

Application of Turbo Codes in Unmanned Aerial Systems

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Abstract — *In the modern world, unmanned aerial systems play an extremely important role in the economy, research, environmental protection, and military operations. Unmanned aerial vehicles, as elements of these systems, operate and perform their tasks by transmitting data and commands over communication radio channels that often face harsh conditions and limitations on frequency-time and energy resources. At the same time, the demand for higher quality and accuracy of the information obtained and the commands issued are constantly increasing. The purpose of this research work is to examine and evaluate the potential of using turbo codes for error correction, especially packet codes, in the communication radio channels of unmanned aerial systems. Different types of turbo encoder designs are reviewed, along with their advantages and disadvantages, to assess their applicability for these channels. The importance of interleaving is discussed, and a structure and algorithm for the operation of an interleaver is proposed as an essential element of the turbo encoder design. Finally, conclusions and recommendations are made for directions for further research and the application of turbo codes in unmanned aerial systems.*

Keywords— *communication channel, interleaver, turbo encoder design, unmanned aerial system.*

I. INTRODUCTION

Unmanned aerial systems (*UAS*) are currently employed across a wide range of applications, including aerial photography and mapping, target engagement, search and rescue operations, delivery services, environmental and infrastructure monitoring, surveillance and policing, and much more.

Communication technologies used as a means of control and data transfer between main *UAS* elements – unmanned aerial vehicles (*UAVs*), also commonly known as drones and the command center (*CC*) – play an essential role in the effective and safe operation of these systems.

The most commonly used types of communication technologies between elements of *UAS* are autonomous

radio channels; Wi-Fi (IEEE 802.11 family) networks; mobile cellular networks (3G, 4G, 5G) and satellite communication networks. These communication technologies, serving as a medium between *UAS* elements, possess distinct advantages and disadvantages. They determine the main technical parameters of the electronic equipment of *UASs* such as the frequency range, the transmitter power and the data transfer rate. In the majority of cases, the purposes, encoding methods and techniques of the control and command signals and data are strongly affected by this medium, as well.

In the *UASs*, especially those using satellite communication networks, control commands and data are transmitted over radio channels that are susceptible to noise and interference, which can lead to errors in the transmitted information.

Thus, error correction coding in communication channels is required to increase the reliability of transmission of control commands and data transfer. An encryption to protect information and control over the *UASs* from unauthorized access is necessary, as well.

Technological complexity, along with challenges in ensuring reliable and sustainable operation, is observed in *UAVs* using satellite communication networks, as illustrated in Fig. 1.

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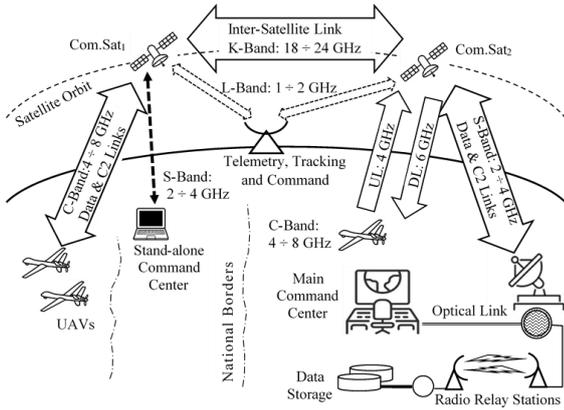


Fig. 1. UAS deployed via satellite communication network.

II. MATERIALS AND METHODS

A combination of quantitative and qualitative analysis methods, stochastic methods from Probability Theory, mathematical modelling and computer simulation were used to explore the conditions in the radio channels of *UAS* and assess the applicability of various turbo codes for error correction in these channels.

Satellite communications provide global coverage and are suitable for missions where UAVs operate in remote or hard-to-reach areas – forests, deserts or mountains.

Satellite communications are less susceptible to industrial interference compared to other communication methods, because of frequency range used (1 ÷ 40 GHz). However, in these cases, the signal-to-noise ratio (*SNR*) suffers greatly due to the large and varied attenuations in the communication channels. The frequency dependence of molecular absorption, along with absorption peaks caused by oxygen and water vapor in the Earth's atmosphere necessitates allocating higher frequency transmission range to the equipment with more energy resources and the frequency range around 22.5 GHz for inter-satellite links.

One of the most characteristic features of lines involving a communication satellite (*CS*) is their great physical length. For low Earth orbit (*LEO*) constellations of communication satellites, it ranges from 400 to about 2,000 km, but for highly elliptical orbits (*HEO*), it can reach up to 42,000 km. This is also the order of the line length when the communications are carried out via a communication satellite located in geostationary orbit (*GEO*), when visible at low elevation angles. The propagation attenuation reflects this significant physical length without taking into account additional factors affecting attenuation. These include such as molecular absorption, absorption by hydrometeors, refraction and inaccurate pointing of antennas, mismatch between the polarizations of the receiving and transmitting antennas, etc. This attenuation can be estimated by (1):

$$L_0 = 21.984 + 20(\lg D - \lg \lambda), dB \quad (1)$$

where D is the distance between the transmitter and receiver in the communication line, and λ is the wavelength.

