EEE420 | Wireless Communication

Final Report

Coding techniques for 5G networks: Polar and LDPC

Project Supervisor: Mr. Waheed Ullah

Team Members: 545 – S. M. Jayakody

570 – J. S. Cole

580 - B. M. M. E. Warapitiya

674 - S. N. Vellupille

Abstract

Research on 5G wireless communications strives to bring about higher data rates, higher bandwidth, high spectrum efficiency, higher energy efficiency and that too at lower latency. To meet these demands, channel coding plays a major role by increasing the reliability and efficiency of any associated wireless communication system. In the context of 5G, LDPC Codes and Polar Codes have received much more interest, opposed to other channel coding methods because of their inherent advantages of excellent bit-error-rate performance. Fast encoding and decoding procedures make them strong contenders among other 5G Channel Codes, and are replacing 4G LTE Turbo Codes. This report provides a detailed analysis and comparison between 5G Polar and LDPC Codes with their advantages, drawbacks and performance with respect to several parameters including encoding decoding complexity (processing time) and BER (Bit Error Rate).

Table of Contents

Abstract 2

Table of Contents 3

Introduction 4

- 5th Generation Technology Standard for Cellular Networks 4

Introduction to Channel Coding 6

- General Performance and Efficiency Comparison of Turbo, Polar and LDPC codes 6
- Channel coding in 5G 7

LDPC Codes 9

- Encoding and Decoding LDPC codes 10
- Quasi-Cyclic LDPC Codes 10

Polar Codes 12

- Construction of Polar Codes 12
  - Channel Polarization 12
  - Code Design 13
- Encoding 13
- Decoding 13
- Complexity of polar codes 14

Comparison of Bit Error Rate 16

Conclusion 18

1. Introduction

1.1. 5th Generation Technology Standard for Cellular Networks

Every day, the need for higher internet speeds grows, while the internet of things itself introduces a new challenging demand for upcoming wireless communication technologies. 5th Generation communication is the newest standard of wireless communication (IMT-2020) which provides enhanced wireless communication through efficient use of cutting-edge technologies.

In the context of Wireless Mobile Communication there is a requirement for extensive data bandwidth to bring about crucial services. 5G networks are to be designed to fulfill these requirements by providing significant speed, low latency, and peak throughput. It schedules 5th generation networks to work on different demands for organization and other alternative use cases.

5G is not only a new radio interface; it is a set of standards which are set by the ITU to achieve higher data rates, low latency and massive connectivity also known as enhanced mobile broadband (eMBB), ultra-reliable low latency communications (URLLC) and massive machine-type communications (mMTC).

There are three main scenarios to be fulfilled in the era of 5G communication which cannot be satisfied in LTE.

ITU has defines the technical aspect of these scenarios as such:

eMBB

- eMBB refers to enhanced mobile broadband; it supports stable connections with very high peak data rates, as well as moderate rates for cell-edge users.
- The ITU has set a minimum peak data rate requirement of 20 Gbps for downlink and 10 Gbps for uplink for eMBB services also ITU has set the minimum requirement for latency to 4 ms and eMBB services should be supported by mobile stations traveling at speeds of up to 500 km/h in rural areas. [1]

- Quadrature Phase-Shift Keying (QPSK) and Quadrature Amplitude Modulation (QAM) such as 16-QAM, 64-QAM and 256-QAM are supported for both uplink and downlink transmissions.

URLLC

- URLLC refers to ultra-reliable low latency; it supports low-latency transmissions of small payloads with very high reliability from a limited set of terminals
- The ITU has set a standard of the minimum latency for URLLC services is 1 ms. [1]
- The key contributors to latency at the physical layer are time-to-transmit delay, processing latency, and retransmission time, all of which can be decreased with proper design.

mMTC

- Massive machine type communication (mMTC) refers to the support of a large number of Internet of Things (IoT) devices that are only occasionally active and communicate modest data payloads.
- ITU's requirement for mMTC services is that a connection density of 1 million connected devices/km^2 should be supported. [1]
- Low-energy devices must exchange short packets of a few bytes for mMTC services, and transmissions will be uplink-dominated with irregular transmission intervals.
- For linked devices to maintain high energy efficiency, channel codes selected for mMTC must give good performance with short block lengths and low complexity.

