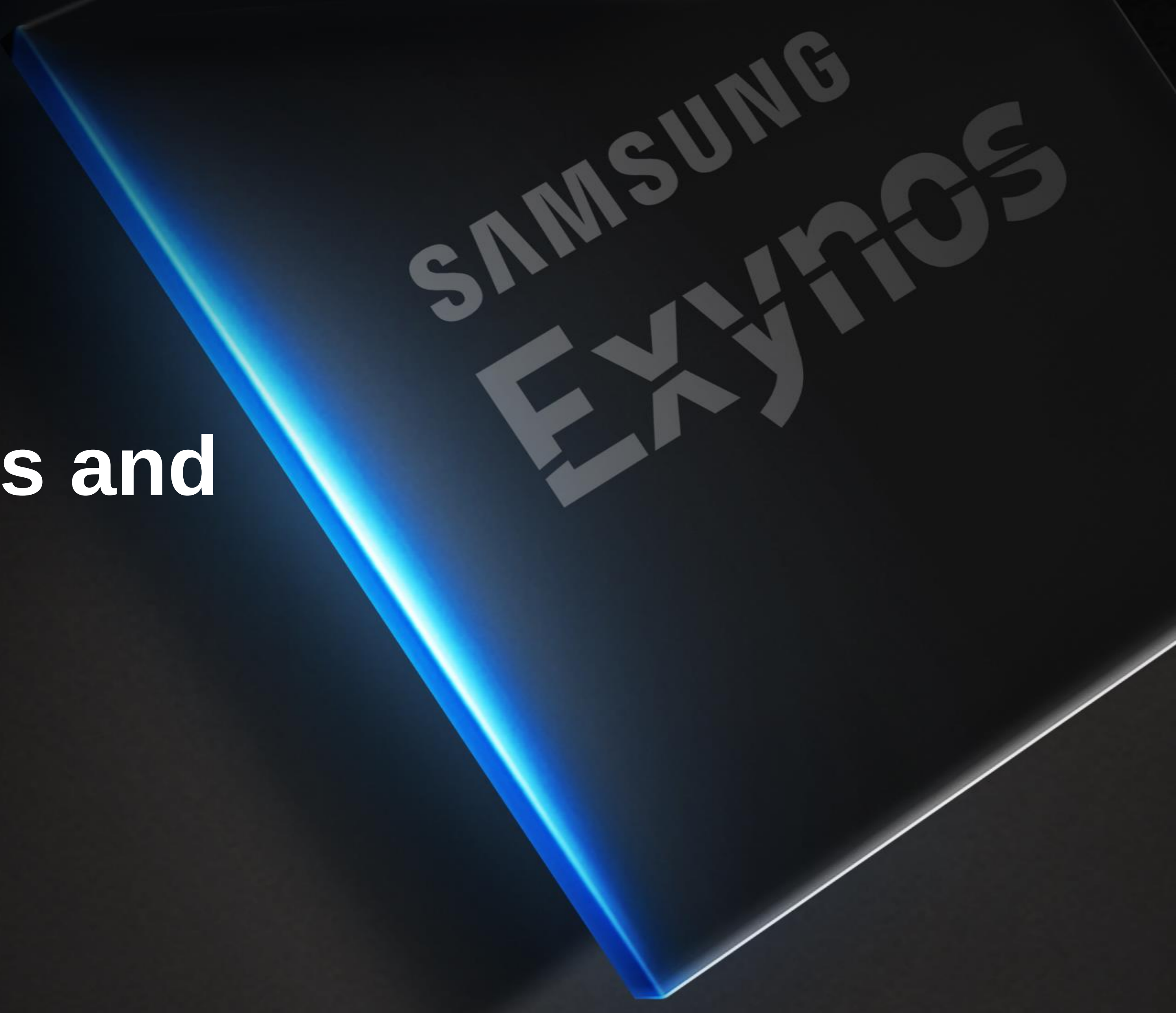
6G Technologies and Research



Jung Hyun Bae

Sr. Principal Engineer / SOC R&D lab

Samsung Semiconductor, Inc.

August 2022

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5G Initial Phase

From Vision to Commercial Deployment

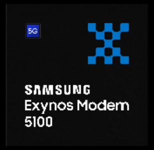
3GPP[2] Rel-15

NR[1] NSA[3] → NR SA[4]

2018 — Feb.: PyeongChang 2018

PyeongChang Winter Olympics Pre-commercial Trial

Aug.:



World's 1st 5G 3GPP NR Compliant Modem OTA[5] Call

Dec.: **World's 1st 5G NR Commercialization**

5G Mobile Hot Spot

2019 — Apr.:

World's 1st 5G Smartphone

PHY[6] Technology Highlights

- **Scalable OFDM**
  - 15/30/60 kHz SCS[7] for FR1
  - 60/120/240 kHz SCS for FR2
- **New Spectrum on mmWave**
  - Beam Training and Management
- **New Channel Coding**
  - LDPC[8] and Polar codes

1. New Radio
2. 3rd Generation Partnership Project
3. Non-standalone
4. Standalone
5. Over-the-Air
6. Physical Layer
7. Subcarrier Spacing
8. Low Density Parity Check

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5G Second Phase

3GPP Rel-16 (2018~2020) and 17 (2020~2022)

Use Case Expansion

NR V2X[1] and Sidelink

Industrial IoT[2]

NR Unlicensed (5GHz and 60GHz)

NTN[3]

RedCap[4] (for wearables etc.)

