4G vs 5G Channel Coding Techniques

Student paper

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***Abstract*- This paper provides an overview of the coding techniques used in the 4G network: Turbo and Convolutional codes and the coding techniques used in the 5G network: Polar and Low Density Parity Check (LDPC) codes. The encoding and decoding mechanisms for all the mentioned codes will be described in detail. Long-Term Evolution (LTE) network also known as 4G brought improved wireless Internet access and higher data rates. 5G network brings improvement of the quality of service (QoS), the reliability of data transmission, and the security of the systems. An important role in the quality of information transmission is played by channel coding, which contributes to a more reliable transmission through its error correction process. The paper will also discuss why the same coding techniques are not used for 5G as for 4G and why one coding technique is not sufficient for all applications.**

Keywords-LDPC codes; Polar codes; Turbo codes; Convolutional codes; 4G; 5G

I. Introduction

Along with other technological developments, mobile networks have developed and changed over time as well. So in the last forty years, five generations of mobile networks have been introduced to the world. 1G, as it was symbolically called, or more exactly the first generation of mobile networks, could only transmit voice, the basis for this transmission being analog transmission. In the 1980s, when the first generation of mobile networks appeared, all people around the world were allowed to use mobile networks for the first time in history. After that, after about 10 years or so, the second generation of mobile networks appeared. 2G presented a novel approach, a digital transmission via a radio link. Although voice transmission was still the primary service offered by the 2G network, digital transmission enabled a plethora of new services such as call hold, international roaming, text messages, etc. Especially in Europe but also in the world, the most common technology of the second generation of mobile networks was certainly Global System for Mobile Communication (GSM), which was also developed in Europe. In the early 2000s, the third generation of mobile networks brings faster and more efficient wireless Internet access which improved the data capacity of services and data transmission. Since then, video calls, playing video games, internet browsing, and sharing multimedia content have become an indispensable part of every person's life. All this has been achieved through the evolution of 3G - HSPA (High-Speed Packet Access) [1]. In 2009, new technology was introduced, which presents the beginning of a 4G network that is often called LTE network. Among the main benefits of LTE was improved wireless Internet access, which has allowed end-user to experience higher data rates. LTE technology is based on HSPA and transmission that is based on Orthogonal Frequency-Division Multiplexing (OFDM) [1]. After higher data rates were achieved, it became possible to have human-to-machine as well as machine-to-machine communication. The emphasis of the 5G network are the improvement of the quality of service (QoS), the reliability of data transmission, and the security of the systems [1]. Higher data rates, low latency, and a large number of connections are three main conditions for good coverage with very good performance. Maintaining a good connection for customers moving at high speeds should prove to be a major improvement of the quality of the user experience. The need for ultra-reliable low-latency communications has emerged in many environments where constant connectivity is essential due to the transmission of large amounts of information in real time. Ability of the network to connect from several thousands to several million of such devices is a major goal of 5G, so a good coverage over a wide area, while providing good indoor signal strength and scalable connectivity are very important.

Forward error control coding (FECC) which is known as channel coding, presents a process of correcting the communication errors which are caused by noise, interference and signal attenuation [2]. Since the aim is to get the signal to the receiver with as few errors as possible, channel coding has a very important role in a communication system. The Third Generation Partnership Project (3GPP) chose LDPC codes and Polar codes for 5G network, instead of Turbo and Convolutional codes, which were used in LTE [3].

In Section II, there will be a discussion of the channel coding. Section III presents 4G channel coding schemes followed by 5G channel coding schemes in Section IV. Section V contains the conclusion in which the difference between 4G and 5G coding techniques is given in brief as well as the reason why the same coding techniques are not used in both 4G and 5G generations of mobile networks.

II. CHANNEL CODING

A communication system is an integrated structure of hardware and equipment that is designed to transmit information from the transmitter to the receiver. As far as this paper is considered, such a system is a digital communication system which means that information being transmitted is in digital form. A regular problem that is well known and faced by this type of transmission is fading. For one, fading occurs when the signal from the transmitter to the receiver does not reach the receiver through only one path but through several different paths, and then we have what is called a multipath propagation. But there are also other causes of fading, i.e. when the signal encounters certain physical obstacles during transmission along its paths. Various interferences also affect the quality of the transmitted signal, which is being distorted due to interference from them.

Channel coding is a strategy being employed by the communication system in order to counteract the effects of the environment through which the message is being distorted. This strategy entails adding redundant bits to the message being transmitted so that the transmission errors can be recognized by the receiver, and then possibly corrected. Such error-control codes are being used in all kinds of radio communications where high reliability is needed, such as mobile networks, satellite communications, industrial networks and so on.

