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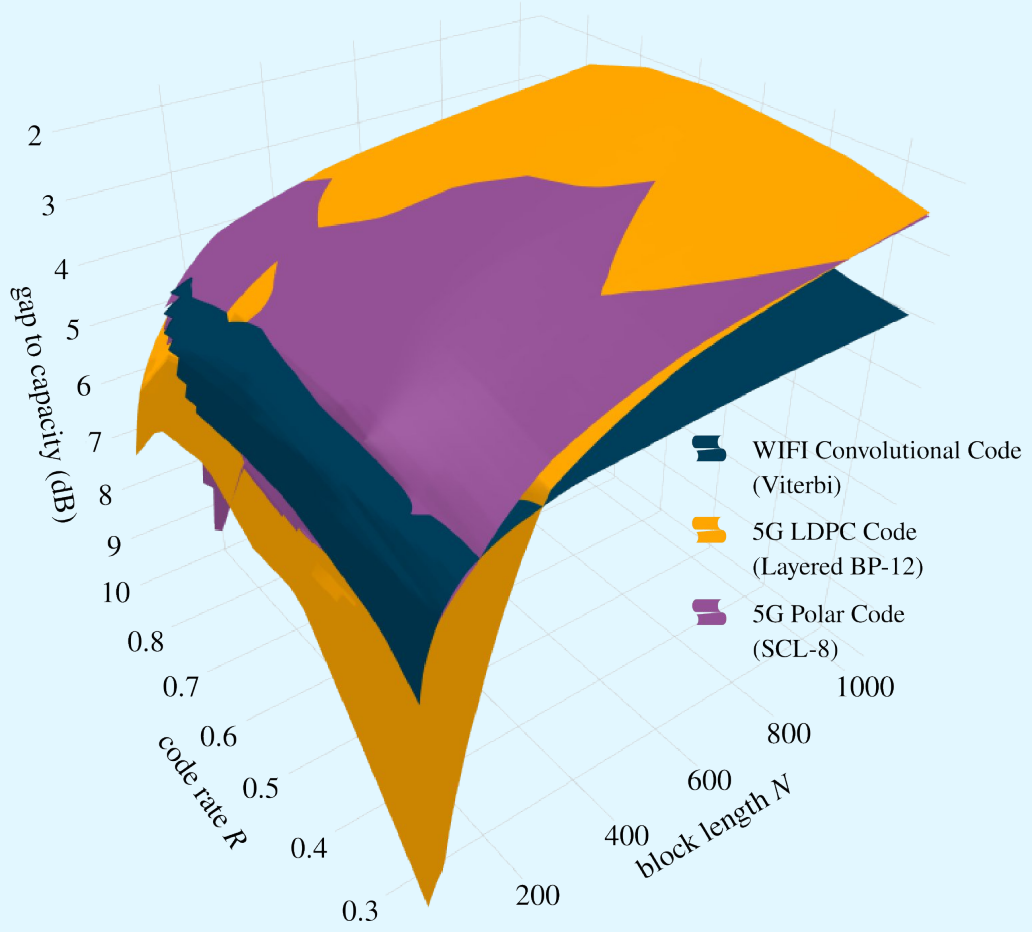


6G: A Welcome Chance to Unify Channel Coding?

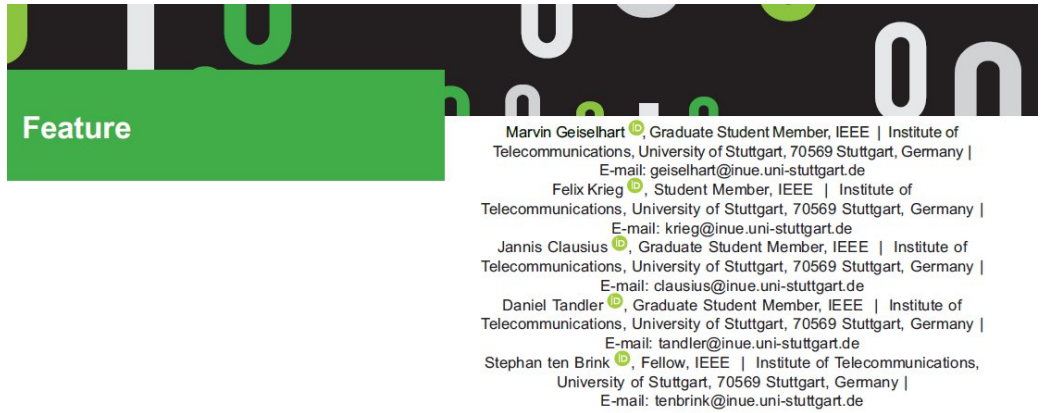
Munich Workshop on Shannon Coding Techniques
April 03, 2024

Stephan ten Brink with Stuttgart Coding Group

Supported by the German Federal Ministry of Education and Research (BMBF)
project Open6GHub (grant no. 16KISK019).

Credits

- Based on pre-print
  M. Geiselhart, F. Krieg, J. Clausius, D. Tandler and S. ten Brink,
  "6G: A Welcome Chance to Unify Channel Coding?,"
  in IEEE BITS the Information Theory Magazine
- Coding team at INÜ
  - Marvin Geiselhart, Felix Krieg, Jannis Clausius, Daniel Tandler, Tim Janz, Paul Bezner, Andreas Zunker, Simon Obermüller and Stephan ten Brink
- Collaborators in BMBF project Open6GHub
  - Oliver Griebel, Claus Kestel, Lucas Johannsen, Sisi Miao, Jonathan Mandelbaum, Laurent Schmalen, Norbert Wehn
- Associates (e.g., joint pre-print paper on “Trends in 6G Coding”)
  - Alexios Balatsoukas-Stimming, Gianluigi Liva



Outline

- Evolution of Channel Coding for Wireless Mobile
- Key Challenges for 6G Channel Coding
- Unified Coding
- Conclusion

1950 1960 1970

- Convolutional codes
- ★ Turbo codes
- ▲ LDPC codes
- ■ Polar codes
- ♦ Promising proposals

A Bold Prophecy: Codes on Sparse Graphs
When Gallager initially discovers LDPC codes, their dominance was still written in the stars. It will take several years before they break through [17].