The molecular absorption (2) in the atmosphere is:

$$L_a = \frac{[L_{O_2}(h_{O_2} - h_s) + L_{H_2O}(h_{H_2O} - h_s)]}{\sin \theta}, dB \quad (2)$$

where L_{O_2} and L_{H_2O} are the specific absorption coefficients from oxygen and water dissolved in the air, respectively in dB/m; h_{O_2} and h_{H_2O} are equivalent atmospheric heights for oxygen and water dissolved in the air, respectively in m; h_s is the altitude of the ground station or *UAV*, communicating with satellite, and θ is the elevation angle of the communication satellite above the horizon.

Other factors leading to signal attenuation in the long satellite communication links include absorption by hydrometeors, dust and smoke in the lower layers of the atmosphere, as well as obstruction by tall vegetation, and others. The accurate assessment of these additional losses (L_a) is a complex problem of a stochastic nature, in the solution of which the climate model of Crane [1] is often used.

The total signal power losses L_x are defined as (3):

$$L_x = L_0 + L_a + L_d, dB \quad (3)$$

The total attenuation in a satellite communication line is significant and difficult to predict accurately, so some redundancy in terms of signal power is required. In addition, it should be taken into account that highly directional antennas are not used on board *UAVs* to ensure their maneuverability. This results in an even worse *SNR* compared to the lines between a communications satellite and a fixed earth station. At the same time, it is pointless to take into account the losses from tropospheric and ionospheric refraction of radio waves, which are different in cause but the same in result as the losses coming from inaccurate pointing of antennas towards each other in the radio channels between receiver and transmitter if at least one of whose antennas is non-directional.

Other characteristic features of satellite communication channels are significant values and fluctuations in the Doppler shift F_D and signal spectrum broadening, especially at *CS* on *LEO*. There are detailed studies of the distance D between the *CC* or *UAV* and the *CS*, as a function of the altitude H_s and the inclination i of the orbit of the *CS*, the latitude B of the *UAV*, and the time t , i.e. $D(H_s, i, B, t)$ and as a consequence of its change – the Doppler shift of the signals $F_D(H_s, i, B, t)$. The large Doppler shift of the frequency spectrum of the signals means that the receiver bandwidth must be expanded to capture them. Expanding the frequency band of the receiver beyond the width of the frequency spectrum of the signals means a deterioration of the *SNR*. Therefore, the lower attenuation of signals in *LEO*-based systems compared to those using *GEO* is to some extent compromised by the high noise level after the receiver input and the associated low *SNR*.

The Doppler shift in the system is given by the radial velocity $V_R(t)$ between the transmitter and the receiver through the expression:

$$F_D = -F_0 V_R(t) [V_R(t) + c]^{-1}, \text{ Hz} \quad (4)$$

where $c = 2,998 \cdot 10^8 \text{ m/s}$ is speed of light.

The change in the distance $D(H, i, B, t)$ between CC or UAV and CS determines the radial velocity V_R between them :

$$V_R(H, i, B, t) = \frac{\partial D(H, i, B, t)}{\partial t}, \text{ m/s} \quad (5)$$

and the solution of the task of determining the Doppler shift F_D is reduced to deriving an expression for the instantaneous distance between CC or UAV and CS .

Although the variation is complex and the amplitudes are large, the Doppler shift is accurately predictable, e.g. Doppler Shift in Globalstar satellite communication system – Table 1 [2], especially if the latitude of the CC or UAV , the 22 km difference between the equatorial and polar radii of the Earth, and the ephemeris data of communication satellites are taken into account. Thus, it becomes easily achievable to compensate for the Doppler shift of the signals and the damage to the reliability of the data, if the UAV is equipped with a receiver for one of the global positioning systems and a change in the heterodyne frequency is applied in the superheterodyne receiver circuit to neutralize this shift and stabilize the intermediate frequency.

TABLE 1. DOPPLER SHIFT IN GLOBALSTAR SATCOM SYSTEM.

$H_s=1414 \text{ km}$ (LEO), $i=52^\circ$; $f_0=2,5 \text{ GHz}$ (Down Link XIII ch.)			
Maximum elevation, θ_{\max}	Time of visibility, s	Relative Doppler shift	Absolute Doppler shift, kHz
1. Latitude of the CC or UAV $B=42^\circ \text{ N}$			
30°	± 433	$\pm 1,51 \cdot 10^{-5}$	$\pm 37,75$
60°	± 511	$\pm 1,79 \cdot 10^{-5}$	$\pm 44,75$
90°	± 526	$\pm 1,83 \cdot 10^{-5}$	$\pm 45,75$
2. Latitude of the CC or UAV $B=0^\circ$ (equatorial position)			
30°	$-438 \div 440$	$-1,48 \div 1,50 \cdot 10^{-5}$	$-37,0 \div 37,5$
60°	$-512 \div 514$	$-1,78 \div 1,79 \cdot 10^{-5}$	$-44,5 \div 44,75$
90°	± 525	$\pm 1,83 \cdot 10^{-5}$	$\pm 45,75$