To meet the above requirements, 5th generation networks use technologies such as mmWaves, massive MIMO antennas, small cells, beamforming, etc.

2. Introduction to Channel Coding

Channel coding schemes are considered as the embedding of signal constellation points in higher dimensional signaling space needed for communication. They play an important role in achieving higher data rate in order to have fast and error free communications. When choosing a channel coding scheme for a wireless communication system, the coding scheme needs to have low computation complexity, low latency, low cost and higher flexibility for having a better performance in the system. These are generally the parameters used for evaluating the performance of coding schemes (under specific code word lengths, decoding algorithms, channel environments, constellations etc.). Channel coding schemes are commonly measured against the channel capacity and there is a possible limit that can practically be achieved for any channel code in accordance with the Shannon capacity theorem. [2]

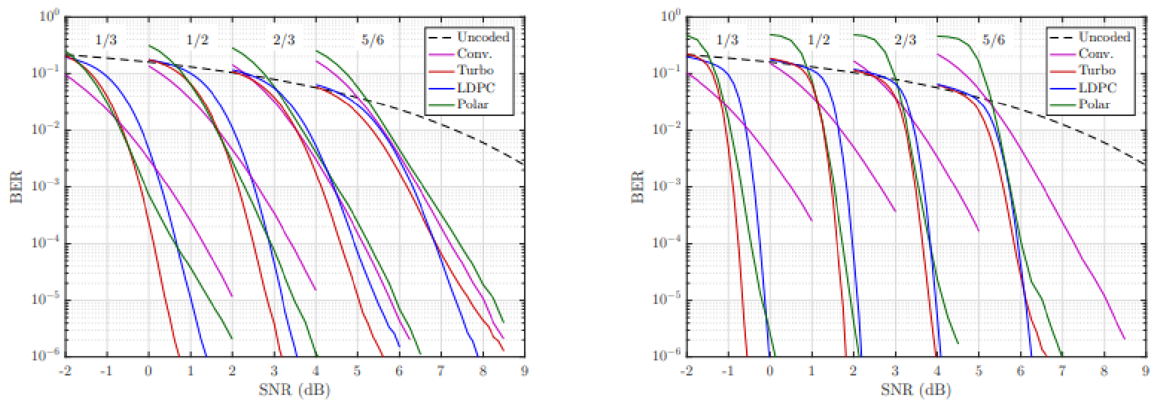
First gaining interest in research fields, through Shannon's landmark paper in 1948, channel coding bounds were explored with the invention of Turbo codes in 1993. They were later adapted in both 3G and 4G standards. LDPC codes, first invented by Gallager in 1962, were re-discovered by MacKay and Neal in 1997 and it was adapted in multiple wireless communication standards including Wi-Fi (IEEE 802.11n) (IEEE, 2012), Digital Video Broadcasting (DVB-S2/T2) (2005) and mobile WiMAX (IEEE 802.16e) (IEEE, 2006).

2.1. General Performance and Efficiency Comparison of Turbo, Polar and LDPC codes

	TURBO	**LDPC**	**POLAR**
Low speed performance	Average	Average	Perfect
Low speed efficiency	Average	Average	Perfect
High speed performance	Perfect	Perfect	Average
High speed efficiency	Bad	Perfect	Average

The paper “BER Comparison Between Convolutional, Turbo, LDPC, and Polar Codes” published in 2017 24th International Conference on Telecommunications (ICT) [3] has discussed the comparison of these coding schemes according to the above conditions.

Here are their results:



BER comparison for different code rates, $K = 256$ (For LDPC, $K = 252$ for $R = 1/2$, and $1/3$, and $K = 260$ for $R = 5/6$.)

BER comparison for different code rates, $K = 2048$ (For LDPC, $K = 2052$ for $R = 1/2$, and $1/3$, and $K = 2040$ for $R = 5/6$.)

Figure 1 - B. Tahir, S. Schwarz and M. Rupp, "BER comparison between Convolutional, Turbo, LDPC, and Polar codes,

This represents the behaviour of each coding scheme that can be observed at different code rates of BPSK modulated signals over an AWGN channel.
We can clearly observe that the LDPC and Polar codes perform better than convolutional codes when the K (message bit) size is high. Therefore, LDPC and Polar codes are better than convolutional codes for sending long data streams.