Efficiency Improvement

Accurate positioning

Integrated access and backhaul (IAB)

UE power saving

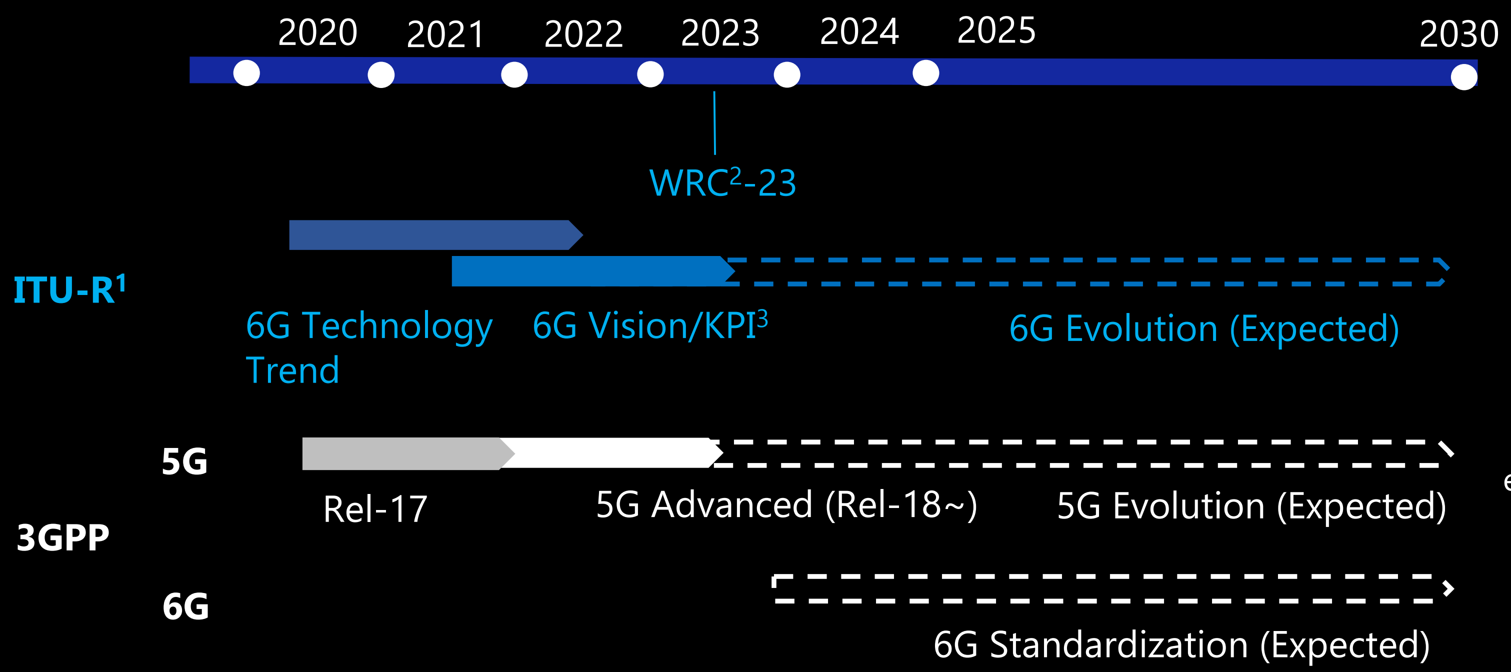
Coverage enhancement (for PUSCH/PUCCH)

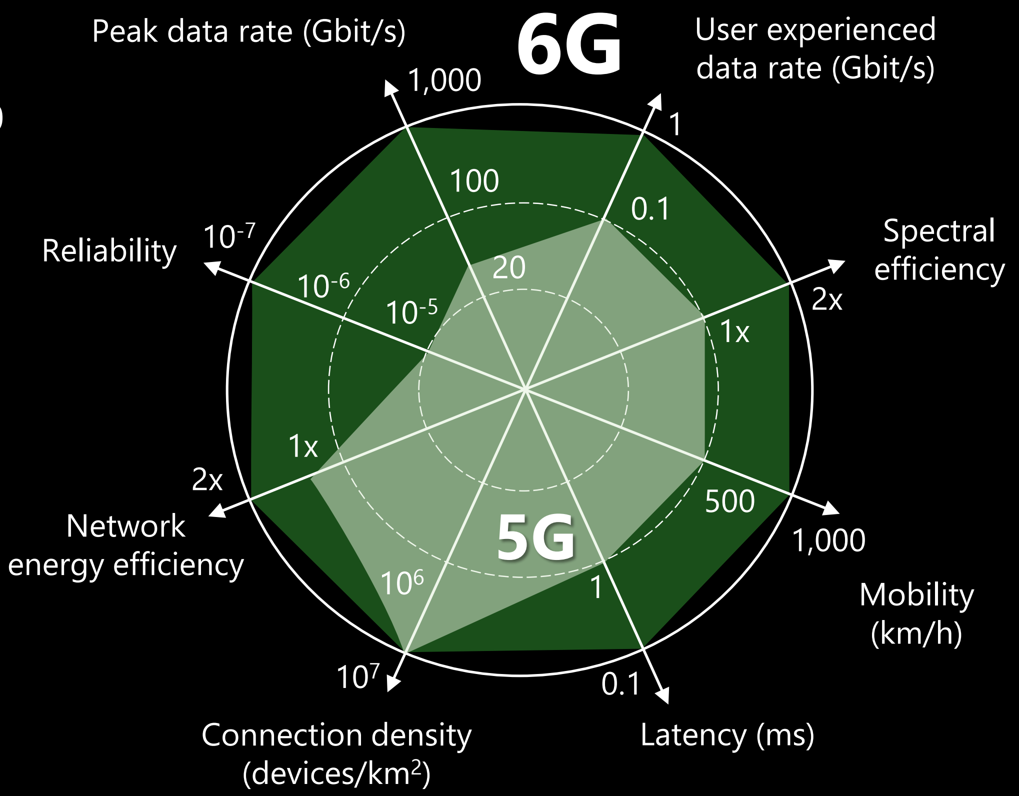
MIMO[5] enhancement

1. Vehicle-to-everything
2. Internet of things
3. Non-terrestrial network
4. Reduced capability devices
5. Multiple-input multiple-output

B5G and 6G

Roadmap and Performance Target





1. International Telecommunication Union Radiocommunication Sector
2. World Radiocommunication Conference
3. Key performance indicator

