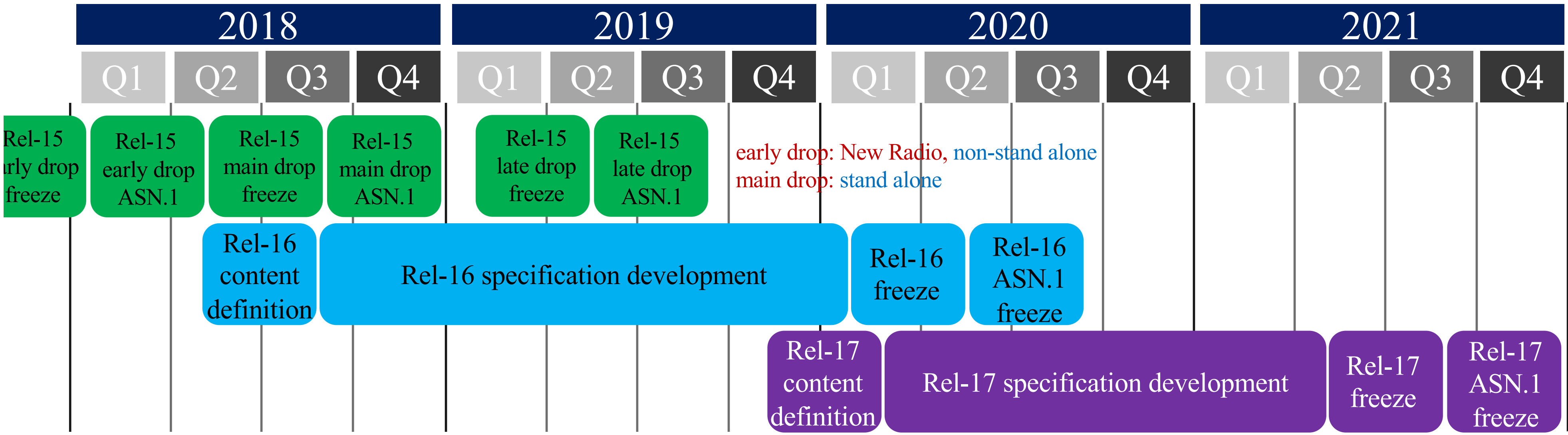
Definition of 5G

- **Latency**:
  - radio contribution to latency between transmit and receive
- **Connection density:**
  - devices per km^2
- **Network energy efficiency:**
  - Include network bits/Joule and user bits/Joule
- **Area traffic capacity**:
  - Throughput per m^2



Key Applications and Schedule

- eMBB (enhanced Mobile BroadBand)
- URLLC (Ultra-Reliable and Low Latency Communications)
- mMTC (massive Machine Type Communications)



Key Applications

- **eMBB**: human centric communication
  - Better mobile phones and hot spots, high data rates, high user density
- **URLLC**: human and machine communication
  - Vehicle-to-vehicle communication, industrial IoT, 3D gaming
- **mMTC**: machine centric communication
  - Very large number of devices, low data rate, low power, IoT with long battery life time

Schedule

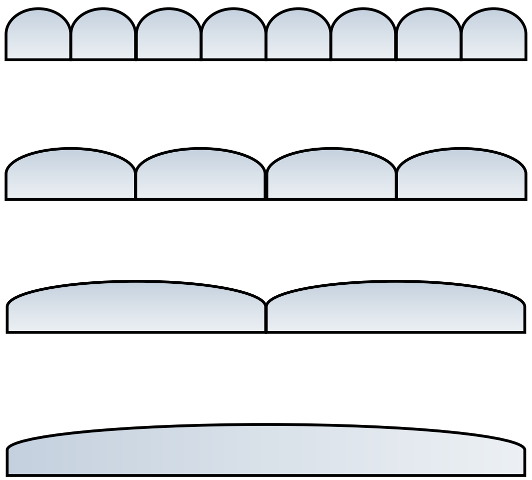
- No major changes are done after a release is frozen.
- Abstract Syntax Notation One (ASN.1) is the notation used to specify message formats in the final specification.
- Release 15 has 3 stages: Non-standalone (NSA), Standalone (SA), and Late Drop.
- Rel-15 early drop versus main drop
  - **Non-Standalone (NSA)**: Use 5G RAN + 4G Core
    - Help accelerate 5G NR deployment
  - **Standalone (SA)**: Full 5G RAN + 5G Core

Spectrum for 5G

- Two Frequency Ranges (FRs) specified in Rel-15
  - **FR1**: 450-6000 MHz (Sub 6-GHz)
  - **FR2**: 24.25-52.6 GHz (mm-Waves)
    - Good for high throughput in small cells

Scalable OFDM in 5G

- 4G specifies a fixed 15 kHz subcarrier spacing (SCS).
- 5G can have many SCSs.
  - $2^n \times 15$ kHz : 15, 30, 60, 120 kHz for $n = 0, 1, 2, 3$
- R15 allows 15/30/60 kHz SCS for FR1 and 60/120 kHz for FR2.