In addition to the large and highly variable attenuations and Doppler shifts, the control and data transfer between CC and $UAVs$ in $UASs$ using communication satellites is characterized by significant latency due to the large distances that signals must overcome in such systems. This means that control commands to the $UAVs$ and data from them arrive at their destinations with a noticeable time delay. $UAVs$ are extremely fast and highly maneuverable flying vehicles due to the absence of a human factor on board. If, during the performance of a complex task, a UAV needs to change abruptly its flight mode, and the command for this is not recognized correctly, then approaches requiring

retransmission of commands or automatic repeat query (ARQ) are not very suitable because of this latency.

The aforementioned characteristics of satellite communication networks and their role as a medium in UAS are a prerequisite for special attention to the reliability and error protection of the transmitted information (data and commands) in these systems. To increase the reliability of transmitted control commands and data transfer in unmanned aerial systems, the implementation of channel coding with error correction codes is absolutely required [3]. The choice of **Forward Error Correction (FEC)** code depends on both the specific requirements of the communication system and the characteristics of the communication channel [4], [5].

III. RESULTS AND DISCUSSION

A. Error Correction Codes in UAS – General Overview

Several types of error correction codes are suitable for use in communications in $UASs$, including the following:

- Low Density Parity Check (**LDPC**) codes that are a special case of block linear codes with parity check. What is special about them is that the check matrices contain a small number of significant elements (sparse matrices), which achieves relative simplicity of the encoding process on the one hand, and provides a relatively high net data rate on the other, while maintaining their high error correction capabilities.

- Reed-Solomon codes are non-binary cyclic codes and represent a special case of Bose–Chaudhuri–Hocquenghem (**BCH**) codes, widely used in digital communications. The elements of the code vector are not individual binary symbols, but entire groups of them, the most common being those that work with bytes (octets). Reed-Solomon codes are optimal in terms of packet length and possible errors to correct – when using $2n$ check symbols, no less than n errors can be corrected. Reed-Solomon codes are particularly well-suited for communication channels prone to packet errors, making them highly effective for communication systems implemented in UAS , where such type of errors frequently occur.

- Convolutional codes are a type of non-separable, continuous (recurrent) codes, which, in combination with a subsequent interleaving process, are one of the most effective and commonly used measures of combatting packet errors resulting from fading. Even better results in channels with strong interference are obtained if a convolutional code with a subsequent interleaving procedure is used as the inner error protection coding, and a Reed-Solomon code as the outer one. Of course, in this case too, the increased reliability of data transfer comes at the expense of the net data rate.

- Turbo codes are a relatively young class of **FEC** codes and are the first practically usable codes that bring the actual channel capacity extremely close to the maximum channel capacity (Shannon limit). Due to their

undoubtedly valuable characteristics, turbo codes have established themselves as usable in 3G (UMTS) and 4G (LTE, IEEE 802.16 – WiMAX) mobile cellular communications, as well as in satellite communications and communications with objects in deep space.

Turbo code types and their capabilities, as well as their application in *UASs* are the subject of further consideration in this work.

B. Turbo Codes – Advantages and Drawbacks.

Turbo codes, while a class of *FEC* codes, differ significantly from traditional *FEC* codes (e.g. Reed-Solomon, convolutional codes) in the way they achieve error correction. The key advantages of turbo codes compared to traditional *FEC* codes are, as follows [6], [7]:

- Superior error correction performance – turbo codes are very useful with their ability to approach the theoretical Shannon limit, and this near-Shannon-limit performance provides highly efficient error correction even at low *SNR*.

- Enhanced decoding accuracy – turbo codes use an iterative decoding process based on soft-decision inputs, which provides higher error correction accuracy. Traditional *FEC* codes (e.g. Reed-Solomon) often rely on hard-decision decoding, which can be less effective in correcting errors.

- Robustness in noisy environments – turbo codes perform exceptionally well in environments with high noise, interference, or fading, while traditional *FEC* codes tend to degrade faster in such environments. This feature makes turbo codes ideal for *UAV* operations in challenging conditions.

- Efficiency at low *SNR* – turbo codes are optimized for environments with low *SNR*, enabling reliable communication with reduced power or over long distances (e.g. satellite communication line). Traditional *FEC* codes typically require higher power or higher *SNR* for similar error correction performance.

- Adaptability for different applications – scalable code rates are applicable in turbo coding processes, i.e. they can be configured for different rates and block lengths. This adaptability makes turbo codes highly versatile for different data types, including telemetry, command, and video transmission. Although some of the traditional *FEC* codes can be adaptive, they often lack the full flexibility or efficiency of turbo codes in *UAS* applications.