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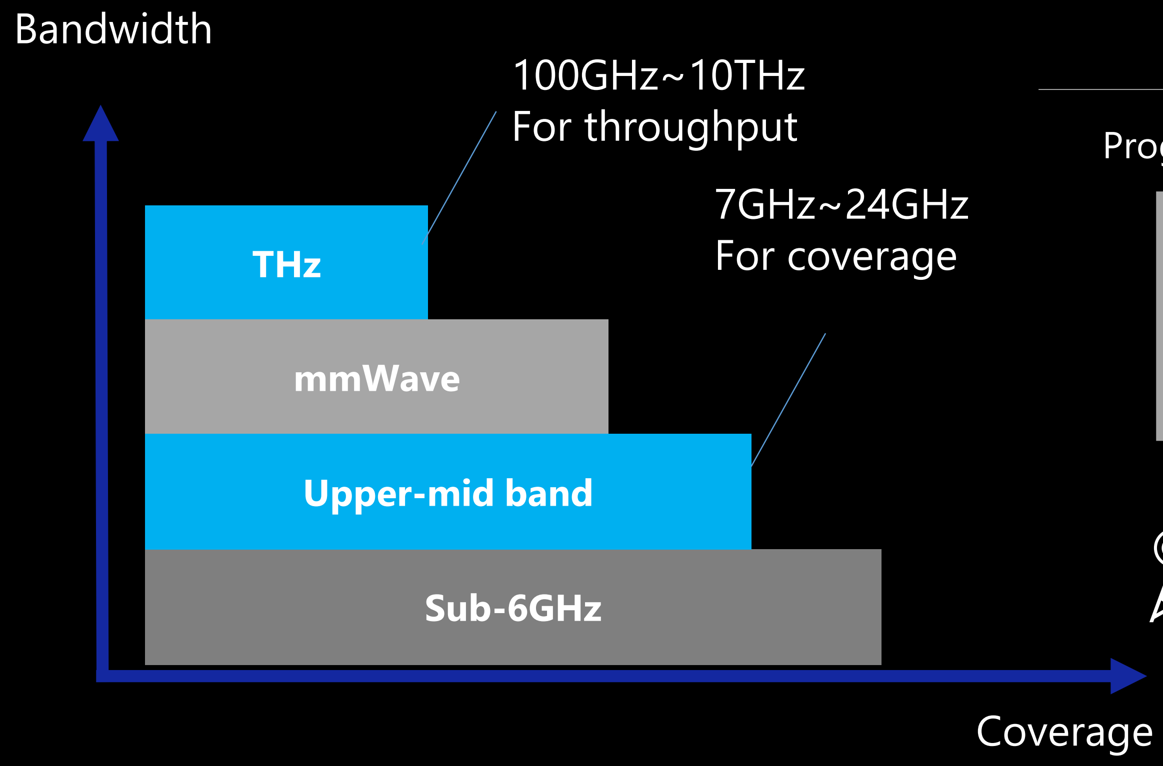
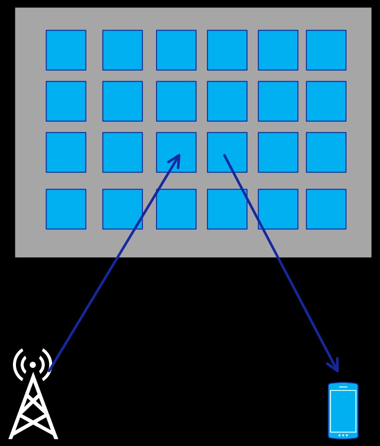
More Spectrum and More Antenna

- THz provides large bandwidth, but challenges are there for RFIC/transceiver design and coverage
- Upper-mid band will provide an anchor for coverage
- Large amount of advanced antennas is critical for reliable communication in such 6G spectrum