15 KHz spacing < 3GHz macro cells

30 KHz spacing > 3GHz small cells

60 KHz spacing 5 GHz Unlic. Indoor

120 KHz spacing mmWave small cells + backhaul

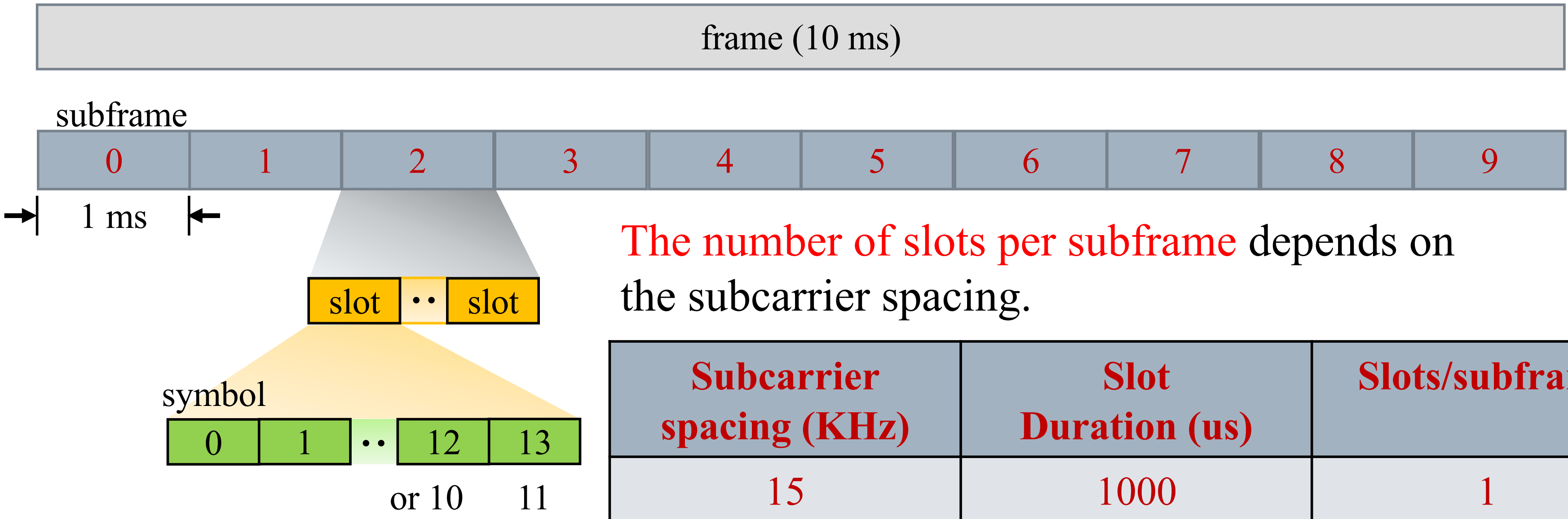
Subcarrier spacing (KHz)	$2^n \times 15$
Symbol duration (us)	$66.67 / 2^n$
Cyclic prefix (us)	$4.69 / 2^n$
Symbol + CP (us)	$71.36 / 2^n$
Symbols per slot	14
Slot duration (us)	$1000 / 2^n$

Scalable OFDM in 5G

- Max FFT size 4096
  - Max 3300 subcarriers for 50, 100, 200, 400 MHz band

	4G (LTE)	5G NR	5G NR
Channel Bandwidth (MHz)	20	20	$2^n \times 50$
FFT Size	2048	2048	4096
Number of Subcarriers for 15 KHz Spacing	1200	1200	
Number of Subcarriers for $2^n \times$ 15 KHz Spacing, $n = 0, 1, 2, 3$			3300

Frame Structure

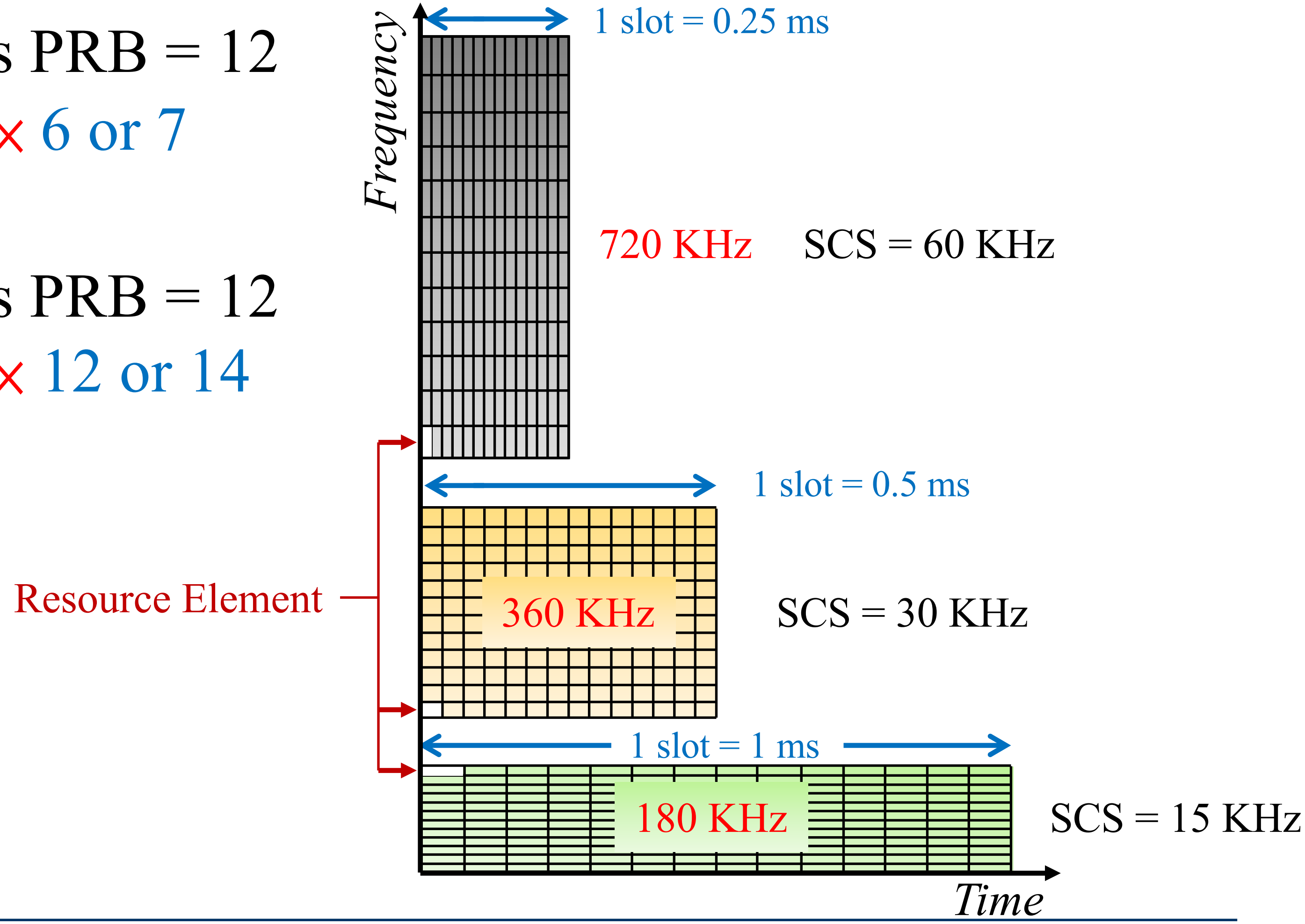


The number of slots per subframe depends on the subcarrier spacing.