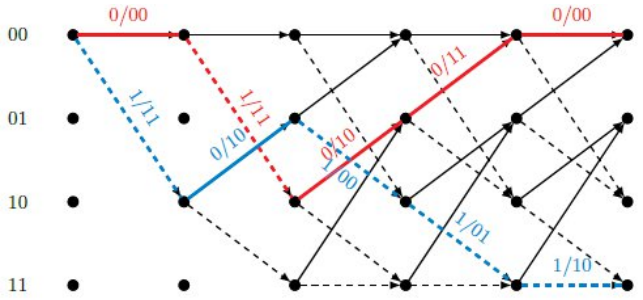
BCJR decoding [10]

The Journey Begins
Elias's invention of convolutional codes marks one important milestone on the long path to capacity-achieving codes [3].

Maximum Likelihood Decoding on a Trellis
Viterbi's discovery of an efficient decoding algorithm manifested convolutional codes as the de facto coding standard of the time [4].

Concatenation of codes [6] ★

https://webdemo.inue.uni-stuttgart.de/timeline



2G GSM: Convolutional Codes

Convolutional Codes: general purpose
- easy to use, rate/length flexibility
- optimal decoder (Viterbi)

	Control Channels	Data Channels
2G GSM	**Convolutional** Memory 4 Zero termination	**Convolutional** Memory 4, 6 Zero termination
3G UMTS	**Convolutional** Memory 8 Zero termination	**Turbo** Memory 3 Non-regular π
4G LTE	**Convolutional** Memory 6 Tail-biting termination	**Turbo** Memory 3 Contention-free π
5G New Radio	**Polar** Reliability index-sequence CRC-aided decoding	**LDPC** Protograph lifting Raptor-like

1980

1990

2000

SCL decoding [27]

The Turbo Code Awakens
Berrou develops an iterative decoding scheme for parallel concatenated convolutional codes [9].

3G

LDPC Codes Strike Back!
MacKay's re-discovery indicates near-Shannon performance of the codes, which has spurred industrial and academic interest [18].

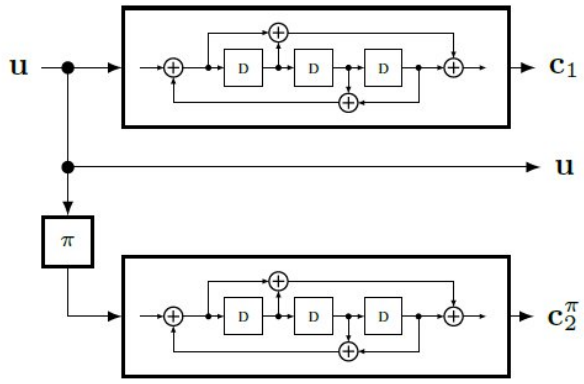
SISO decoding [8]

♦OSD [51]

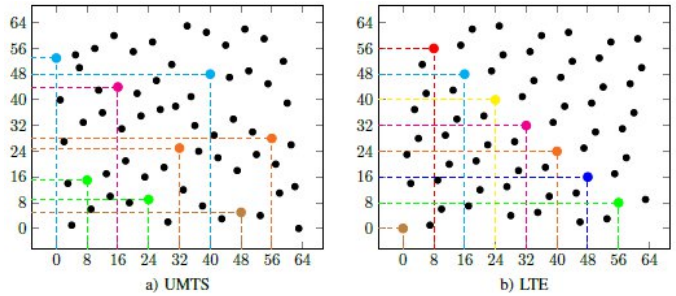
▲Raptor Codes [22]

2G

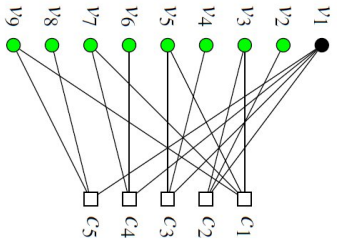
TBCC [11]



3G, UMTS, LTE: Turbo Codes



4G, LTE: Contention-free interleaving



5G: LDPC Codes

Turbo and LDPC:

- the race for capacity
- code concatenation
- the rise of BP decoding, factor graphs
- joint detection and decoding

2010

2020

2030

4G

5G

Automorphism Ensemble Decoding
Combining algebraic properties and soft-decision algorithms enables ultra low latency decoding [36]

Autoencoder [59]

A New Hope
CRC-aided polar codes with list decoding [26].

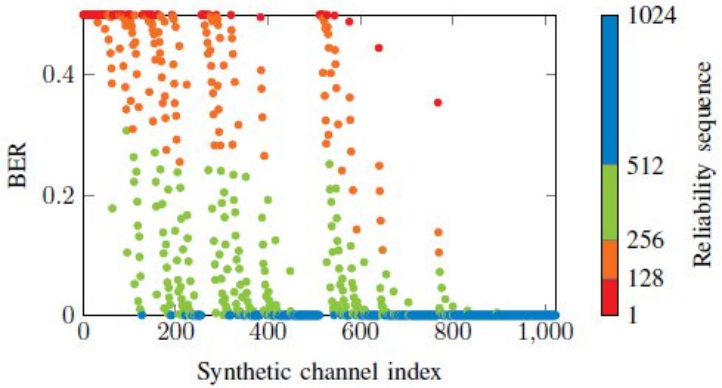
The Polarization Principle
Arıkan's discovery popularized polar coding [25].