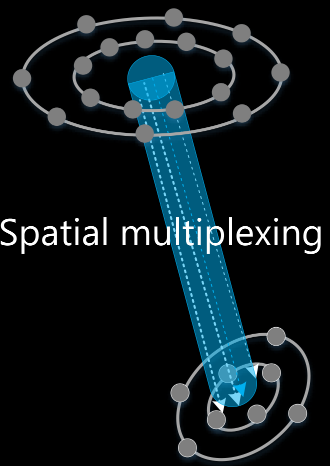


Large Intelligent Surface

Programmable meta-surface

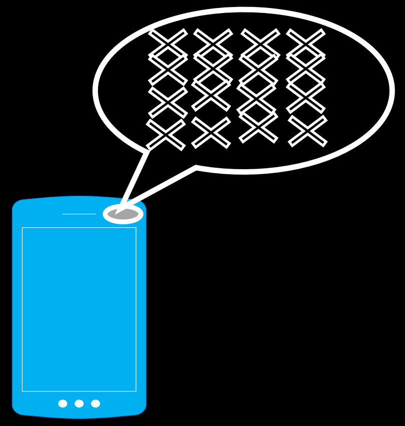


LOS[1] MIMO



Ultra-Massive MIMO

>100 antennas/cm^2



1. Line of sight

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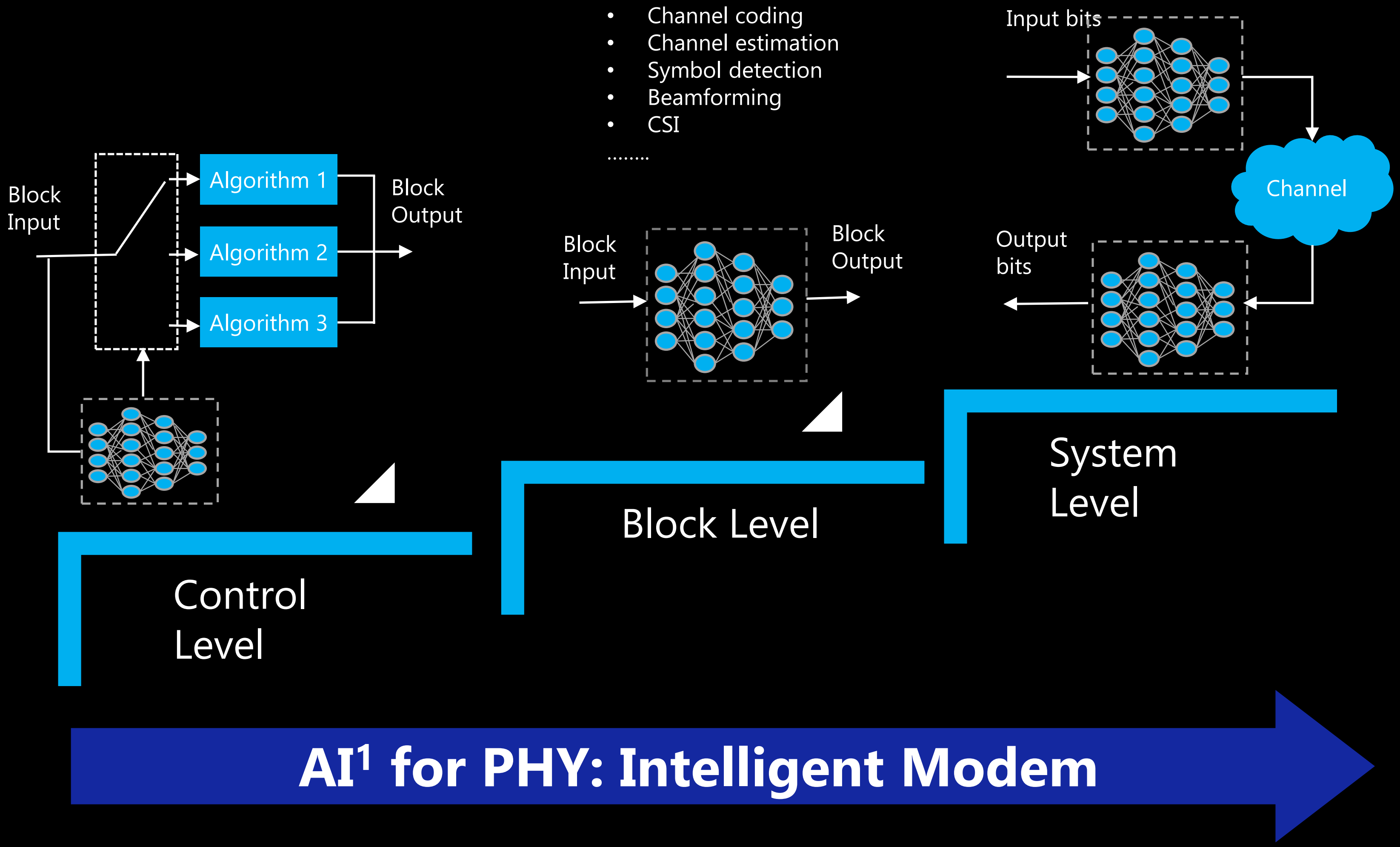
Higher Efficiency

- **Advanced duplex**
  - BS[1]-side sub-band full duplex in 5G advanced (no UE[2] full duplex)
  - BS and UE true full duplex in 6G; self (internal/reflected) interference cancellation
- **Waveform, modulation and coding**
  - High phase noise tolerance
  - New baseband signal processing for full-digital massive MIMO with low resolution ADC[3]/DAC[4]
  - New channel coding for high reliability and low latency
- **Energy efficiency**
  - Near-zero energy communications
  - BS and UE energy saving

1. Base station
2. User equipment
3. Analog to digital converter
4. Digital to analog converter

6G Technologies

Higher Intelligence



- **AI for PHY in 5G advanced**
  - CSI
  - Beam management
  - Positioning
- **AI native PHY for 6G**
- **Comprehensive AI in all layers**
  - End-to-End AI
  - Split computing
  - Federated learning

1. Artificial Intelligence
2. Channel state information

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Information Theory and Cellular PHY

- Information theory has provided reference of achievability limit for the rate of communication.
- In many cases, it has also provided specific schemes achieving the optimality which commercial systems have also taken advantages of.
- Point-to-point channel (memoryless, no feedback) – Capacity established
  - Source-channel coding separation
  - BICM[1]
  - Coding across fading

  (Source-channel coding separation, BICM and coding across fading:) a backbone of the current cellular system framework
  - LDPC code (spatially coupled) - currently used for 5G data channel
  - Polar code - currently used for 5G control channel

1. Bit-interleaved coded modulation

Information Theory and Cellular PHY

- MIMO AWGN channel - Capacity established
  - Successive cancellation receiver with MMSE/whitening - popular MIMO detection implementation
  - SVD beamforming and rank selection equal power constraint - popular in CSI framework
- Multi-user (MU) MIMO AWGN channel - Capacity partially established
  - Broadcast (DL MU)
    - Superposition for single antenna case - 4G Rel-13 MUST[1]
    - Non-linear precoding for multiple antenna case - 5G candidate
  - Multiple access (UL MU) - transparently realizable in the current system -> 5G Rel-16 NOMA[2] study
  - Interference (DL multi-Tx)
    - No capacity yet, the current system mostly does TIN[3]
    - Interference alignment - 4G Rel-11 CoMP[4] and 5G
    - TIN, but as structured noise - 4G Rel-12 NAICS[5]

1. Multi-user superposition transmission
2. Non-orthogonal multiple access
3. Treating interference as noise
4. Coordinated multi point
5. Network-assisted interference cancellation and suppression

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6G Research

Deep-learning based channel coding

- Optimal algorithms for point-to-point communication are often available.
  - Model mismatch breaks optimality.
  - Optimal algorithms are often too complex.
  - With emergence of AI, we increasingly rely on 'machine' to resolve the issue.