Subcarrier spacing (KHz)	Slot Duration (us)	Slots/subframe
15	1000	1
30	500	2
60	250	4
120	125	8

Physical Resource Block (PRB): Example

- 4G specifies PRB = 12 subcarriers × 6 or 7 symbols
- 5G specifies PRB = 12 subcarriers × 12 or 14 symbols

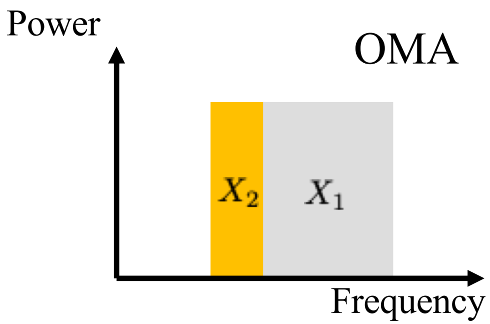


Non-Orthogonal Multiple Access

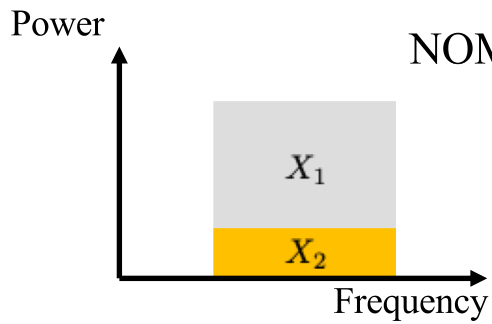
- The development of NOMA in 3GPP
  - Release-12 Network-Assisted Interference Cancellation and Suppression (NAICA) in 2014
  - Release-13 Downlink Multiuser Superposition Transmission (MUST) in 2015
    - Focus on downlink
    - Power-domain NOMA
  - Release-15 NOMA for NR in 2018
    - Focus on uplink
    - Power-domain NOMA, interleave division multiple access (IDMA), multi-user shared access (MUSA), sparse code multiple access (SCMA)…

Non-Orthogonal Multiple Access

- Massive IoT technologies for 3GPP Rel-16
  - Can be either scheduled or grant-free
  - Increase device density and network efficiency

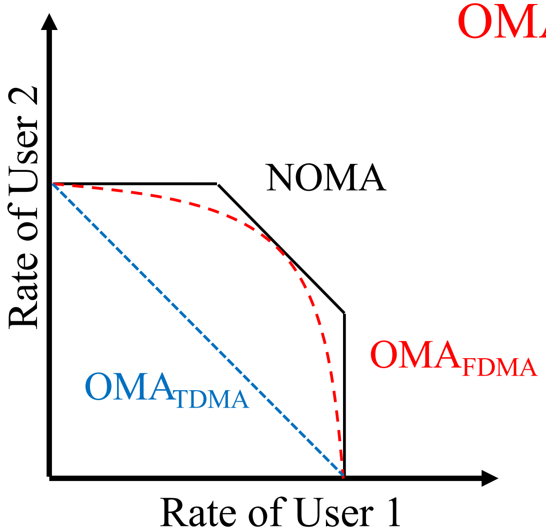


$$Y = \sqrt{P_1}X_1 + \sqrt{P_2}X_2 + Z$$



Successive Interference Cancellation (SIC) or joint maximum-likelihood (JML)

NOMA for Multiple Access Channel



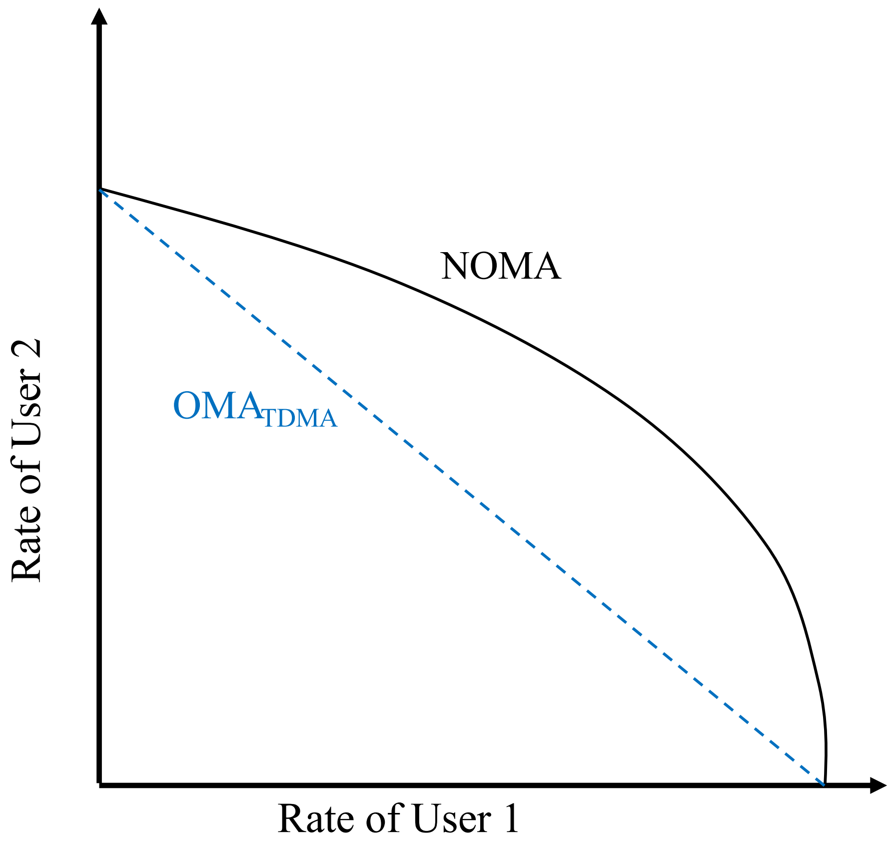
OMA$_{\text{TDMA}}$: $R_1 + R_2 \le W \log_2\left(1 + \frac{P}{N_0 W}\right)$