GRAND [52]

Neural BP [57]

BP for Turbo codes [56]

Generalized Automorphisms [50]



5G: Polar Codes

Where do we go from here?

- many special coding/decoding schemes?
- or converge to unified coding?

Polar Codes: short-length performance

- we learned a lot about different decoders (other than BP)
- and code designs for short-length

Current Research Directions in Coding

- A plethora of research directions in the community, to name a few...
  - Combination of coding with shaping, multiuser detection, equalization, MIMO, ...
  - Code-agnostic decoding (OSD, GRAND and friends)
  - Spatially coupled codes (staircase, zig-zag, zipper and buddies)
  - Non-binary coding
  - Coded caching, coding for storage, ...
  - Automorphism ensemble decoding, or other “diversity code/decoding” schemes
  - AI for code design, decoder improvement, real-valued codeword sequences, ...
  - Codes under consideration: Polar, LDPC, BCH, ...

- “Risk”: Specialization into niche applications/improvements, losing “big picture”

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- Evolution of Channel Coding for Wireless Mobile
- **Key Challenges for 6G Channel Coding**
- Unified Coding
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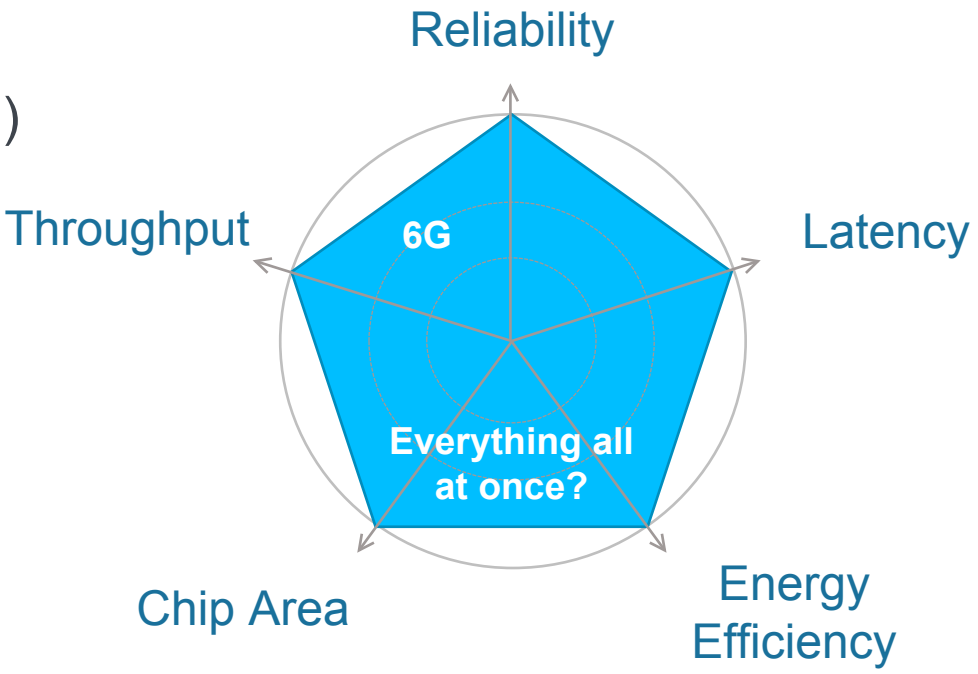
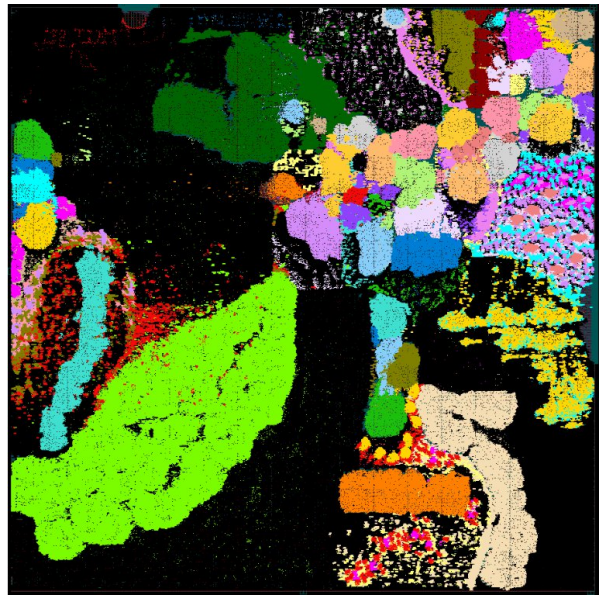
Key Challenges for Channel Coding

- New applications from 5G to 6G, expressed in KPIs
  - **Throughput:** from enhanced mobile broad-band (eMBB) to next-generation broadband
  - **Latency:** from ultra-reliable low-latency communication (URLLC) to real-time control
  - **Energy efficiency:** from massive machine-type comms (mMTC) to pervasive access
- New enabling technologies towards, e.g.,
  - Immersive platform services like artificial intelligence (AI)
  - Augmented reality, holograms



Key Challenges for Channel Coding

- Implementation constraints
  - channel decoding algorithms require dedicated hardware implementations
  - power consumption and physical size of the decoder on chip is an issue in mobile
  - backward compatibility to existing standards is a must
  - requiring many different decoder implementations on same chip; bottleneck...
- Thus, we need codes that are
  - energy efficient to encode/decode
  - flexible in rate and length
  - allow decoders designed for different KPI trade-offs
- A “unified coding scheme” would be an elegant way out



L. Johannsen, C. Kestel, M. Geiselhart, T. Vogt, S. ten Brink and N. Wehn, "Successive Cancellation Automorphism List Decoding of Polar Codes," *2023 12th International Symposium on Topics in Coding (ISTC)*, Brest, France, 2023, pp. 1-5, doi: 10.1109/ISTC57237.2023.10273499.