- We will discuss designing of channel codes using deep learning.
  - Interleaver Design and Pairwise Codeword Distance Distribution Enhancement for Turbo Autoencoder, **GLOBECOM 2021**
  - Product AE: Towards Training Larger Channel Codes based on Neural Product Codes, **ICC 2022 best paper award**

Turbo Autoencoder (AE)

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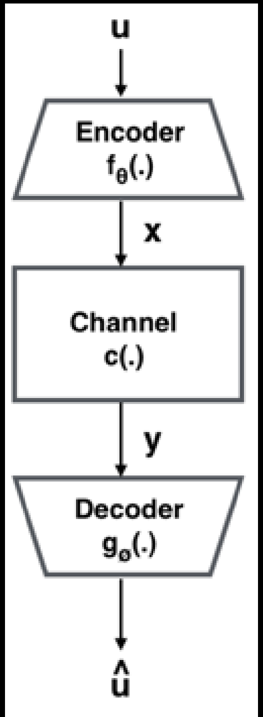
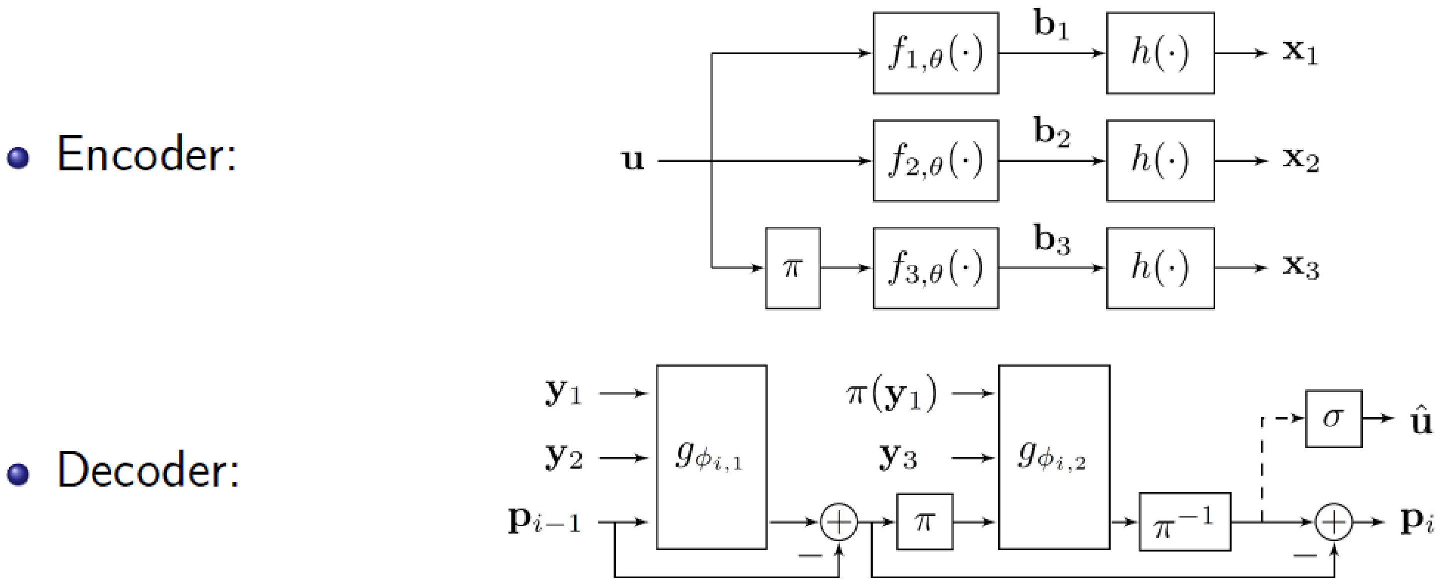
- System model: $\boldsymbol{y} = \boldsymbol{x} + \boldsymbol{n}$ where $\boldsymbol{n}$ is AWGN.



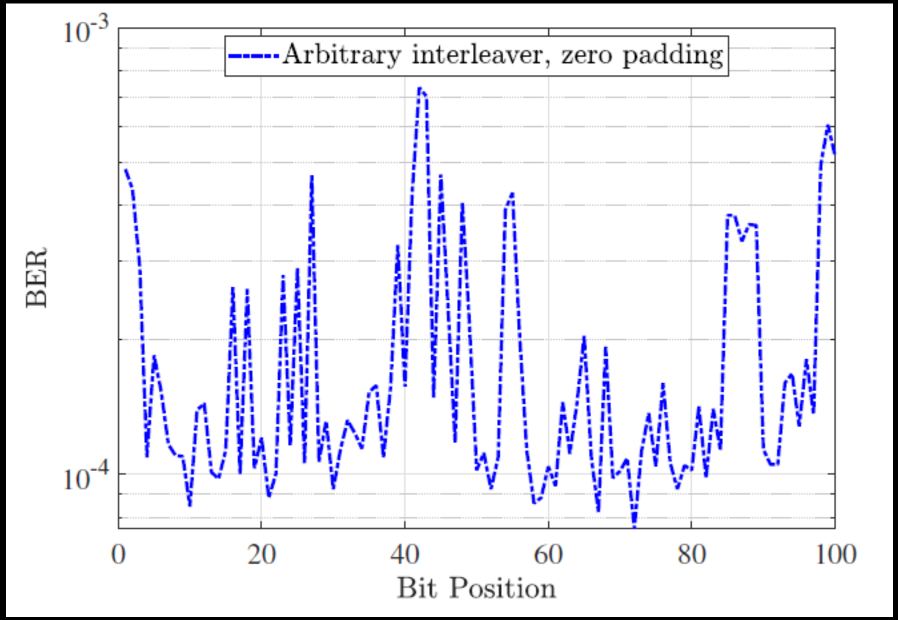
- Turbo AE: based on either CNN[1] or RNN[2] for f or g