OMA$_{\text{FDMA}}$: $\begin{cases} R_1 \le W_1 \log_2\left(1 + \frac{P}{N_0 W_1}\right) \\ R_2 \le W_2 \log_2\left(1 + \frac{P}{N_0 W_2}\right) \end{cases}$ (See Slide IDC6-60.)

with $W_1 = \alpha W$ and $W_2 = (1-\alpha) W$ for $0 \le \alpha \le 1$

NOMA: $\begin{cases} R_1 \le W \log_2\left(1 + \frac{P}{N_0 W}\right) \\ R_2 \le W \log_2\left(1 + \frac{P}{N_0 W}\right) \\ R_1 + R_2 \le W \log_2\left(1 + \frac{2P}{W N_0}\right) \end{cases}$

NOMA for Broadcast Channel



Channel Coding in 5G

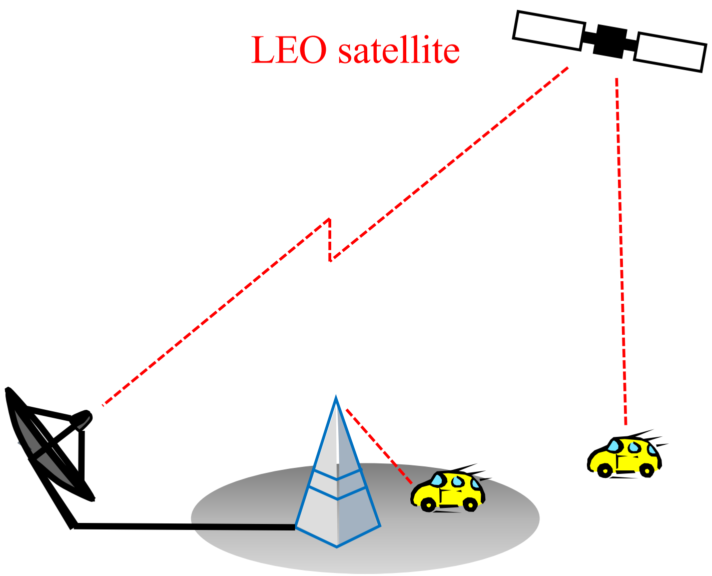
- (Quasi-cyclic) multi-edge low-density parity-check code (LDPC) for data
  - Less complex than 4G turbo codes
  - Good for high data rates
- Polar code for control
  - Contrary to 4G tail-biting convolutional codes (TBCC)
  - Use CRC for joint detection and decoding

5G Trials

- Many operators have announced 5G trials
  - Verizon, SK Telecom, Korea Telecom, NTT DoCoMo, AT&T, China Mobile, ...
  - Most are using sub-6GHz spectrum

Non-Terrestrial Transmissions towards 6G

- Use of satellites with 5G
  - Not for high throughput but for continuity of coverage.
  - PHY retransmission procedure shall be more delay tolerant.
  - Impact of propagation delays should be studied.
    - Low-earth orbit (LEO) 500-1000 km
    - Geo-stationary earch orbit (GEO) 35786 km
  - Handover and paging



Vision of 6G

	5G	6G
Traffic Capacity	10 Mbps/m^2	1-10 Gbps/m^3
Data rate DL	20 Gbps	1 Tbps
Data rate UL	10 Gbps	1 Tbps
Uniform user experience	50 Mbps 2D everywhere	10 Gbps 3D everywhere
Latency (radio interface)	1 ms	0.1 ms
Reliability (frame error rate)	10^{-5}	10^{-9}
Localization precision	10 cm on 2D	1 cm on 3D

[1] D. Klaus and B. Hendrik, "6G vision and requirements: Is there any need for beyond 5G?," *IEEE Veh. Technol. Mag.*, Sept. 2018.
[2] E. C. Strinati, S. Barbarossa, J. L. Gonzalez-Jimenez, D. Ktenas, N. Cassiau, L. Maret and C. Dehos, "6G: The next frontier: From holographic messaging to artificial intelligence using subterahertz and visible light communication," *IEEE Veh. Technol. Mag.*, Sept. 2019.

Vision of 6G

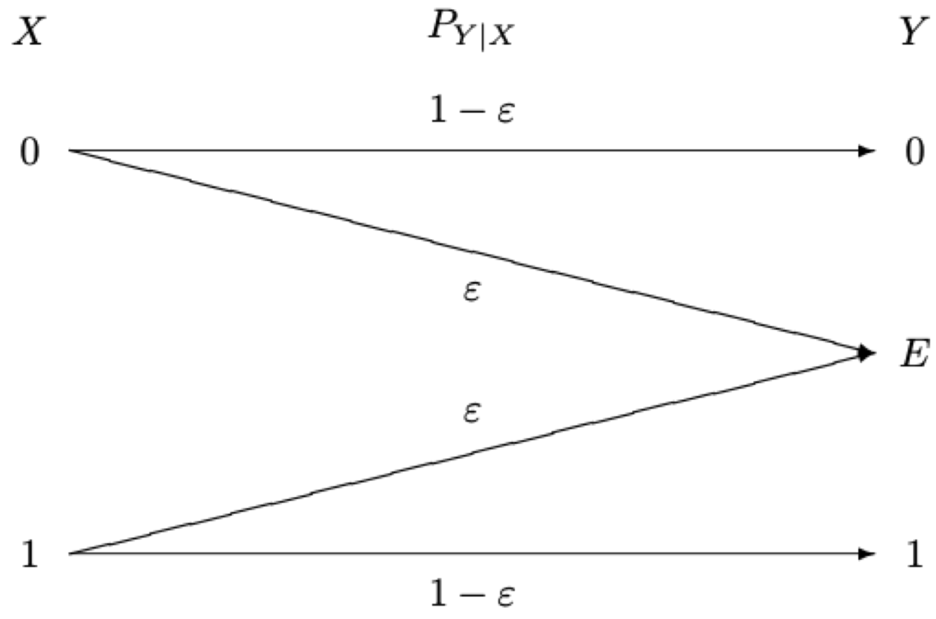
- Sub-THz communications
  - In < 10 meters of line-of-sight communication range, one Tera bps is theoretically possible by a single link with hundreds GHz of carrier frequency.
- Visible light communication (VLC)
  - VLC over short range (few meters) links is perhaps a technology option that can provide optical-fiber comparable performance.
  - Compared to RF band communication, VLC offers ultra-high bandwidth (Tera Hz), zero electromagnetic interference, free unlicensed abundant spectrum, and very high frequency reuse.