Possible Directions

- Codes for jointly optimized detection and decoding
  - tailored to specific channel interface, collect remaining “fractions of a dB”
  - (iterative) multiuser detection and decoding
  - (iterative) (shaped) constellation detection and decoding
- Or stay generic?
  - binary codes and soft-input decoders over Gaussian(-like) channels
- For the latter one, a “unified coding scheme” (across rate/length) easier to design
  - at, possibly, some loss compared to specifically tailored “niche” coding/decoding schemes
  - but transparently including important features such as incremental redundancy/HARQ etc.

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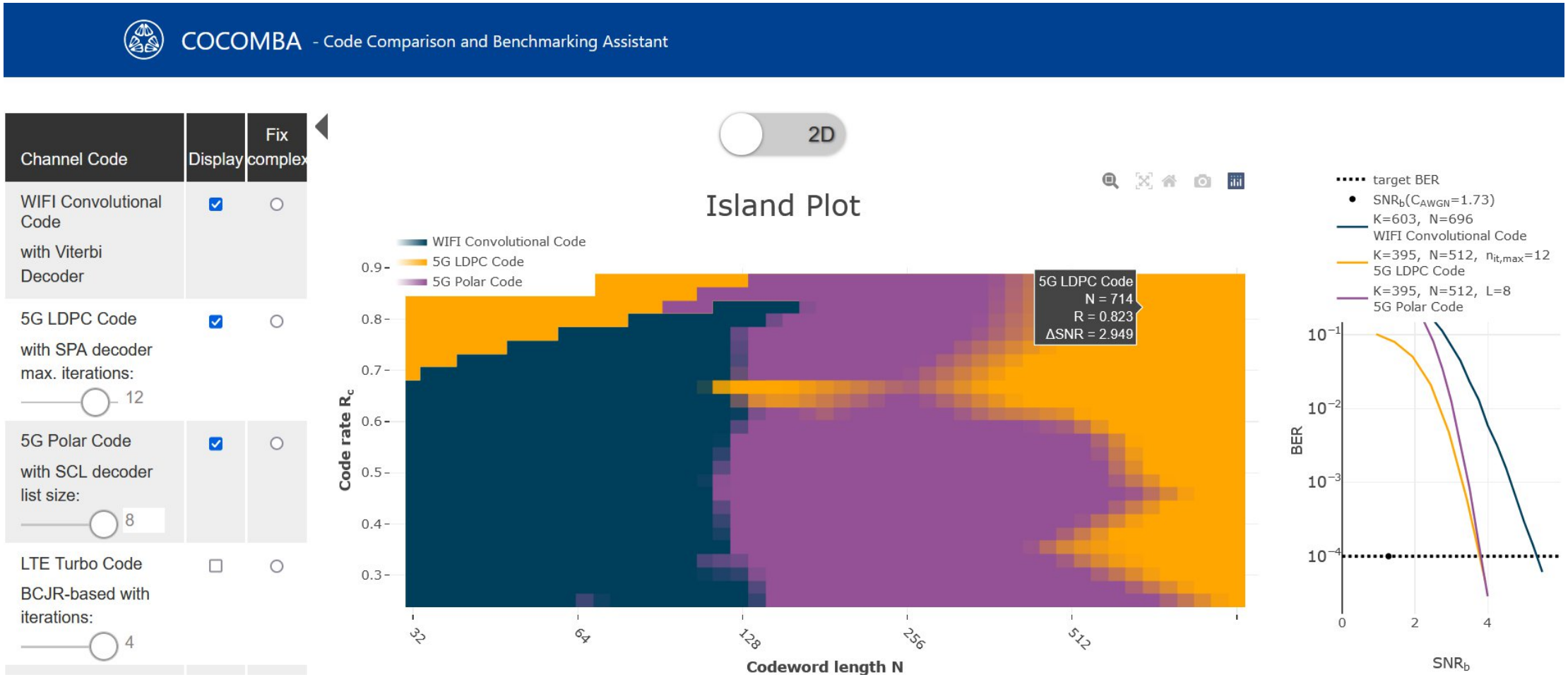
5G to 6G Standard Transition offers Unique Opportunity for Innovation

- 6G standardization efforts still in their infancy
- Unique opportunity to think “blue sky”
- Unified coding as a possible enabler
- If not now, how will 7G, 8G... further evolve?
  - many different coding/decoding schemes?
  - very specialized solutions for any sort of detection/decoding task?
- We need to “Cut this Gordian Knot of Coding”...

Tool for Comparing Codes: CoComBA — Code Comparison and Benchmarking Assistant

https://cocomba.inue.uni-stuttgart.de/



- Coding browser “CoComBA”: plot code/decoder pairs with lowest SNR to achieve BER of 10^{-4}
  - over code rate and codeword length