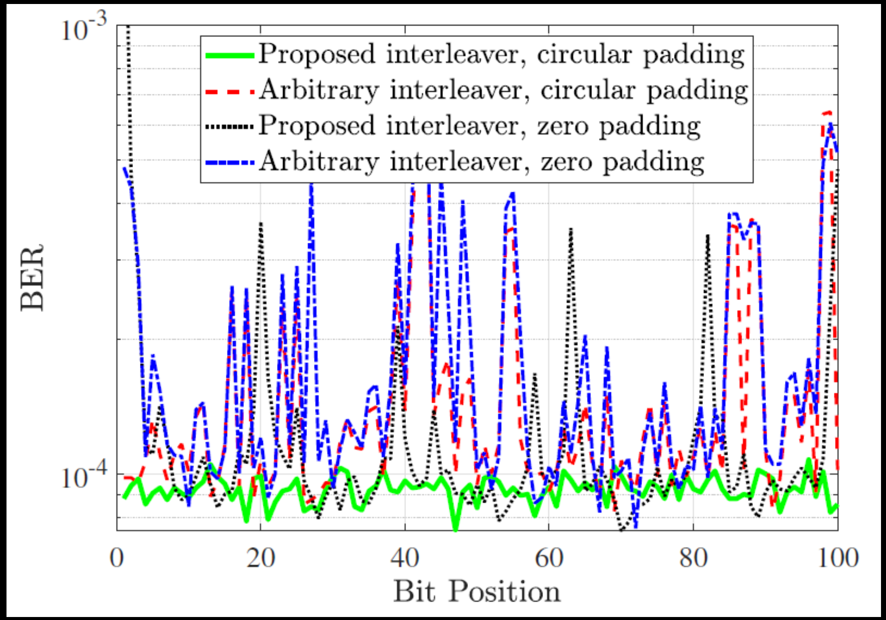


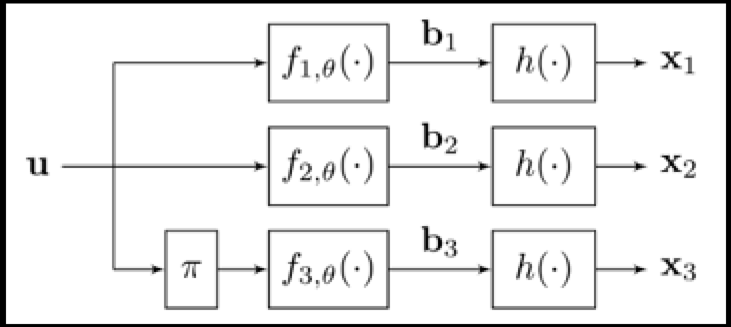
[1]Y. Jiang, H. Kim, H. Asnani, S. Kannan, S. Oh, and P. Viswanath,"Turbo autoencoder: Deep learning based channel codes for point-topoint communication channels" in Advances in Neural Information Processing Systems, H. Wallach, H. Larochelle, A. Beygelzimer, F. dAlch´e-Buc, E. Fox, and R. Garnett, Eds., vol. 32. Curran Associates, Inc., 2019.

1. Convolutional neural network
2. Recurrent neural network

Turbo AE: Resolving Non-Uniform BER[1]







- Circular padding instead of zero padding for CNN encoder f and decoder g.
- Interleaver $\boldsymbol{\pi}(i) = i\delta \bmod K, i = 0,1 \ldots, K-1$.
  - Ensuring certain symmetry $(\boldsymbol{\pi}(i) - \boldsymbol{\pi}(i+k)) \bmod K = (\boldsymbol{\pi}(j) - \boldsymbol{\pi}(j+k)) \bmod K$