2.2. Channel coding in 5G

With the introduction of 5G, there has been quite a lot of research regarding the channel codes to be chosen for 5G. The precise and conflicting requirements established for URLLC in 5G have rendered it as the most challenging service class, with the main channel code contenders for 5G URLLC being Turbo codes, LDPC codes, Polar codes and Rateless codes. These contenders have their own advantages and disadvantages and none of them outperforms all the others at all code-rates and code-lengths

LDPC and Polar codes have been the most effective for error correction. In 5G, LDPC codes are used for the data channel and for the control channel Polar Codes are used. These provide high throughput, low power dissipation, and low latency and a higher coding gain. Polar codes depend on channel polarization and is considered as the first code that achieved Shannon channel capacity. Polar codes have wide applications in Information theory. Further, other variants including Quasi Cyclic LDPC code, Irregular Repeat-Accumulate (IRA) code, Spatially Coupled LDPC (SP-LDPC), NB LDPC- Polar Codes play an important role in achieving the objectives required for 5G and come with their own advantages, disadvantages and performance benchmarks. [4] Among all different types of channel coding schemes researchers claim that overall Polar and LDPC codes remain to be strong contenders in meeting the 5g requirements.

These are some of the main attributes that 5G channel codes are expected to fulfill.

- Throughput

In 5G NR throughput can be classified into encoded processing throughput and decoded processing throughput. For eMBB services in 5G a high throughput of 20 Gbps is required inturn demands a higher channel encoder/decoder throughput of at least 20Gbps so as it doesn’t bottleneck the network. These encoding/decoding speeds could be achieved through various methods including parallel processing.

- Latency

An end-to-end latency of 0.5 milliseconds is required for 5G which is a large improvement from the 4G 10 millisecond latency. In 5G, ultra-low latency is used for real-time applications by reducing the latency associated with the channel code encoding and decoding process by including multiple decoders to decode several data blocks simultaneously.

- Error correction capabilities

In 5G, channel codes are expected to perform well enough such that in the worst case, the block error rate (BLER) of the decoded data blocks is 1×10^{-5}, which is a tenth of what is experienced with 4G. With this the need to retransmit packets would be reduced hence reducing overall latency. Further this in turn minimizes the requirement of HARQ (Hybrid automatic repeat request) and latency.

- Implementation complexity

The 5G channel encoders and decoders are expected to have a low complexity with lower resource requirements and energy consumption, similar to 4G.

- Flexibility

With 5G being used for multiple applications and services a requirement for channel codes to be adaptive in coding rates and codeword length is introduced, with the different devices or applications supporting different data blocks. It should optimize the use of excessively encoded bits which may reduce spectrum efficiency, latency and throughput. [2] [4]

3. LDPC Codes

Low-density Parity-check (LDPC) codes belong to a class of Forward Error Correction (FEC) codes which have been attracting attention due to their low complexity and their near channel capacity performances. These codes were first introduced by Gallager. The concept of parity check codes, when it was invented, was not initially applied to systems due to the requirement of complex decoding operations. This slowed down the communication process to the point it was no longer viable. However, Gallager later devised a system having short block lengths optimizing LDPC instead of earlier large block LDPC Codes. These codes provided a higher data rate along with excellent bit-error rate performances, which came at the cost of its encoding intricacy being very high. LDPC Codes can be depicted in two peculiar ways: one using parity check matrix (PCM) representation and other using a graphical depiction.

In LDPC Codes, two base parity check matrices called Base Graph are used which employ the Base Graph corresponding to the input length and code rate. They operate by having one of them for a short length with a low code rate and another for a great length with a high code rate.

This code is flexible for all block sizes with higher spectral efficiency supporting a higher throughput for 5G. [2]

3.1. Encoding and Decoding LDPC codes

For encoding of LDPC codes double-diagonal structures of the parity check matrix are used. The encoding is constructed systematically with a relatively low complexity. At the output of the encoder, a certain amount of the systematic bits are punctured. These punctured bits never enter the circular buffer.