CoComBA — Code Comparison and Benchmarking Assistant

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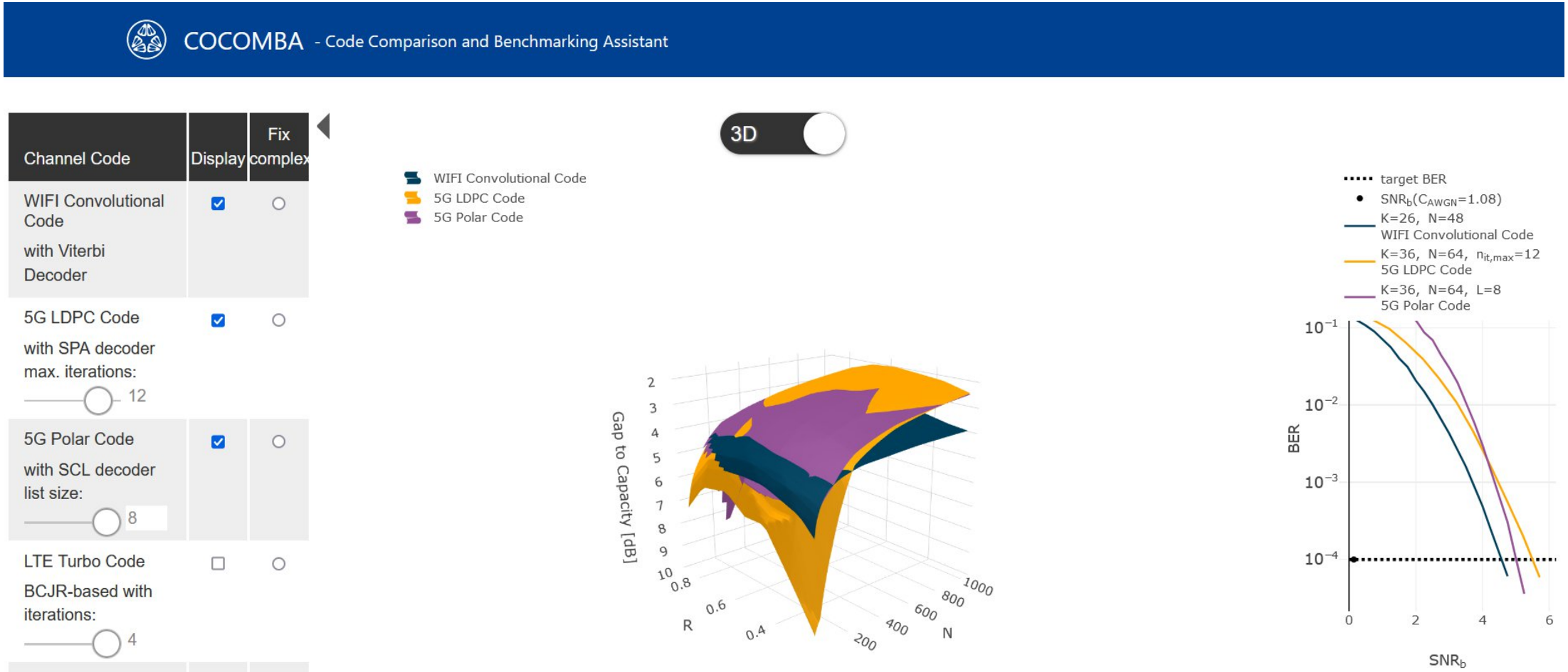
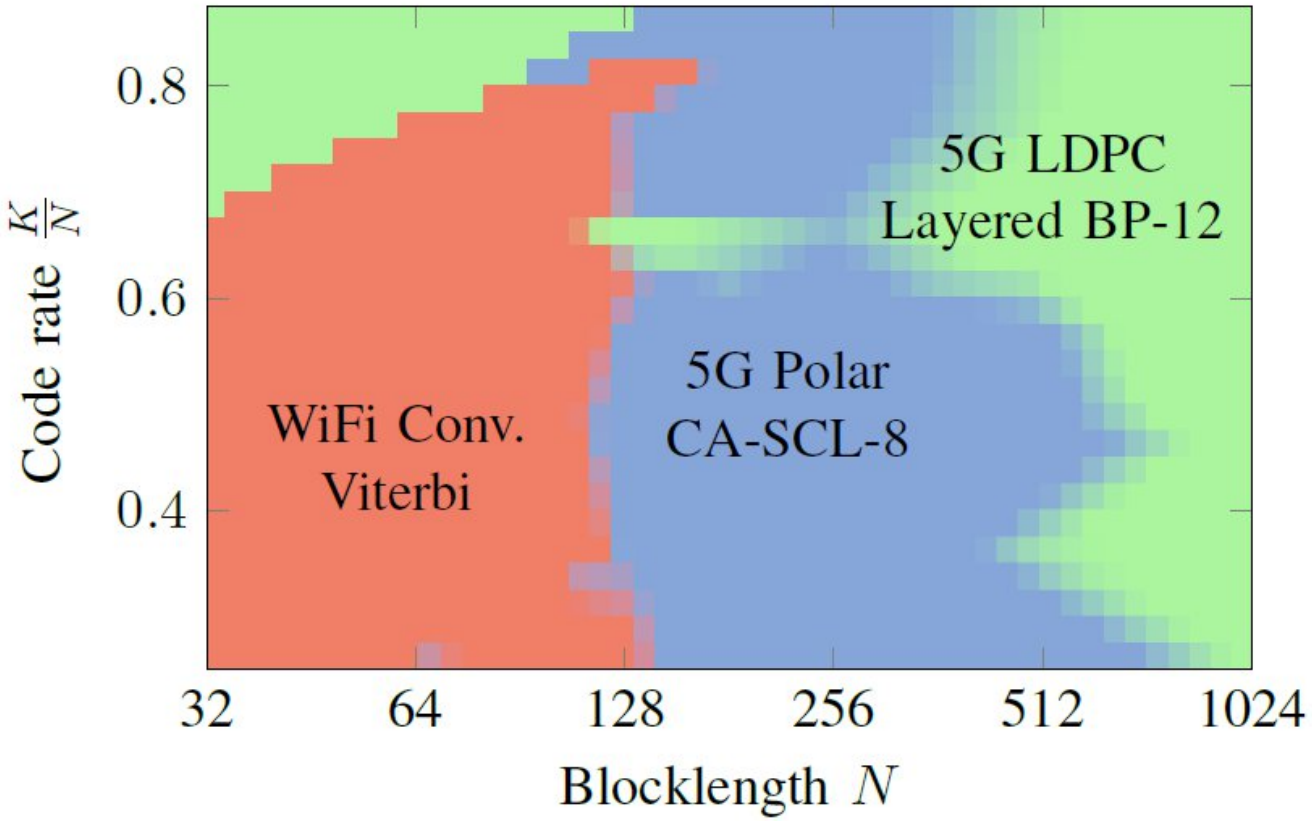