Among existing approaches to protecting radio communication from errors, two are most commonly used: forward error control (FEC) and automatic repeat request (ARQ) methods [4].

Forward error control means that added redundant bits are used at the receiving side to try and determine if the message is incorrect, and to attempt the reconstruction of correct message. In other words, it is up to the receiver to do all the work if an error appears.

As for the automatic repeat request, transmitter still adds redundant bits, and receiver tries to determine if there was an error. Only in this case, receiver will ask the transmitter to repeat the transmission, in hope that this time the message will be correct.

This, of course, does not specify the way in which redundant bits are added, and how they are used. This is another facet of channel coding. There were many methods of creating redundancy in radio messages. Some were quite simple, like repetition codes, or Hamming codes.

In repetition codes, for example, every data bit is sent more than once. Sending it twice would let us know that there was an error, but there is not enough information as to what the correct value is. So let us say that it is sent three times, also known as a repetition code of block-length three. Repeating of data bits creates a sort of a “voting” system at the receiver end. The exact value of a data bit is determined by the majority of bits in each group of three. Here we can note that it is also an example of FEC. So, here an error on the receiver end will appear only when the majority of bits in a group of three is wrong. As three bits are sent for every bit of the message, only one third as many coded signals can be sent for the available bandwidth, compared to the uncoded signal. We say that the rate of transmission is one third [5].

Another example of a coding system, which has a better rate of transmission, is Hamming code [6]. This code is used to encode four-bit messages. For example, let us say that the message consists of bits *d1, d2, d3*, and *d4*. Hamming code adds three more bits to this message. First bit, *p1*, is so calculated that the sum of bits in *d1, d2* and *d4*, together with *p1* is an even number. This is a standard parity bit check calculation. Second parity bit, *p2*, when summed up with *d2, d3* and *d4* will also give an even number. Third parity bit, *p3*, will do the same for the sum of *d1, d3* and *d4*. So the coded message, at the end will be *d1d2d3d4p1p2p3*. This code can detect, and correct single bit errors. If there is a failed parity check, we know that there was an error in transmission. Location of the error can be determined by process of elimination, through two subsequent parity checks. Double errors will cause a failed transmission. There is way of detecting them by adding one more parity bit, an overall parity bit for the message. A graphic presentation of Hamming coding process is shown in the following figure:

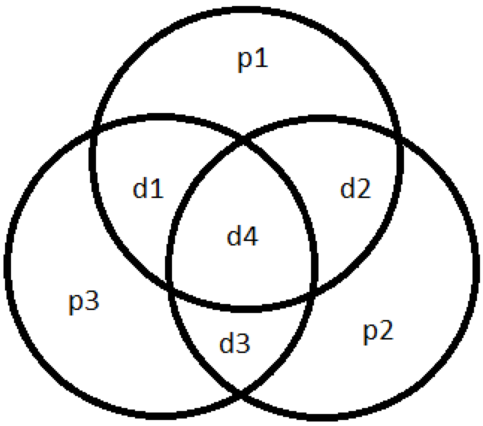

Figure 1. Hamming coding process

III. 4G CHANNEL CODING SCHEMES

The LTE standard lists Turbo coding as the basis for channel coding. Although turbo coding has been used in earlier standards in the 4G network it is considered an indispensable component along with convolutional coding schemes.

A. Turbo codes

Turbo codes were developed in 1990. but were not published until 1993. [7]. They are based on Convolutional codes. In the LTE network they are used for data channels. Turbo codes have found their application in several types of communication systems such as deep space communications, 3G/4G mobile communication in Universal Mobile Telecommunications System (UMTS) and Long Term Evolution standards and Digital Video Broadcasting (DVB) [8].

The Turbo code encoder consists of two convolutional encoders that are separated by an interleaver as it is shown in Fig 2.

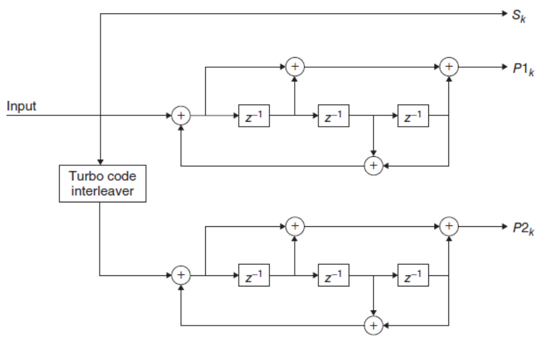

Figure 2. Turbo encoder [9]

There are three streams at the encoder output: Systematic bits, Parity 1 and Parity 2 bit streams. Parity bits 1 and 2 represent the outputs of two parallel encoders. Base code rate for Turbo encoder is 1/3. Since each of the encoders terminates with tail bits each of the streams are size of K + 4, if K is the number of bits of input block. Due to this fact, the code rate of the turbo encoder is slightly less than 1/3. In addition to the two encoders that exist, there is also an interleaver based on Quadratic Polynomial Permutation (QPP) scheme.