- Reduced bandwidth requirements – turbo codes allow communication systems to achieve reliable data transmission at lower *SNR*, which can be translated to reduced bandwidth usage. Traditional *FEC* codes often require more bandwidth to achieve comparable reliability.

- Handling burst errors – turbo codes are highly effective at correcting burst errors, which are common in *UAS* communications due to interference, multipath fading, or obstacles. Some traditional *FEC* codes fail with

burst errors but are better suited for correction of randomly distributed single errors.

- Energy efficiency – by reducing retransmissions through effective error correction, turbo codes can save energy. These power savings are an important factor for *UAVs*, which have limited on-board power. Traditional *FEC* codes may require higher transmission power or multiple retransmissions, consuming more energy.

Turbo codes have some drawbacks compared to traditional *FEC* codes:

- Computational complexity – the iterative decoding requires more processing power, which is bad for systems with limited computational resources.

- Memory requirements – turbo decoders require more memory to store intermediate decoding states.

- The intensive decoding process consumes more energy, which can be critical in *UAVs* where power is a precious resource. Increased power usage for decoding reduces the available energy for other systems, like motors, sensors, and communication hardware and impose a battery life impact.

- Latency for iterative decoding – in some applications turbo codes exhibit higher latency compared to traditional *FEC* codes with simpler decoding processes. Critical applications and processes in *UAS* requiring minimal latency are *C2* links, collision avoidance, live video streaming, etc. Moreover, the number of iterations depends on the error level, leading to variable and unpredictable latency.

- Sensitivity to interleaver design – turbo codes rely heavily on interleaving to fight burst errors. Poor interleaver design can lead to suboptimal performance, making the system more sensitive to specific error patterns. Applying a more complex interleaver design in order to optimize it for specific use cases adds complexity to the system design.

- Lack of universal suitability – turbo codes are not optimal for short blocks. Their performance advantage is most apparent with long block sizes. *UAS* transmitting short control messages may benefit more from simpler *FEC* codes. In some cases, e.g. extremely high data rates or low latency requirements other codes like *LDPC* outperform turbo codes.

C. Turbo Codes – Main Types and Features.

The main idea that led to the achievement of the unique characteristics of turbo codes is in the joint work of at least two encoders on different variants of the same block of data. The classic scheme of a turbo encoder implementing this idea is shown in Fig. 2 [8].

Based on this classic turbo encoder design, several basic types have been developed and used. They differ in the type of specific encoders embedded in the basic circuit, additional devices such as interleaving blocks and memory blocks, as well as the way in which these essential elements are connected in the overall turbo encoder circuit.

Although convolutional encoders are most often used as embedded encoders in designs, and their connection structure is mostly parallel, there are also more specific solutions created in search of characteristics suitable for different conditions. These particularities in the design naturally lead to different properties of the resulting turbo codes, such as capabilities for combating different types of errors, applicability to different types of data and different conditions in the communication channel, latency, capabilities for adapting to different speeds and volumes of the processed data blocks, computational complexity, power consumption, etc.

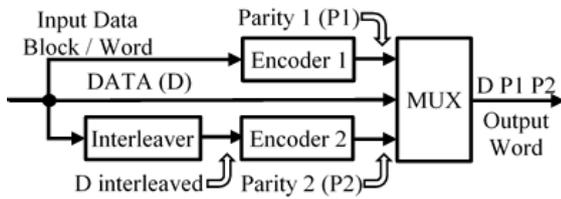


Fig. 2. Classic design of turbo encoder

The design of the decoders in the receiving devices is intrinsically linked to that of the encoders in transmitting devices, with variations in decision-making methods for received code words. For instance, the Viterbi decoding algorithm can be employed using either a hard decision (based on Hamming distance) or a soft decision (based on Euclidean distance).

A soft-in soft-out (SISO) design is a typical one for turbo decoding and for serial concatenated decoders, in common. The SISO decoder is based on the assumption of an independent input sequence and a memoryless channel.

The types of turbo codes, their most characteristic properties, and their possible applicability in UASs are described below:

- Parallel-concatenated convolutional (PCC) encoder – The most widely used turbo encoder design consists of two or more recursive systematic convolutional (RSC) encoders connected in parallel, with their inputs interleaved. RSC encoders differ from non-recursive ones due to the presence of feedback in their shift-register design, making them infinite impulse response filters [9]. An example of RSC encoder with constraint length K of 4, and feedback from outputs of second and third stage of the shift-register (D-Triggers), realized by Boolean XOR function units is shown in Fig. 3.

A structure of PCC turbo encoder, consisting of three RSC encoders and two interleavers is shown as an example in Fig. 4.

A block of N data bits is applied to the input of the PCC turbo encoder above. The data block goes to the first RSC encoder directly, but to the inputs of the other two encoders through two interleavers. The interleavers have the same size of N bits, but different maps of interleaving, so in the inputs of the three encoders are entering three

different permuted variants of the data block – ND , $NDI1$ and $NDI2$.