1. Bit error rate

Enhanced Average BER

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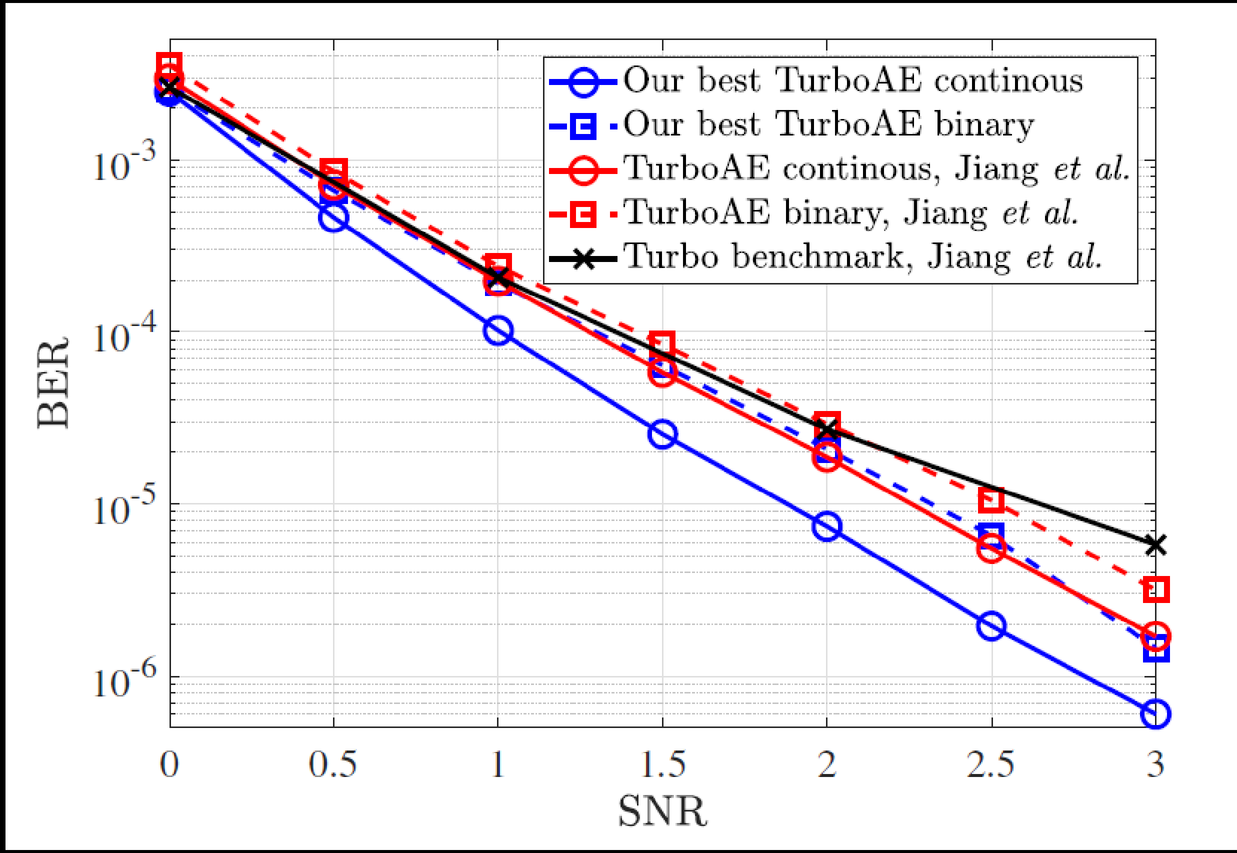
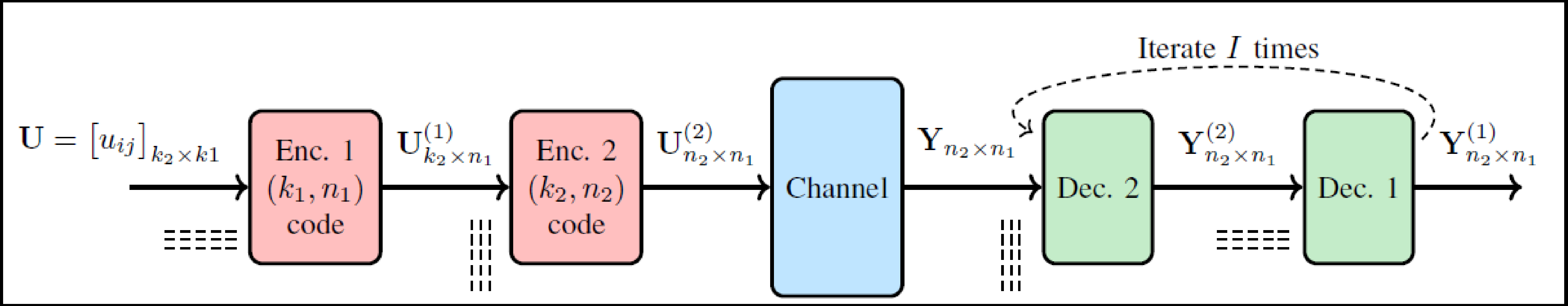
- A regularizer ensuring good minimum distance 'T'.
  - $\text{Loss} = \text{BCE} + \lambda \sum_{1 \le i,j \le 2^K, i \ne j} \left(T - d(\boldsymbol{c}_i, \boldsymbol{c}_j)\right)_+$, $\boldsymbol{c}_i$ is 'i'th codeword, $(x)_+ = \max\{0, x\}$.
- As a result, we achieved enhanced average BER performance (K=100).