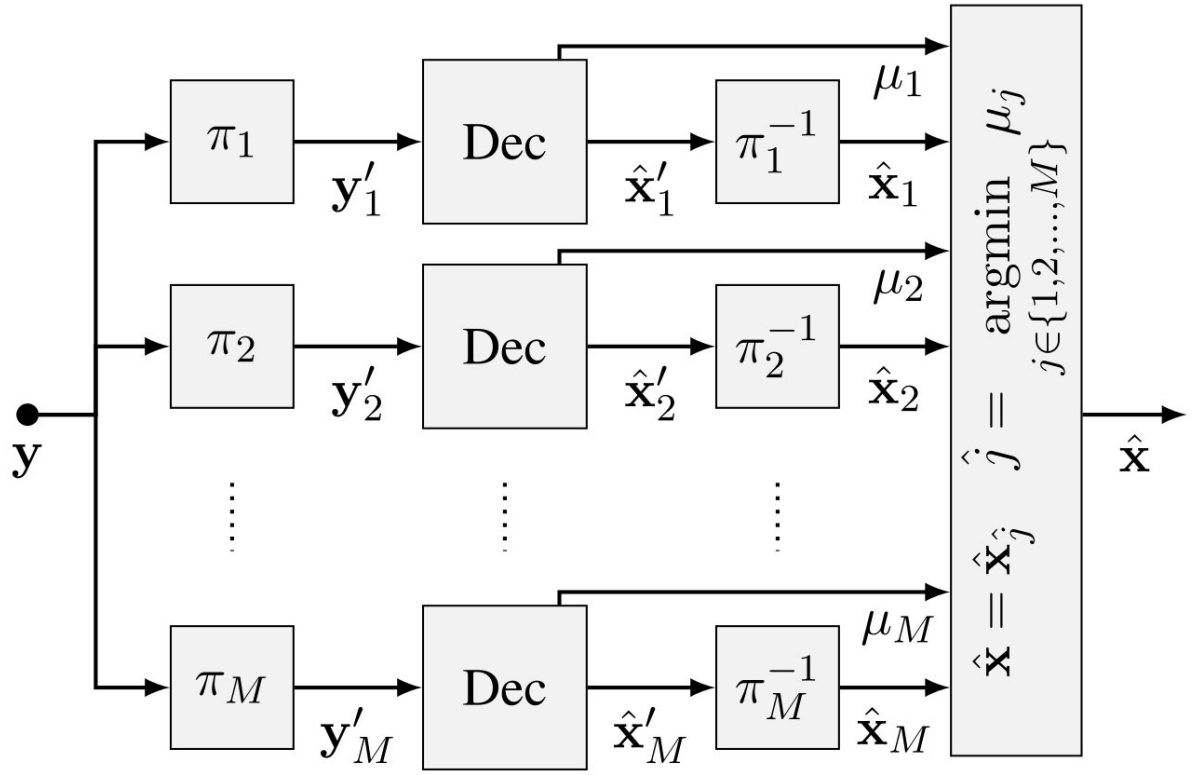
- Coding browser “CoComBA”: to quickly assess flexibility and performance of code families

CoComBA — Codes (and Decoders) versus Rate and Length



- None of the standardized channel codes dominates
  - i.e., none suitable for all applications (either code, and/or decoder limit performance)
- Unified channel coding approach: “one code fits all”
  - decode short codes with low latency for URLLC; long codes enable high throughput for eMBB, ...