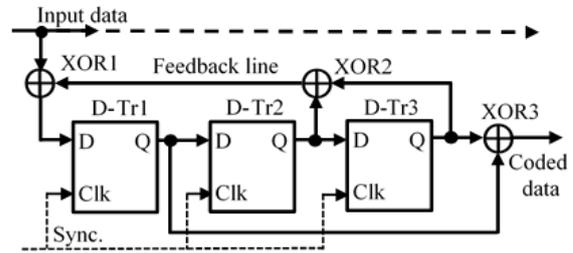


Fig. 3. An example of RSC encoder.

Because all of the embedded encoders are systematic ones, they generate at their outputs N parity bits – $NP1$, $NP2$ and $NP3$. Multiplexing them and adding the raw input data block to the output digital stream, at the output of this turbo encoder exists a coded data block with volume of $4N$ bits, i.e. the rate of the encoder above is $R=1/4$. They can be utilized in a serial or parallel manner for different modulation schemes. This type of turbo encoding has high coding gain and is appropriate to UASs where reliability and low latency are strongly required, e.g. satellite communication lines of UASs.

- Serial concatenated convolutional (SCC) encoder – it uses convolutional encoders in a serial configuration, so the data stream at the output of one of the decoders is input data stream to the next one. This type of codes are very suitable for iterative decoding, which is the essential point when transferring data using turbo codes. The typical SCC encoder includes outer convolutional coder, which processes input from a data source, an inner convolutional encoder that transmits its output data stream to a noisy channel, and an interleaver that connects the two encoders, as illustrated in Fig. 5.

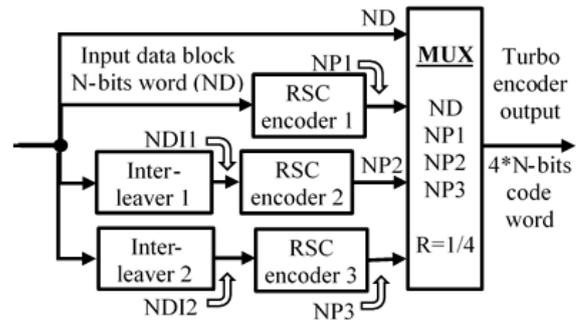


Fig. 4. An example of turbo encoder with PCC design.

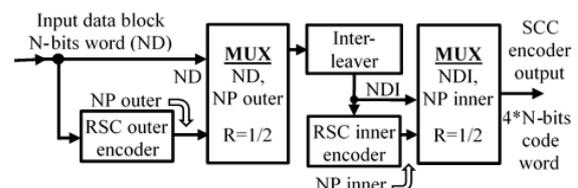


Fig. 5. An example of turbo encoder with SCC design.

A very important feature of **SCC** encoders is the inclusion of an **RSC** encoder as an inner encoder, which ensures their superior coding gain. Codes of this type have better characteristics compared to **PCC** codes around so-called **error floor** – the area of the diagram of the bit error probability (**BER**) as a function of the **SNR**, after which the trend of decreasing **BER** with increasing **SNR** decreases significantly. In such cases, the use of other types of **FEC** codes (e.g. Reed-Solomon or **LDPC**) is more appropriate than the use of turbo codes, precisely because of the **error floor** phenomenon.

- Hybrid concatenated convolutional (**HCC**) encoder, which combines both serial and parallel connections between its built-in **RSC** encoders, and the relevant interleavers in the structure, is shown in Fig. 6.

The combination of the two main types of connection between the built-in **RSC** encoders allows the turbo encoder with the **HCC** design to achieve the very good performance (high coding gain) of **PCC** encoders at low **SNR** and, as inherited from the **SCC**, a low error floor at high **SNR**. In addition, the complex **HCC** design creates wider possibilities for adapting the encoder to different coding rates, by puncturing (taking away part of the check bits according to a certain pattern) at several points in the connection scheme. The superior performance of turbo codes with **HCC** design over a wide range of **SNR**, as well as the ability to adapt to work with different data types makes them extremely suitable for use in **UAS**. This is because during the execution of a mission, the distance between the **CC** and the **UAV**, and thus the **SNR**, varies widely. These changes are even more drastic if a satellite communication system, whose satellites are located on **LEO**, is used as the medium between the **UAS** elements. In addition, limitations in energy resources and the mass of the payload on board a **UAV** require that the same elements be used in the widest possible range of purposes and conditions.

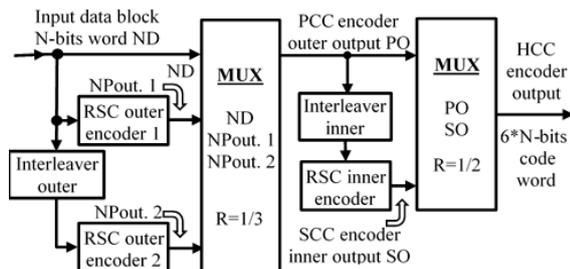


Fig. 6. An example of turbo encoder with HCC design.