1. Binary cross entropy

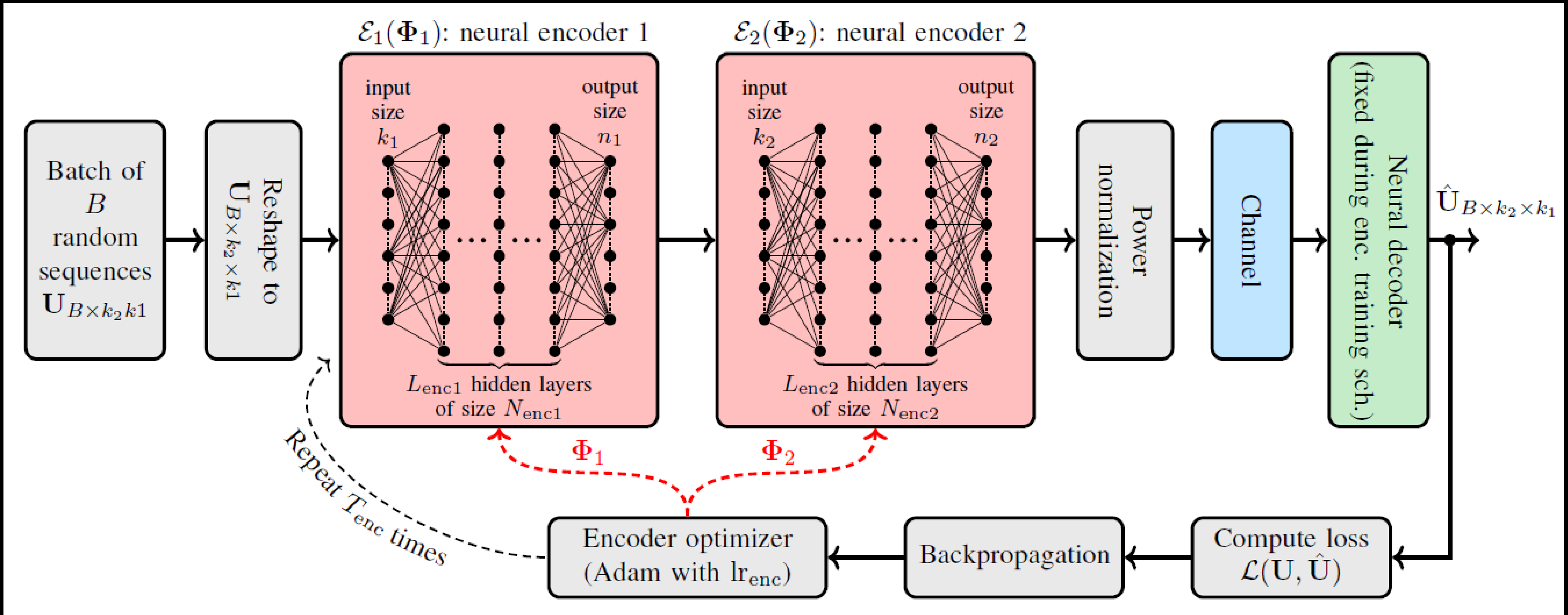
Product Autoencoder



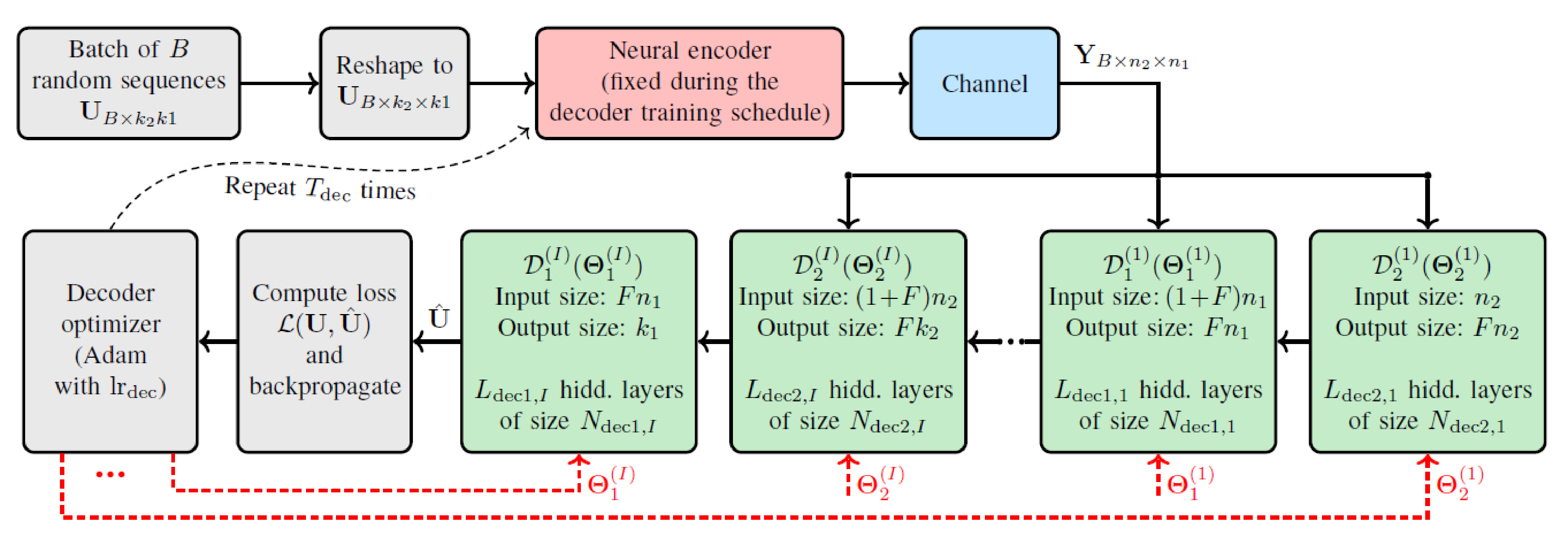
- The main motivation is to design a trainable large block length codes using smaller length component codes.

- Enc. 1 encodes each row using an (n_1, k_1) code.
- Enc. 2 encodes each column using an (n_2, k_2) code.
- Dec 2 encodes the columns while Dec. 1 decodes the rows.
- The decoder iterates the process several times (I times).

Product AE: Encoder training

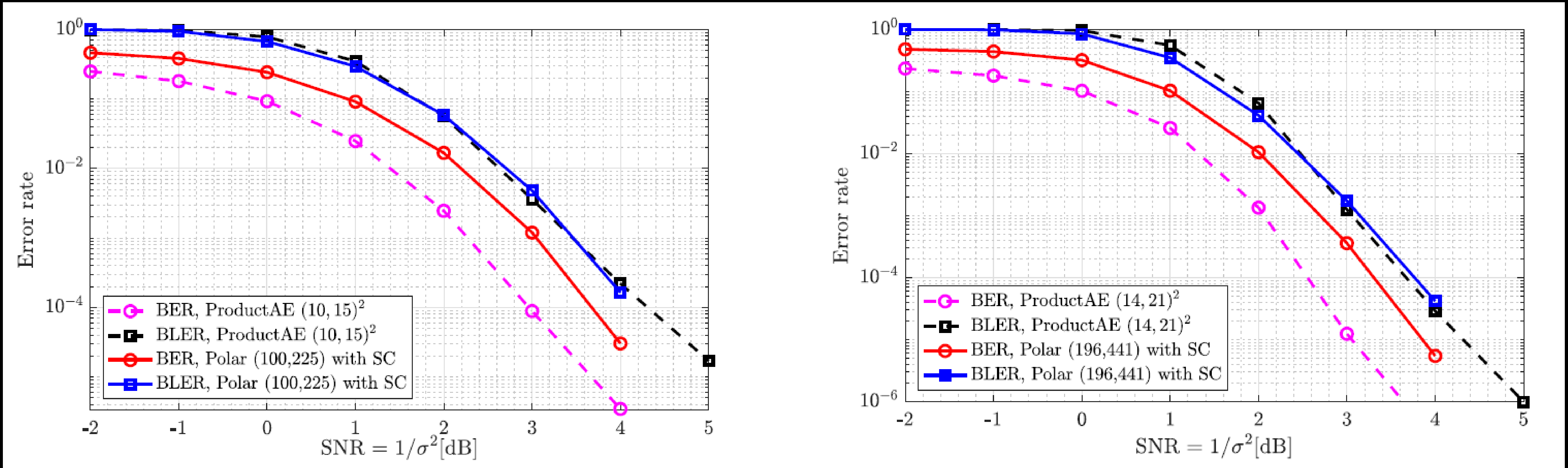


Product AE: Decoder training



Product AE: Results

- Product AE shows better BER performance than polar codes.
  - The current BCE loss function is not designed for BLER performance.



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Thank you!