Example of Polar Codes for the Binary Erasure Channel (BEC)

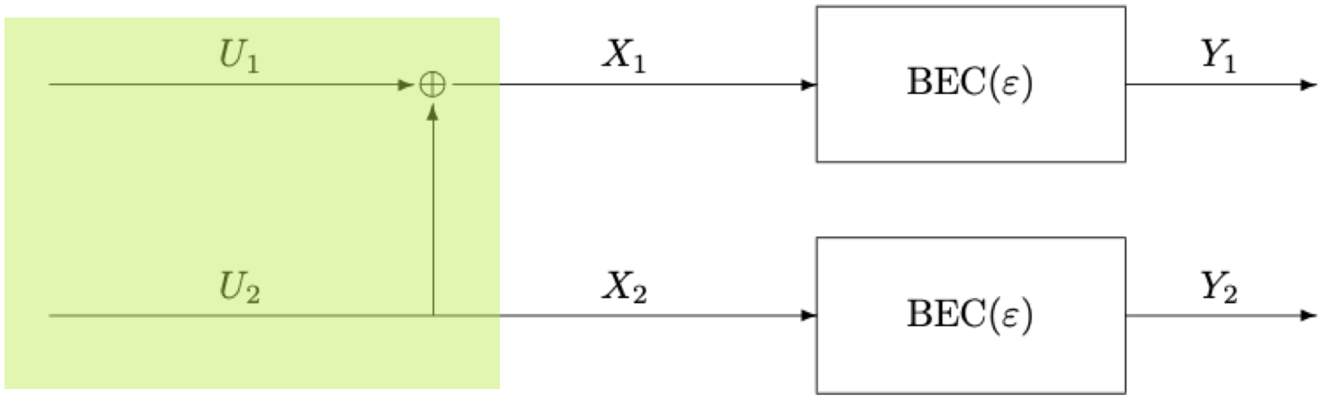
- A new channel code invented by E. Arikan in 2008.
- The idea behind polar codes is *channel polarization*, which transforms n uses of BEC(ε) into extremal polarized channels; i.e., channels which are either perfect (noiseless) or completely noisy.
- It is shown that as n goes to infinity, the number of unpolarized channels converges to zero and the fraction of perfect channels converges to $I(X;Y) = 1 - \varepsilon$ under a uniform input, which is the capacity of the BEC.
- A polar code can be obtained by sending information bits directly through those perfect channels and sending known bits (usually called frozen bits) through the completely noisy channels.

Example of Polar Codes for the Binary Erasure Channel (BEC)

- Specific property of BEC
  - When $Y = 0$ or 1, X is exactly equal to Y.
  - When $Y = \boldsymbol{E}$ is erased, nothing is known about X.



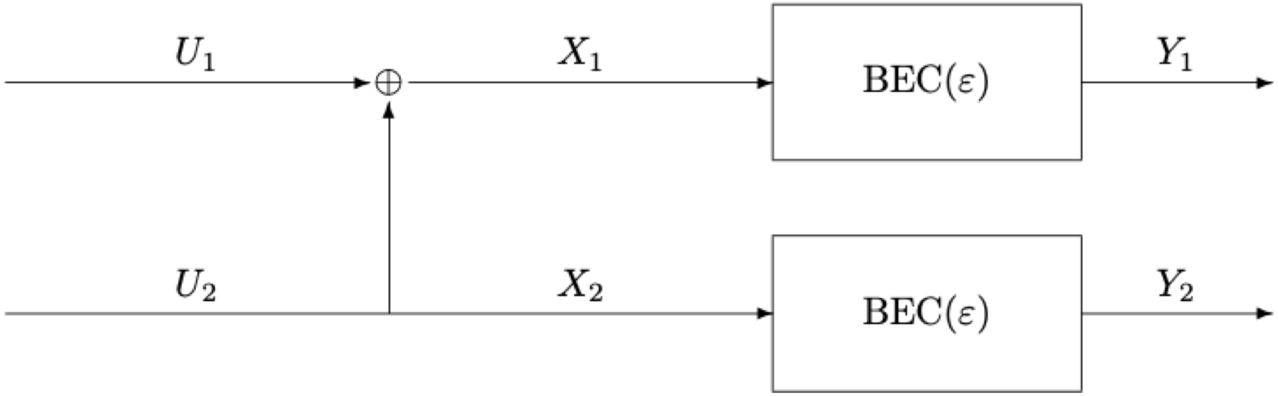
Example of Polar Codes for the Binary Erasure Channel (BEC)



- We start with the simplest case (often named basic transformation) of n=2.
- Under uniformly distributed X_1 and X_2, we have

$$I(\mathbb{Q}):=I(X_1;Y_1)=I(X_2;Y_2)=1-\varepsilon.$$

Example of Polar Codes for the Binary Erasure Channel (BEC)