Turbo codes with **HCC** design, with their ability to adapt to different data types, coding rates and data rates, as well as to work well under different conditions in communication channels, meet these requirements to a high degree.

- There are several other types of turbo codes that will be mentioned briefly only for the sake of completeness. This is because they either are tailored to specific types of communication systems or are used in conditions very different from those in **UAS** communication channels and equipment.

Block turbo codes – in the design of these encoders, unlike the aforementioned types of turbo encoders, the typical embedded **RSC** encoders are replaced by block ones (e.g. LDPC, Reed-Solomon or other BCH). Due to the simplified decoding compared to that of convolutional codes, as well as the robust error correction for large blocks of data, these turbo codes are used in data storage devices or high-speed optical communications.

Turbo product codes: two or more different block codes are applied in the encoding process on multidimensional data structure – each code in different dimension of the data structure. This code design is so-called “product of codes”. Turbo product codes have very good performance on data blocks with long lengths and with soft-decision decoding. This is why they are implemented widely in deep space communications and optical communications.

UMTS/LTE turbo codes – Optimized and standardized code design for 3G/4G mobile communications needs. They consist of two 8-state **RSC** encoders and a quadratic permutation polynomial interleaver for optimal interleaving. The optimization of the encoding process for such communication systems allows for high data throughput and very low latency in them. The implementation of these turbo codes in **UAS** is the default when 3G/4G cellular communication systems are used as the medium between the **UAS** main elements – **UAVs** and **CC**.

D. Interleaver – design and features.

The interleaver performs the important task of spacing the pulses that share the information from one input pulse for the convolutional encoder at a sufficient distance (as a time interval) from each other. This ensures effective control of burst errors, which are a common occurrence in channels with pronounced fading from multipath propagation, from shadowing by local objects and landscape features, mobility of the environment, from working with **UAVs** beyond the line of sight – all conditions typical of communication channels in **UAS**. The design of the interleaver determines the memory required to perform the interleaving, largely the performance, latency, and power consumption of the turbo encoder as a whole.

A possible variant of performance and design of an interleaver working together with a convolutional encoder with code rate $R=1/3$ are proposed below.

The encoder is adapted to a set of standard data rates and a frame (data block) duration of 20 ms – in the given example the data rate is 28.8 kbps. A similar design was used in the Globalstar satellite communications system [10], operating on a modified version of the Interim Standard 95 (IS-95) CDMA-based radio interface.

The digital data stream obtained after the **RSC** encoder output is divided into frames with a standard duration of 20 ms and with a volume of 576 bits, i.e. 192 triplets of bits, which are input and processed in the interleaving block.

The pulses from the frame are recorded sequentially in a memory with a capacity of 576 bits, represented as a square matrix with dimensions of 24x24, as it is shown in Fig. 7. Time duration of the frame is 20 ms, and is formed by time duration of 24 rows ($24 \cdot 833.33 \mu\text{s} = 20000 \mu\text{s}$).

104.17 μs			833.33 μs												34.72 μs															
X_1^1	X_1^2	X_1^3	X_2^1	X_2^2	X_2^3	...	X_7^1	X_7^2	X_7^3	X_8^1	X_8^2	X_8^3	X_9^1	X_9^2	X_9^3	X_{10}^1	X_{10}^2	X_{10}^3	X_{15}^1	X_{15}^2	X_{15}^3	X_{16}^1	X_{16}^2	X_{16}^3						
X_{49}^1	X_{49}^2	X_{49}^3	X_{50}^1	X_{50}^2	X_{50}^3	...	X_{55}^1	X_{55}^2	X_{55}^3	X_{56}^1	X_{56}^2	X_{56}^3	X_{57}^1	X_{57}^2	X_{57}^3	X_{58}^1	X_{58}^2	X_{58}^3	Y_1^1	Y_1^2	Y_1^3	Y_2^1	Y_2^2	Y_2^3	Y_7^1	Y_7^2	Y_7^3	Y_8^1	Y_8^2	Y_8^3
Y_9^1	Y_9^2	Y_9^3	Y_{10}^1	Y_{10}^2	Y_{10}^3	...	Y_{15}^1	Y_{15}^2	Y_{15}^3	Y_{16}^1	Y_{16}^2	Y_{16}^3	Y_{17}^1	Y_{17}^2	Y_{17}^3	Y_{18}^1	Y_{18}^2	Y_{18}^3	Y_{19}^1	Y_{19}^2	Y_{19}^3	Y_{20}^1	Y_{20}^2	Y_{20}^3	Y_{25}^1	Y_{25}^2	Y_{25}^3	Y_{26}^1	Y_{26}^2	Y_{26}^3
Z_1^1	Z_1^2	Z_1^3	Z_2^1	Z_2^2	Z_2^3	...	Z_7^1	Z_7^2	Z_7^3	Z_8^1	Z_8^2	Z_8^3	Z_9^1	Z_9^2	Z_9^3	Z_{10}^1	Z_{10}^2	Z_{10}^3	Z_{15}^1	Z_{15}^2	Z_{15}^3	Z_{16}^1	Z_{16}^2	Z_{16}^3	Z_{25}^1	Z_{25}^2	Z_{25}^3	Z_{26}^1	Z_{26}^2	Z_{26}^3
Z_{49}^1	Z_{49}^2	Z_{49}^3	Z_{50}^1	Z_{50}^2	Z_{50}^3	...	Z_{55}^1	Z_{55}^2	Z_{55}^3	Z_{56}^1	Z_{56}^2	Z_{56}^3	Z_{57}^1	Z_{57}^2	Z_{57}^3	Z_{58}^1	Z_{58}^2	Z_{58}^3	Z_{63}^1	Z_{63}^2	Z_{63}^3	Z_{64}^1	Z_{64}^2	Z_{64}^3	Z_{65}^1	Z_{65}^2	Z_{65}^3	Z_{66}^1	Z_{66}^2	Z_{66}^3