For decoding LDPC codes various methods were used in studies. Message passing algorithm, belief propagation algorithm, Minsum Algorithm and Sum-product algorithm were among the most popular algorithms. Some algorithms like the Sum product algorithm come with a large computational complexity These operate on hard decision decoding, whereas for better output, soft decision decoding is used. [2]

3.2. Quasi-Cyclic LDPC Codes

Among the other channeling coding techniques available a well-known LDPC variation is the Quasi-Cyclic LDPC Codes. These codes have a quasi-cyclic structure and come with low encoding and decoding complexity. Hardware implementation is easy and it gives a good iterative performance. A lifting degree is used for the operation. This code provides a good performance over the AWGN channel as it converges fast.

QC LDPC codes were compared with Turbo and Polar codes by Gamage et al. (2017) [5] to determine which of these FECs are most suitable for eMBB. They devised that the advantage of using QC LDPC codes over conventional LDPC codes is that the former has a parity check matrix made up of small square blocks of circulant permutation matrices or zero matrices, using up less memory. In their paper they concluded that Polar codes gave the best error performance for short block lengths, Turbo codes were the least competent of 3 compared codes, giving a low area and energy efficiency while Quasi-cyclic (QC) LDPC codes provided a relatively good error performance at all block lengths and code-rates and also had a low complexity. QC-LDPC codes have already been incorporated in the 5G standards for eMBB. Yet, research was still ongoing to determine whether LDPC codes can be used for URLLC. Diao et al. (2016) [6] observed that structured QC-LDPC codes can reach a BER of order 10^{-15} at low E_b/N_0 without hitting an error floor. Thereby they concluded that LDPC codes can be good candidates even for URLLC which has a block error rate (BLER) requirement of 10^{-5} for short data package transmission

4. Polar Codes

Polar codes are a type of Channel coding which was introduced by Erdal Arıkan in 2008. Polar codes are the first error-correcting codes to achieve the capacity of arbitrary binary-input symmetric discrete memoryless channels (DMCs). [7]

In the 5G standardization, polar codes have been accepted as channel coding for uplink and downlink control information for eMBB (enhanced mobile broadband), and for the two other frameworks 5G foresee; URLLC (ultra-reliable low-latency communications) and mMTC (machine-type communications), polar codes are among the possible coding schemes.

An effort has been made in the design and construction of polar codes in5G that it is easy to implement, has low description complexity and good error performance over multiple code and channel parameters. [8]

4.1. Construction of Polar Codes

4.1.1. Channel Polarization

Channel polarization is done to construct code sequences that can achieve symmetric capacity of binary-input discrete memoryless channels (B-DMC).
Channel polarization creates a second set of a given B-DMC that shows a polarization effect. This is done in two phases; channel combining phases and channel splitting phase.

> Channel Combining: here, the copies of the given B-DCM are combined recursively to produce a vector channel. This produces N synthetic bit-channels from N independent copies of B-DMC.
>
> Channel Splitting: the synthesized vector channel is split back into a set of binary input coordinate channels defined by the transition probabilities. In other words, the synthetic channels are polarized such that each can transmit a single bit with a probability of being decoded correctly.

In the case of N being large, the mutual information of the synthetic channel is either a completely noisy channel or perfectly noiseless channel. Which is denoted as completely noisy being 0 and perfectly noiseless being 1.

The foundation of polar codes mathematically, is in the discovery of the matrix $G_2 = \begin{bmatrix} 1 & 0 \\ 1 & 1 \end{bmatrix}$ which is known as the basic polarization kernel. A two-bit vector can be multiplied buy this matrix to create a codeword. [8] [9]

4.1.2. Code Design

Polar codes are based on the concentration on basic polarization kernels which creates a cascade reaction speeding up the polarization of synthetic channels while limiting the complexities in encoding and decoding. The concentration process results in a channel transformation matrix that is defined by the n-fold Kronecker product; $G_N = G_2{}^{\otimes n}$

When recursively calculated it results in $G_N = \begin{bmatrix} G_{\frac{N}{2}} & 0 \\ G_{\frac{N}{2}} & G_{\frac{N}{2}} \end{bmatrix}$..

Polar code length can only be only that is to the power of two $(N = 2^n)$ but, the number of information bits transmitted (K) can be of any arbitrary value.

A (N, K) polar code is designed to identify the K best synthetic channels that provide the highest reliability. These identified channels will be transmitting the information while the remaining $N - K$ channels are not carrying any information hence, frozen channels. [8]

4.2. Encoding

When the input vector $\boldsymbol{u}$ of length N is given as $\boldsymbol{u} = [u_0, u_1, \dots \dots, u_{N-1}]$, the codeword $\boldsymbol{d} = [d_0, d_1, \dots \dots, d_{N-1}]$ can be calculated as;

$$d = u \,.\, G_N$$

The encoding complexity is reduced by performing the G_N matrix multiplications in parallel.