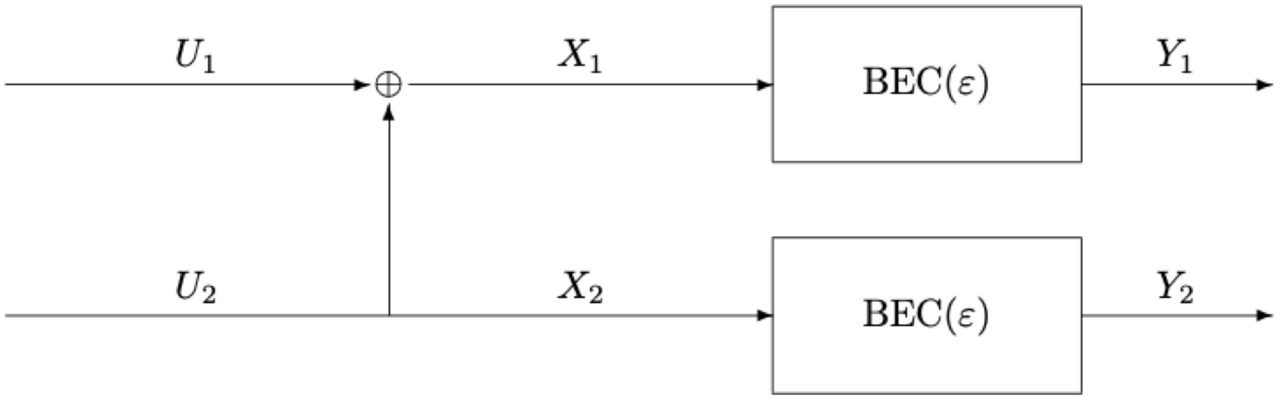


- Now consider the following linear modulo-2 operation:

$$X_1 = U_1 \oplus U_2,$$
$$X_2 = U_2,$$

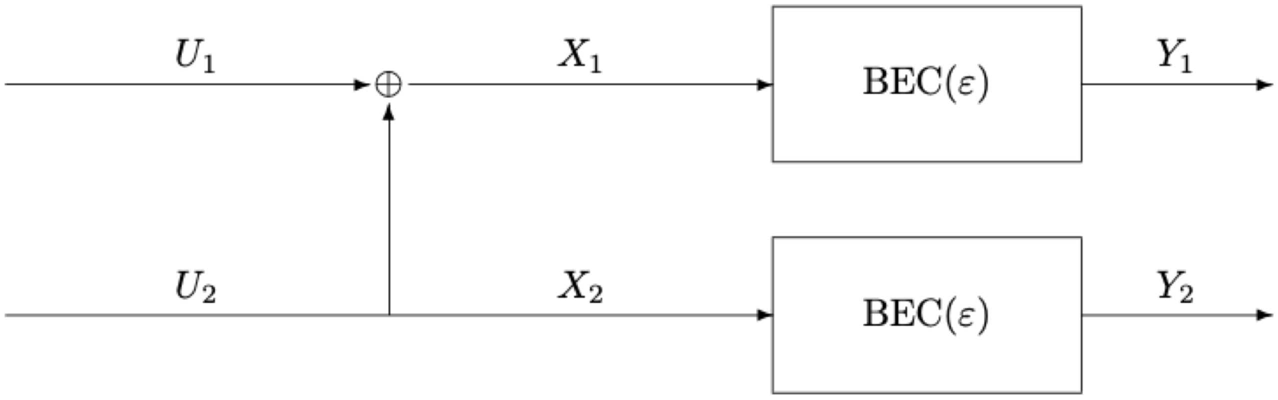
where U_1 and U_2 represent uniformly distributed independent message bits.

Example of Polar Codes for the Binary Erasure Channel (BEC)



- The decoder performs successive cancellation decoding.
  - It first decodes U_1 from the received (Y_1, Y_2).
  - Then decode U_2 based on (Y_1, Y_2) and the previously decoded U_1 (assuming the decoding is done correctly).

Example of Polar Codes for the Binary Erasure Channel (BEC)

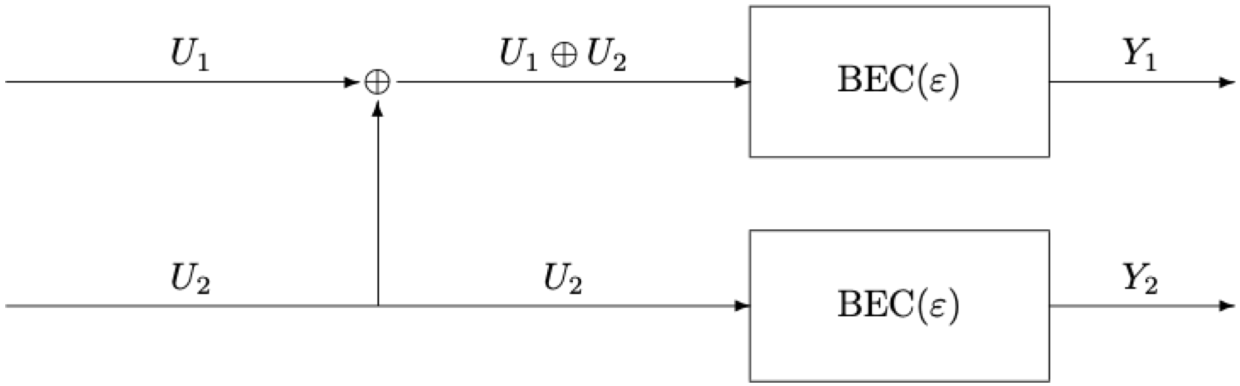


- This will create respectively two new channels; namely the worse channel $\mathbb{Q}^-$ and the better channel $\mathbb{Q}^+$ given by:

$$\mathbb{Q}^- : U_1 \to (Y_1, Y_2)$$

$$\mathbb{Q}^+ : U_2 \to (Y_1, Y_2, U_1)$$

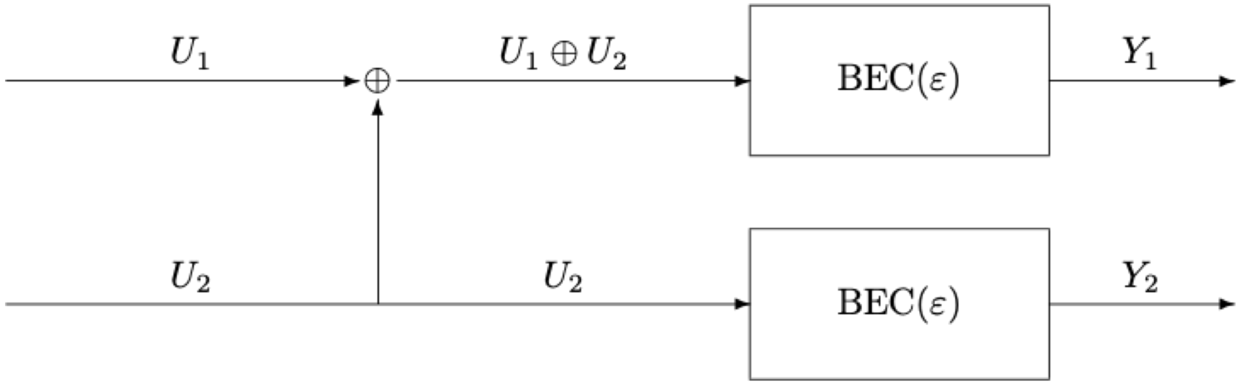
- The names of these channels will be justified shortly.



$$\mathbb{Q}^-: \ U_1 = \begin{cases} Y_1 \oplus Y_2, & \text{if } Y_1, Y_2 \in \{0,1\} \\ \ ? \ \oplus Y_2, & \text{if } Y_1 = E \text{ and } Y_2 \in \{0,1\} \\ Y_1 \oplus \ ?\ , & \text{if } Y_1 \in \{0,1\} \text{ and } Y_2 = E \\ \ ? \ \oplus \ ?\ , & \text{if } Y_1 = Y_2 = E \end{cases}$$

- Given output ***E*** for a BEC, the receiver knows nothing about the input.
- Thus, $\mathbb{Q}^-$ is a BEC with erasure probability

$$\varepsilon^- := 1 - (1-\varepsilon)^2$$



$$\mathbb{Q}^{+}\colon\ U_2 = \begin{cases} Y_1 \oplus U_1, & \text{if } Y_1 \in \{0,1\} \\ Y_2, & \text{if } Y_2 \in \{0,1\} \\ \ ?\,, & \text{if } Y_1 = Y_2 = E \end{cases}$$

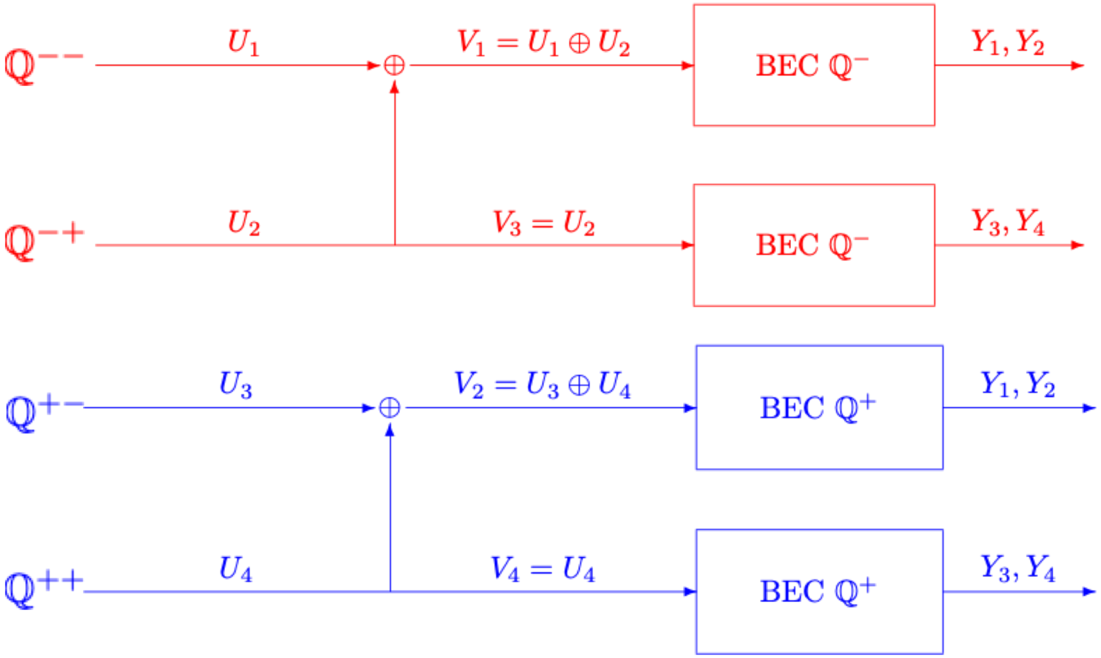
- $\mathbb{Q}^{+}$ is a BEC with erasure probability $\varepsilon^{+} := \varepsilon^{2}$.

Thus, let U_1 be the frozen bit and U_2 be the info bit.
One can transform the system to a BEC(ε^2)
with code rate 1/2 bits/channel usage.