Fig. 7. Records of the RSC output in 576-bits interleaver memory.

The shifting of individual sub-blocks of recorded information occurs according to a certain scheme, in which the bits belonging to a certain triplet (with the same lower indices) are shifted into conditional groups *X*, *Y* and *Z*, the goal being to separate the bits belonging to a certain triplet of bits (these ones with superscripts 1, 2 and 3).

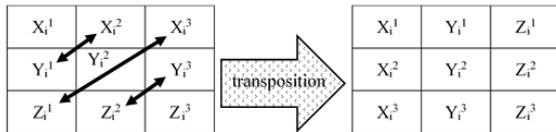


Fig. 8. Recorded bits transposition between groups X, Y and Z.

After the shifting, the bits from the sub-blocks and conditional groups are scattered across the memory matrix as shown in Fig. 9.

This algorithm ensures the dispersion of the triplets of bits involved in the transmission of the same information cyclically at 833.33 μs and 9582.72 μs , which is an average of 5280 μs , or in other words, neighboring bits and the information contained in them, initially vulnerable to packet errors, are separated by an average distance of 150 bits.

X_1^1	Y_1^1	Z_1^1	X_2^1	Y_2^1	Z_2^1	...	X_7^1	Y_7^1	Z_7^1	X_8^1	Y_8^1	Z_8^1
X_9^1	Y_9^1	Z_9^1	X_{10}^1	Y_{10}^1	Z_{10}^1	...	X_{15}^1	Y_{15}^1	Z_{15}^1	X_{16}^1	Y_{16}^1	Z_{16}^1
X_{57}^1	Y_{57}^1	Z_{57}^1	X_{58}^1	Y_{58}^1	Z_{58}^1	...	X_{63}^1	Y_{63}^1	Z_{63}^1	X_{64}^1	Y_{64}^1	Z_{64}^1
X_1^2	Y_1^2	Z_1^2	X_2^2	Y_2^2	Z_2^2	...	X_7^2	Y_7^2	Z_7^2	X_8^2	Y_8^2	Z_8^2
X_9^2	Y_9^2	Z_9^2	X_{10}^2	Y_{10}^2	Z_{10}^2	...	X_{15}^2	Y_{15}^2	Z_{15}^2	X_{16}^2	Y_{16}^2	Z_{16}^2
X_{49}^2	Y_{49}^2	Z_{49}^2	X_{50}^2	Y_{50}^2	Z_{50}^2	...	X_{55}^2	Y_{55}^2	Z_{55}^2	X_{56}^2	Y_{56}^2	Z_{56}^2
X_{57}^2	Y_{57}^2	Z_{57}^2	X_{58}^2	Y_{58}^2	Z_{58}^2	...	X_{63}^2	Y_{63}^2	Z_{63}^2	X_{64}^2	Y_{64}^2	Z_{64}^2
X_1^3	Y_1^3	Z_1^3	X_2^3	Y_2^3	Z_2^3	...	X_7^3	Y_7^3	Z_7^3	X_8^3	Y_8^3	Z_8^3
X_9^3	Y_9^3	Z_9^3	X_{10}^3	Y_{10}^3	Z_{10}^3	...	X_{15}^3	Y_{15}^3	Z_{15}^3	X_{16}^3	Y_{16}^3	Z_{16}^3
X_{49}^3	Y_{49}^3	Z_{49}^3	X_{50}^3	Y_{50}^3	Z_{50}^3	...	X_{55}^3	Y_{55}^3	Z_{55}^3	X_{56}^3	Y_{56}^3	Z_{56}^3
X_{57}^3	Y_{57}^3	Z_{57}^3	X_{58}^3	Y_{58}^3	Z_{58}^3	...	X_{63}^3	Y_{63}^3	Z_{63}^3	X_{64}^3	Y_{64}^3	Z_{64}^3

$A \equiv X; Y; Z$ ($A_1^1 + A_{32}^1$) $\Delta=24$ bits ($A_1^2 + A_{32}^2$) $\Delta=276$ bits ($A_1^3 + A_{32}^3$)
 Δ shifting ($A_{33}^1 + A_{64}^1$) $\Delta=276$ bits ($A_{33}^2 + A_{64}^2$) $\Delta=24$ bits ($A_{33}^3 + A_{64}^3$)

Fig. 9. Recorded bits transposition between groups X, Y and Z.