The decoder performs a reverse operation relative to the encoder. The Turbo decoder consists of two A Posteriori Probability (APP) decoders and two interleavers. The first output of the encoder – Systematic stream and Parity 1 stream are fed to first decoder, while Parity 2 and interleaved version of Systematic stream are fed to the second decoder [10]. Output from the first decoder is interleaved and sent to the second decoder. Second decoder applies deinterleaving and creates output for first decoder. This process is called iteration. Depending on the number of iterations performed, the coding efficiency depends, since the decoders use an iterative decoding model as it is described. Usually 8 iterations are performed.

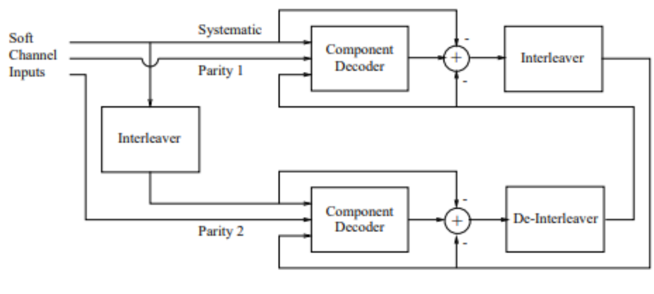

Figure 3. Turbo decoder [11]

B. *Convolutional codes*

Convolutional codes were presented by Elias in 1955. [12]. They are used for 2G and 3G network and in 4G network they are used for control channels. These codes belong to the group of linear error-correction codes.

The convolution code encoder consists of memory elements and XOR operations. The input stream (d_k) of a certain number of bits is passed through memory registers where each register contains only one bit and then fed to the XOR gate (Fig. 4).

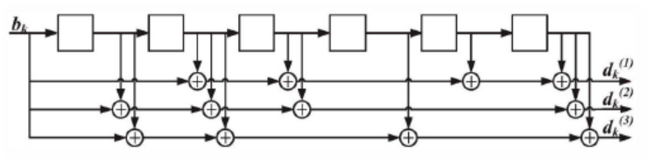

Figure 4. Convolutional encoder [10]

Three numbers determine convolutional codes: the number of input bits, the number of memory registers, and the number of output bits. For rate of 1/3, 1 is the number of input bit(s) and 3 is the number of output bit(s).

There are three decoding algorithms: Viterbi decoder, sequential decoder, and feedback decoder [13]. Two of them, the Viterbi and sequential decoders have almost the same probability of error. However, each of these decoders has its weaknesses. The sequential decoder handicap is that the number of state metrics searched is a random variable [13]. The weakness of feedback decoder is that as the look-ahead length increases, the complexity of the decoder also increases. The shortage of the Viterbi algorithm is that the probability of error increasing with increasing input length. Since the sequential decoder is independent from input length and Viterbi algorithm decoder complexity increases with input length it is suitable to use sequential decoder for long input lengths. Viterbi algorithm decoder on the other side is suitable for short input lengths.

IV. 5G CHANNEL CODING SCHEMES

As stated in the introduction of this paper, two methods of signal coding will be considered for 5G network: LDPC and Polar codes. When the researchers analyzed their characteristics in practical implementations, it has been found that the LDPC codes are suitable for user data, while the Polar codes are more useful for the transmission of control information. This is mainly due to the lengths of codewords being transmitted in user and control planes.

C. *LDPC codes*

LDPC codes were proposed in Robert Gallagher's doctoral dissertation in 1962 [14], but they were not practically used until 1997 when Mackay showed their good performance. In 5G LDPC codes belongs to quasi-cyclic (QS) LDPC codes [3]. The main advantage of QS-LDPC codes is reflected in the possibility of parallel encoding and decoding, which further contributes to the high-throughput of LDPC encoders and decoders.

As their name says, LDPC codes are described with sparse parity check matrix *H* that defines a set of linear equations. Each valid codeword must satisfy the mentioned equations.

Sparse parity check matrix *H*:

$$H = n \times m\,, \quad (1)$$

consists of low-density, nonzero elements where *n* is the number of rows and *m* is the number of columns. The small number of ones in the matrix greatly simplifies the encoding and decoding algorithms. Also, the parity check matrix can be represented as a Tanner graph like the one on the picture below, where all rows correspond to the check nodes and columns correspond to variable nodes.