Overall Capacity Remains the Same

$$
\begin{aligned}
I(\mathbb{Q}^+) + I(\mathbb{Q}^-) &= I(U_2; Y_1, Y_2, U_1) + I(U_1; Y_1, Y_2) \\
&= (1 - \varepsilon^+) + (1 - \varepsilon^-) \\
&= (1 - \varepsilon^2) + [1 - (1 - (1 - \varepsilon)^2)] \\
&= 2(1 - \varepsilon) \\
&= 2\, I(\mathbb{Q})
\end{aligned}
$$

$$
\begin{aligned}
&\mathbb{Q}^- : V_1 \to (Y_1, Y_2), && \text{where } X_1 = V_1 \oplus V_2,\\
&\mathbb{Q}^+ : V_2 \to (Y_1, Y_2, V_1), && \text{where } X_2 = V_2,\\
&\mathbb{Q}^- : V_3 \to (Y_3, Y_4), && \text{where } X_3 = V_3 \oplus V_4,\\
&\mathbb{Q}^+ : V_4 \to (Y_3, Y_4, V_3), && \text{where } X_4 = V_4,
\end{aligned}
$$



$$
\begin{cases}
\mathbb{Q}^{--} : U_1 \to (Y_1, Y_2, Y_3, Y_4) & \text{with erasure probability } \varepsilon^{--} := 1 - (1-\varepsilon^-)^2\\
\mathbb{Q}^{-+} : U_2 \to (Y_1, Y_2, Y_3, Y_4, U_1) & \text{with erasure probability } \varepsilon^{-+} := (\varepsilon^-)^2\\
\mathbb{Q}^{+-} : U_3 \to (Y_1, Y_2, Y_3, Y_4, U_1, U_2) & \text{with erasure probability } \varepsilon^{+-} := 1 - (1-\varepsilon^+)^2\\
\mathbb{Q}^{++} : U_4 \to (Y_1, Y_2, Y_3, Y_4, U_1, U_2, U_3) & \text{with erasure probability } \varepsilon^{++} := (\varepsilon^+)^2
\end{cases}
$$

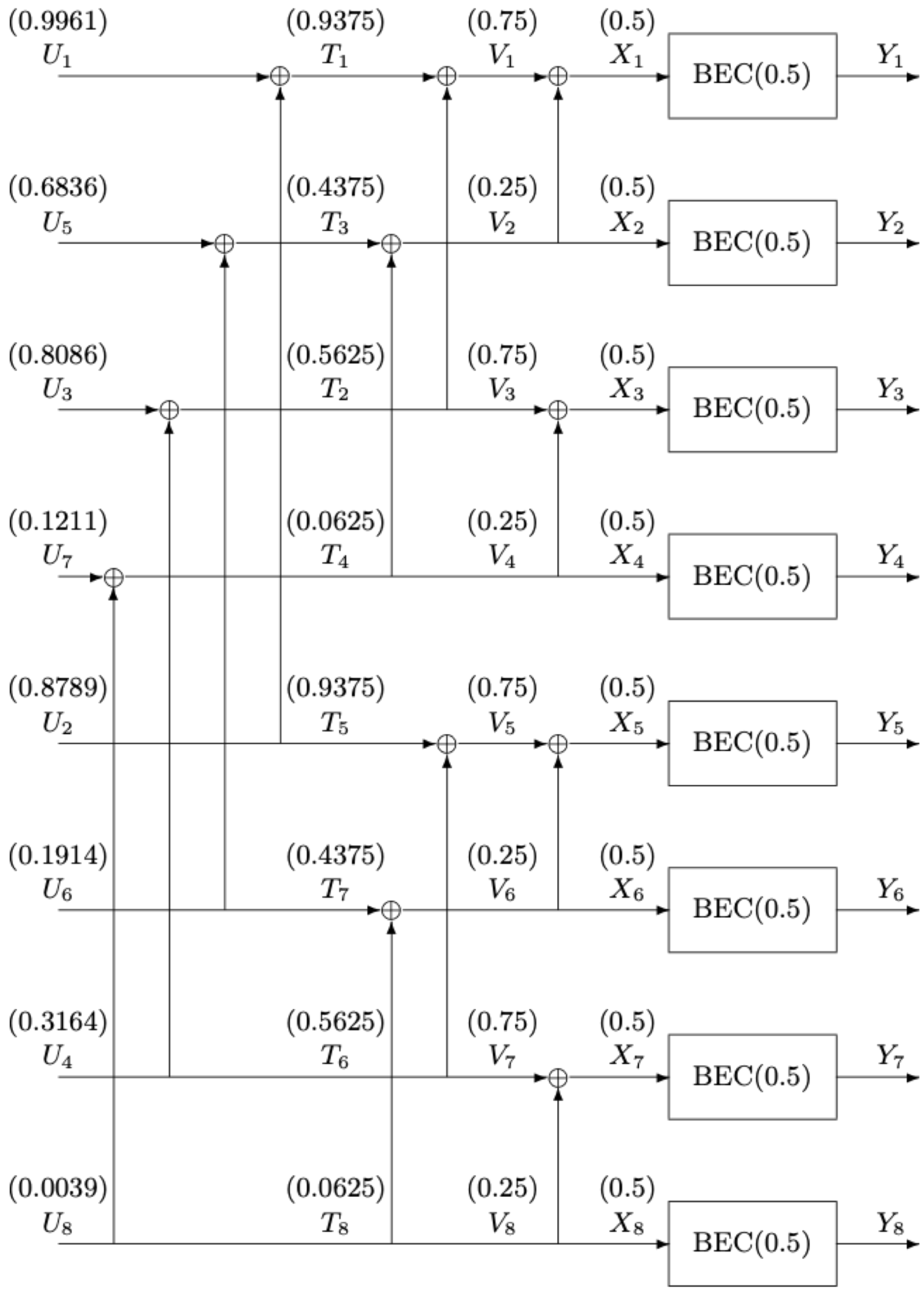
Polar Coding System

- The process of using multiple basic transformations to get $X_1, \ldots, X_n$ from $U_1, \ldots, U_n$, where U_i's are i.i.d. uniform message random variables is called *channel combining*.

- The process of using $Y_1, \ldots, Y_n$ and $U_1, \ldots, U_{i-1}$ to obtain U_i for i in $\{1, \ldots, n\}$ is called *channel splitting*.

- Altogether is called *channel polarization*.

Consider n=8 BECs with erasure probability 0.5



Final Notes

- A key reason for the prevalence of polar coding after its invention is that it has an explicit low-complexity construction structure while being capable of achieving channel capacity as code length approaches infinity.
- More importantly, polar codes do not exhibit the error floor behavior, which Turbo and (to a lesser extent) LDPC codes are prone to.
- Due to their attractive properties, polar codes were adopted in 2016 by the 3rd Generation Partnership Project (3GPP) as error correcting codes for the control channel of the 5G mobile communication standard.