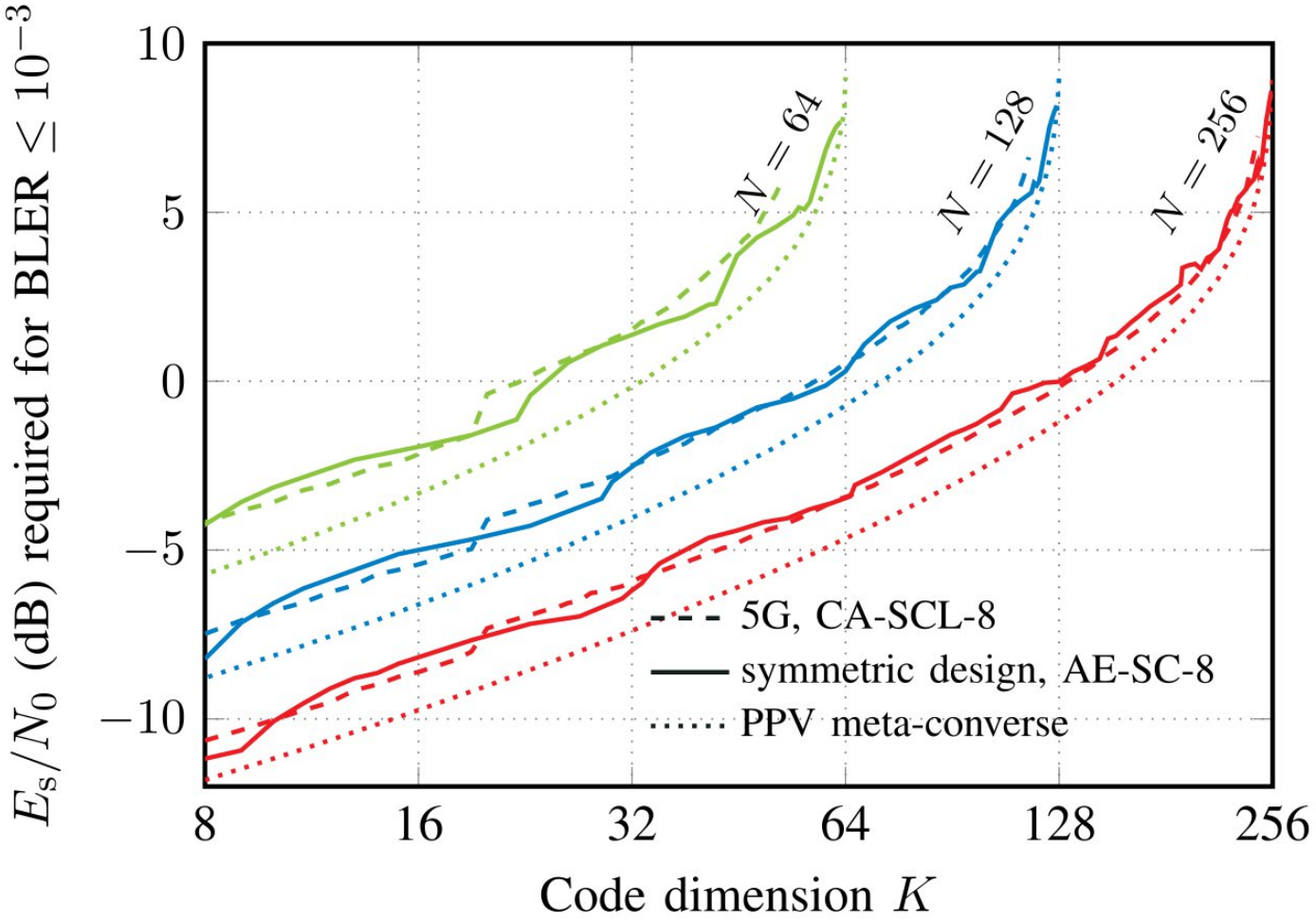
Automorphism Ensemble Decoding (AED) — A Promising Concept for Short Lengths



- Exploit algebraic structure of code (indeed, first applied to Reed-Muller and Polar Codes)
- Parallel decoding on different automorphisms of the code
- Attractive, low latency decoder option for short block-lengths (512 and shorter)

M. Geiselhart, A. Elkelesh, M. Ebada, S. Cammerer and S. ten Brink, "Automorphism Ensemble Decoding of Reed–Muller Codes," in *IEEE Transactions on Communications*, vol. 69, no. 10, pp. 6424-6438, Oct. 2021, doi: 10.1109/TCOMM.2021.3098798.

Automorphism Ensemble Decoding (AED) — One Promising Concept for Short Lengths



- Polar Codes designed for AED perform comparable to the 5G Polar Code, close to the Polyanskyi-Poor-Verdu (PPV) bound

M. Geiselhart, J. Clausius and S. ten Brink, "Rate-Compatible Polar Codes for Automorphism Ensemble Decoding," *2023 12th International Symposium on Topics in Coding (ISTC)*, Brest, France, 2023, pp. 1-5, doi: 10.1109/ISTC57237.2023.10273500.

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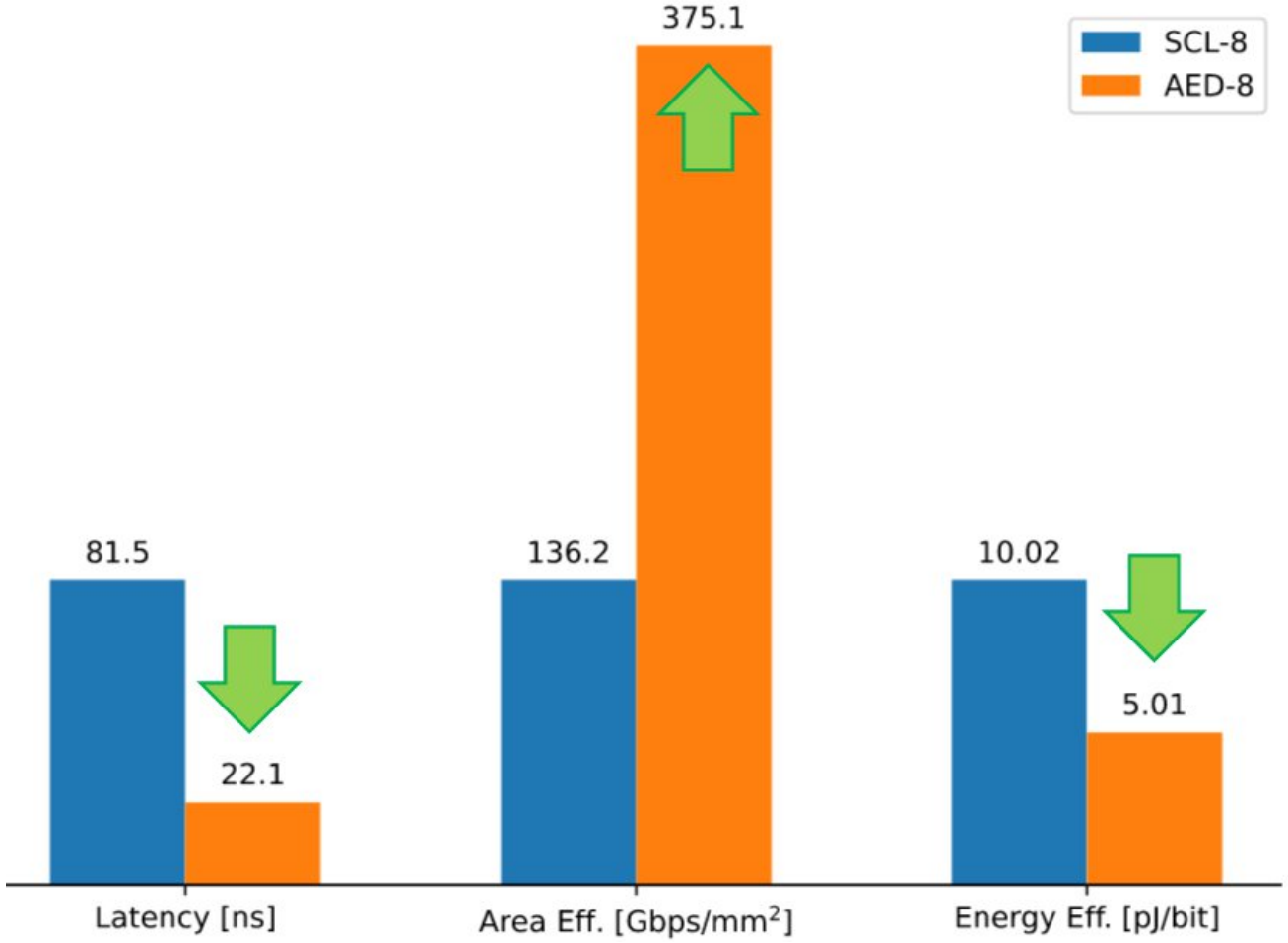