The interleaver memory is read in sub-frames, 16 in number, each with duration of 1250 μs and according to the scheme shown in Fig. 10.

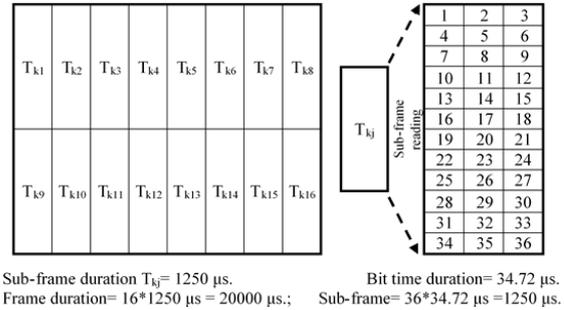


Fig. 10. Reading of the frame by sub-frames and individual bits.

Of course, the processes of writing, reordering and reading are presented as time-separated above, just to illustrate the algorithm and the result of interleaving. In practice, they happen this way and in this order only through a suitably set table for addressing the write and read cells from the memory block.

The time intervals are only representative of the specified standard data rate of 28.8 kbps and can be scaled to any other rate. Thus, the proposed interleaving block design is suitable for combating both medium and fast fading, with these classifications being aligned with the speed of the turbo encoder processes and the rate of the data being processed.

IV. CONCLUSIONS

The conditions in the communication radio channels for data transfer and control commands in *UAS* are extremely difficult, especially in systems using artificial Earth communication satellites for their transmission. On the one hand, they are as a result of very low *SNR* due to the presence of noise and interference with high spectral density and low power level of the useful signal because of limitations in energy resources, especially on board the *UAS*, and high values of channel losses. On the other hand, the ways of propagation of signals in the channels - multipath propagation and mutual motion between transmitters and receivers of the system further worsen the conditions for reception and correct evaluation of the signals.

Therefore, a few key points need to be considered:

- The conditions in communication radio channels for data transfer and control commands in *UAS* create a high likelihood of multiple errors in digital data streams, with packet errors being more typical. This requires the use of correction codes that have good performance close to the theoretical capacity of the channel. Such characteristics are possessed by turbo codes - with some differences in the details for their different type of design and complexity.

- The conditions in *UAS* radio communication channels vary widely, especially with respect to signal-to-noise ratio. Turbo codes, while superior to other *FEC* codes when operating near the Shannon limit, at high signal-to-noise ratios fall behind traditional high-power error correction codes. In this respect, hybrid turbo codes retain their superiority over the widest range of *SNR*, compared to turbo codes with parallel or serial design. Overcoming this problem can be achieved either by using two different types of *FEC* codes – e.g. a hybrid turbo code for low *SNR* and some block code from the *BCH* family for high *SNR*, or by using one hybrid turbo code and power control of the transmitted signals by a reverse channel, which would lead to much better energy efficiency of the communication equipment on board *UAVs*.

- Different types of digital data in *UAS* communication channels have different sensitivity to errors occurring during their transmission. Command and control (*C2*) signals, even at the lowest data rate, should be maximally protected from errors and at the same time this should be done through encoders and decoders that introduce minimal additional latency. The nature of other data types allows for a higher level of single-error rates and even significant additional associated latency due to the sensors onboard *UAVs*, such are, e.g. video streams captured by *UAV* cameras in the infrared light range. This requires careful selection and possible switching of turbo encoders to ensure the necessary and sufficient noise immunity of the different data types.

- The other main building blocks in the design of turbo encoders, besides the built-in RSC encoders, which largely determine the characteristics of the generated turbo code, are the interleavers. The aim of these is to obtain an efficient spreading of the bits belonging to one information group, without this leading to significant added latency and the use of large computational resources and memory volumes.

Carefully constructed, flexible algorithms for the operation of the interleavers can satisfy these requirements.

- Of the turbo codes studied, those derived from turbo encoder hybrid design appear to be most suitable for use in the complex conditions of *UAV* communication channels. The hybrid design offers a wide variety of

multi-level connections and the flexibility to incorporate various built-in encoders: either RSC encoders with different code rates and constraint lengths or replacing some of the built-in RSC encoders with other types of powerful error correction encoders. To fully exploit the potential of hybrid turbo encoders, i.e. to combine the advantages and mutually eliminate the drawbacks of the inbuilt interleavers and encoders of different types, much more theoretical, simulation and practical research is required.

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