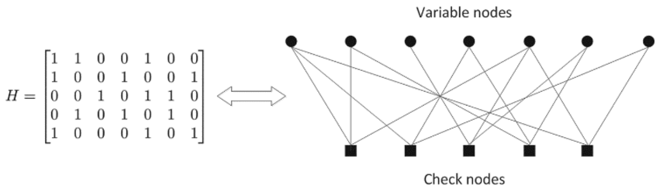

Figure 5. Tanner graph [3]

Parity check matrix *H* is described with three main terms: base graph, lifting size, and cyclic shifts [1]. There are two base graphs [3]: Base graph 1, whose size is 46 x 68, and Base graph 2, with a size of 42 x 52. Which base graph will be applied depends on the code rate and the number of bits of the originating message. For each base graph, there are eight sets of matrices and eight sets of cyclic shifts, per each set of lifting sizes [3].

When it comes to encoding, there are two methods: preprocessing method, which creates generator matrix *G* that corresponds to parity check matrix *H*, and another one, which uses parity check matrix directly [13]. The second mentioned coding method is simpler which makes it more efficient to use in practice.

As with encoding, there are two methods used for decoding [13]. For hard decisions, a bit-flapping algorithm is used. On the other hand, for soft decisions, there is Sum-Product Algorithm (SPA). SPA algorithm works on the principle of forwarding messages between check nodes and variable nodes until the decoding process is completed. This method of working makes this algorithm iterative.

D. Polar codes

In 2009 [15] Arikan Erdal at Bilkent University in Ankara presented Polar codes which are capacity-achieving codes. This means that a full capacity of a channel can be achieved by the use of these codes. Because of this feature, they soon found application in practice. The basic idea is to divide the channels of capacity I(W) into N channels with capacity 0 or 1 so I(W) number of channels will be channels with no noise and the rest, 1-I(W) will become completely noisy [1]. This happens thanks to the phenomenon of polarization. Then, these perfect channels are used for data transmission and the rest are frozen to one or zero.

Generator matrix is given as [16]:

$$G_N = B_N F^{\otimes^n}, \quad (2)$$

Where n = log(N), B_N is a bit-reversal matrix and $F^{\otimes^n}$ is Kronecker product and F is given as [16]:

$$F = \begin{bmatrix} 1 & 0 \\ 1 & 1 \end{bmatrix} \quad (3)$$

Since Polar codes are relatively new, however, there are several methods, which can be used to decode them. Arikan first presented Successive Cancellation (SC) decoding algorithm, but there are also the Successive Cancellation List (SCL) decoding, Cyclic Redundancy Check - Aided Successive Cancellation List (CRC-SCL) decoding, and Adaptive Successive Cancellation List (Adaptive-SCL) decoding [16].

SC decoder has been chosen due to the lowest decoding complexity. The only disadvantage of this decoding method is the delay since the message is being decoded bit by bit. Several solutions are being used in practice to overcome this problem. However, the one, which is most often applied, is to group the bits being processed to speed up decoding.

V. CONCLUSION

Channel coding is a very important component of the communication system that is responsible for correcting errors caused by noise, interference, as well as poor signal quality. Since one type of coding cannot be applied to all applications, it was decided to use two types of coding schemes in the 4G network – Turbo and Convolutional codes as well as in the 5G network – LDPC and Polar codes. 5G network sets high goals on channel coding, as more data needs to be transmitted, faster and with higher throughput than fourth generations of mobile networks.

The paper gives an overview of coding techniques used in 4G and 5G mobile networks with an emphasis on encoding and decoding methods used in each of the coding techniques.

Turbo codes were not chosen for application in the 5G network because they require a large number of iterations and the decoding process has a large delay. The downside of Turbo codes is also the highest power consumption per bit compared to other codes and a very low efficiency area. As well as Turbo codes that are in the LTE network appropriate encoding methods Convolution codes are also not selected for use in the 5G network.

There are numerous papers proving that the Polar and LDPC codes are more efficient compared to the Turbo and Convolution codes for the 5G network. However, when comparing the LDPC and the Polar codes, there are also some differences between them.

Since there is no one coding scheme that outperforms all others and satisfies all applications in the 5G network, two types of coding are represented. For longer message lengths, LDPC encoding replaced Turbo codes for data channels and Polar encoding replaced Convolutional codes for control channels. Taking into account all aspects, implementation complexity, latency, and flexibility, the main reasons that LDPC and Polar codes were chosen for use in the 5G are good Bit Error Rate (BER) performance as well as relatively simple encoding and decoding procedures.

Future work will refer to the performance analysis of LDPC and Polar codes used in the 5G network under the influence of noise only and the influence of both noise and fading.

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