4.3. Decoding

The decoding algorithm called; Successive Cancellation (SC) can be represented as a depth-first binary tree search with priority to the left branch where the leaf nodes are the N bits to be estimated. [8]

4.4. Complexity of polar codes

There are many decoding algorithms used for polar encoding. Successive Cancellation (SC) Decoding, Simplified Successive-Cancellation (SSC) Decoding, LSC (List Successive Cancellation), SCS (Successive Cancellation using Stack), CRC (Cyclic Redundancy Check) decoding, Hybrid Decoding, Sorting and Non-sorting Algorithms aided List Decoding, Belief Propagation, are some of them. Parameters regarding to those different algorithms should be considered when analyzing encoding complexity as well as decoding algorithms.

SC decoding algorithm cancels the interference from the previous bits during each successive step. This algorithm works on branches with higher probability. Each and every branch incorporates message bits. Since the algorithm works on a branch with higher probability, if any single bit gets false from a higher probability branch, it will badly affect the algorithm. The whole procedure fails which proves that this algorithm is not the optimal one. Complexity can be expressed as $O(K\log K)$, where K represents the length of code words. Complexity directly affected by the length of code words. SSC decoding algorithm which is an extension of SC algorithm reduces repeated computations by using categories such as rate 0, rate 1, rate r. This is a less complex algorithm comparatively; it is reduced by 20 times compared with SC decoding algorithm.

The LSC algorithm does its decoding by three steps where initiation, estimation of bits (Inflation, Candidacy, Elimination) and confirmation are done within the algorithm. Complexity of the algorithm which is expressed as $O(MK\log K)$. The reduction of the dimension list will increase the performance of polar codes. This will sometimes cause difficulty to find the ideal value for dimension of the list. SCS algorithm also runs according to some steps such as Initiation, retrieving from stack, Expanding, Saving, Arranging, Conclusion. These algorithms also mostly work according to the same performance as SC algorithm and complexity also define which is same as the SC algorithm. The CRC algorithm works in such a way that Concatenation of CRC encoder before polar encoding and CRC decoder after polar decoding reduces the bit-error rate further and makes it even better than turbo codes. This algorithm is also considered as increasing the complexity too. Hybrid decoding which acts as both a combination of listing and stacking algorithms. Algorithms act in two different modes such as continue and delay mode. These algorithms also mostly act as SC decoding algorithms and act with lesser complexity. [10]

A modification of the SC decoder is called Simplified Successive Cancelation (SSC). In SSC, local decoders for rate-one constituent codes are simplified. This modification reduces the decoding latency and algorithmic complexity while preserving the bit and block error rate. [11] In a research paper published several simulations were conducted that revealed Successive cancellation list (SCL) decoding performed better compared to Successive Cancellation (SC) decoding. [2]

5. Comparison of Bit Error Rate

In the paper of “Overview of the challenges and solutions for 5G channel coding schemes” by Madhavsingh Indoonundon & Tulsi Pawan Fowdur. [4]

They have done a simulation of Release-15 LDPC codes for eMBB’s Downlink Shared Channel (DLSCH) used for the transmission of downlink data. The transport block to be transmitted first goes through Downlink Shared Channel (DLSCH) for LDPC codes.

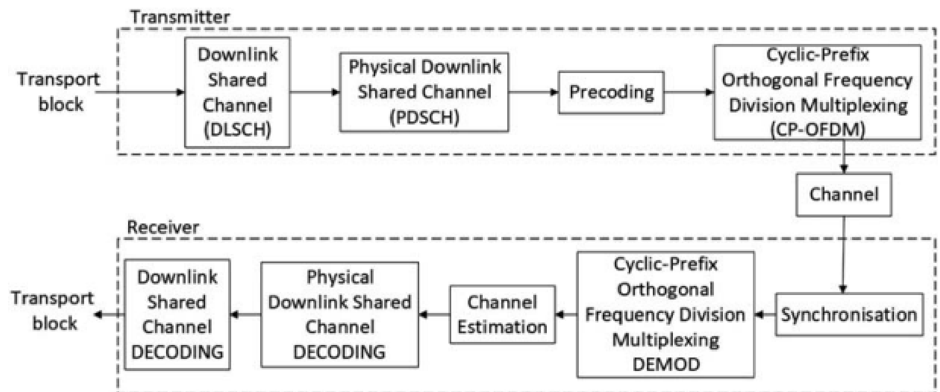


Figure 2 - Mathworks. (2018b). LTE DL-SCH and PDSCH Processing Chain- MATLAB & Simulink