- AED outperforms SCL in implementation metrics for (128, 60) Polar Code

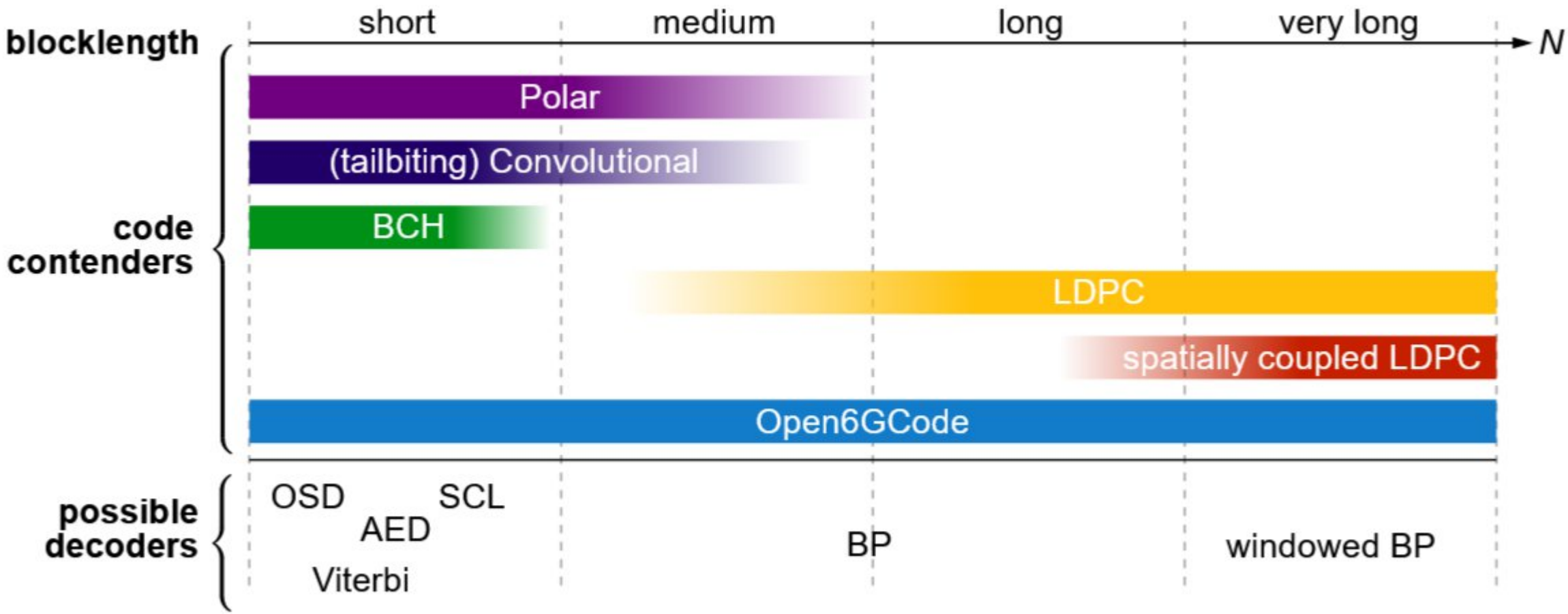
C. Kestel, M. Geiselhart, L. Johannsen, S. ten Brink and N. Wehn, "Automorphism Ensemble Polar Code Decoders for 6G URLLC," *WSA & SCC 2023; 26th International ITG Workshop on Smart Antennas and 13th Conference on Systems, Communications, and Coding*, Braunschweig, Germany, 2023, pp. 1-6.

Open6GCode: Towards a Blue Print for a 6G Channel Code

- Possible approaches to come up with unified coding scheme
  - make polar codes good for long codeword length
  - or, make LDPC codes good for short codeword length
- Envisioned is a code family that can “morph”
  - from a highly symmetric, AED decodable code (or distance optimizing code for code-agnostic decoders) at short length
  - to a state-of-the-art LDPC-like code for high throughput BP decoding at long(er) length
  - possibly spatially coupled codes for very long length (THz broadband?)
- Combine potentially different code designs into a unified, low complexity description
- No proposal ready yet, but white paper is “in the making”
- Currently under investigation within the Open6GHub-Project

https://www.open6ghub.de/

Open6GCode: Towards a Blue Print for a 6G Channel Code



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Conclusion

- Highlighted research directions towards 6G unified coding
- “Cut the Gordian Knot of Coding”: From fragmentation to unification
- One promising concept: AED-enabled codes for short lengths

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Thank you!

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