And for the polar codes they have done the simulation according to the following procedures;

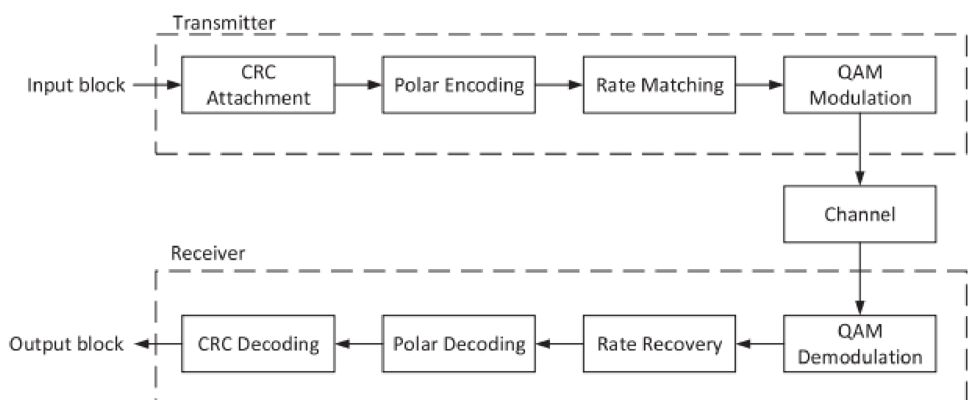
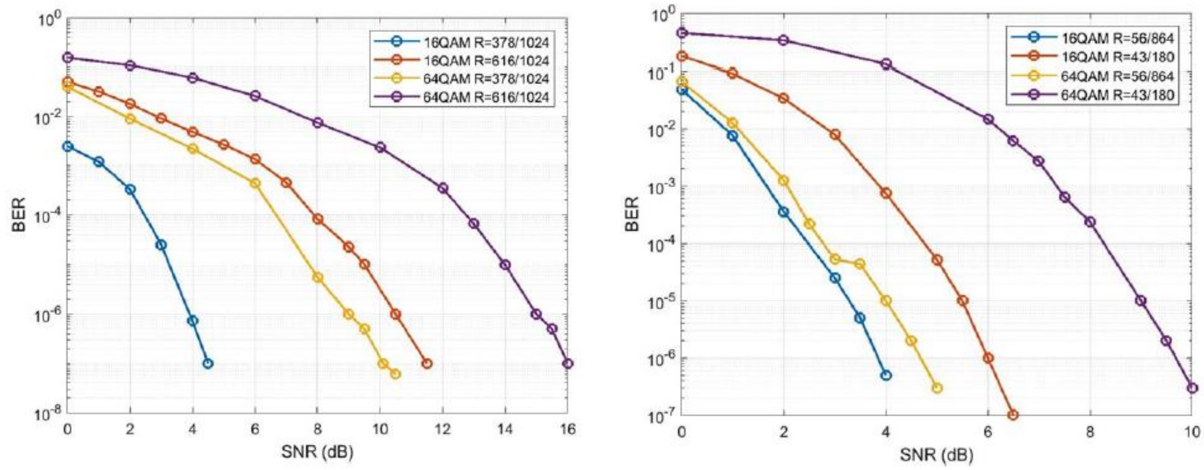


Figure 3 - Mathworks. (2021). 5G New Radio Polar Coding- MATLAB & Simulink.

Here are the simulation results which follows the above procedures:



BER Vs SNR of LDPC code

BER Vs SNR of Polar Codes

Figure 4 - Indoonundon, M. and Pawan Fowdur, T., 2021. Overview of the challenges and solutions for 5G channel coding schemes.

At a BER of 10^-6 LDPC codes can be interpreted as

- The use of 16-QAM allows the system with a PDSCH of code-rate 378/1024 to achieve an SNR gain of 5 dB over the system using the same PDSCH code-rate that uses 64-QAM.
- The use of 16-QAM allows the system with a PDSCH of code-rate 616/1024 to achieve an SNR gain of 4.5 dB over the system using the same PDSCH code-rate with 64-QAM.

At a BER of 10^-6 Polar codes can be interpreted as

- The use of 16-QAM allows the system with a code-rate of 56/864 to deliver an SNR gain of 1.1 dB over the system using the same code-rate but using 64-QAM instead.
- The use of 16-QAM allows the system with a code-rate of 43/180 to deliver an SNR gain of 3.5 dB over the system using the same code-rate but using 64-QAM instead

6. Conclusion

With the demand for much greater efficiency through the introduction of 5G, channel coding challenges have evolved with the new challenges introduced by its different service classes. While eMBB demands channel codes to have high decoding throughputs so that 5G communications are not bottlenecked by it, URLCC demands strong error performance on short data blocks with lower latency. Further for mMTC, the channel codes are expected to have a low complexity to reduce the energy consumption of associated devices and to maintain a good flexibility to work with the varying data block lengths.

Among 5G simulations conducted in various studies, for LDPC and Polar codes it was revealed that for large block lengths, LDPC Codes provided a better performance while for shorter block lengths Polar Codes gave a better performance compared to LDPC with no error floor. Polar codes generally provided higher performance and efficiency at lower speeds while LDPC codes performed better at higher speeds. Applying these onto 5G service classes for eMBB applications which demand a high-speed traffic service (with upto a target peak rate of 20 Gbps for downlink and 10 Gbps for uplink) where, as explored throughout this paper, LDPC coding is mainly considered for eMBB implementation, proving to be an efficient channel coding scheme among its competitors.

As for the other 5G service classes including URLLC and mMTC, no decision has yet been made on their channel coding schemes. While polar codes seem to favor URLLC over LDPC, concatenation of these channel codes are being tested for improving error performances and new channel codes such as spinal codes are being investigated for their suitability in these services.

References

[1] ""Minimum requirements related to technical performance for IMT-2020 radio interface(s)"," ITU, 2021. [Online]. Available: https://www.itu.int/pub/R-REP-M.2410-2017.

[2] S. P. Z. S. Mrinmayi V Patil, "Coding Techniques for 5G Networks: A Review," in *IEEE Xplore*, 2020.

[3] S. S. a. M. R. B. Tahir, "BER comparison between Convolutional, Turbo, LDPC, and Polar codes," in *24th International Conference on Telecommunications (ICT)*, 2017.

[4] M. a. P. F. Indoonundon, "Overview of the challenges and solutions for 5G channel coding schemes.," *Journal of Information and Telecommunication,* pp. pp.460-483, 2021.

[5] H. R. N. &. L.-a. Gamage, "Channel coding for enhanced mobile broadband communication in 5G systems," in *European Conference on Networks and Communications*, Oulu, Finland. EuCNC., 2017.

[6] Q. L. J. L. S. &. B. Diao, " New classes of partial geometries and their associated LDPC codes," *IEEE Transactions on Information Theory,* vol. 62, no. 6, p. 2947–2965, 2015.

[7] E. S. I. L. H. T. F. I. T. T. –. I. I. o. T. I. A. Balatsoukas-Stimming, "Best Readings in Polar Coding | IEEE Communications Society," www.comsoc.org, [Online]. Available: https://www.comsoc.org/publications/best-readings/polar-coding. [Accessed 27 November 2021].

[8] C. C. I. L. V. Bioglio, "Design of Polar Codes in 5G New Radio," *IEEE Communications Surveys & Tutorials,* 2021.

[9] E. Arikan, "Channel Polarization: A Method for Constructing Capacity-Achieving Codes for Symmetric Binary-Input Memoryless Channels," *IEEE Transactions on Information Theory,* vol. 55, no. 7, pp. 3051-3073, 2009.

[10] J. S. S. R. Komal Arora, "A survey on channel coding techniques for 5G wireless networks," 2019.

[11] A. A.-Y. a. F. R. Kschischang, "A Simplified Successive-Cancellation Decoder for Polar Codes," *IEEE Communications Letters,* vol. 15, no. 12, pp. 1378-1380, 2011.