Secure Systems Design and Technology Development. Veliko Tarnovo, Bulgaria
Proceedings of the International Scientific Conference, 2026. Volume III, 309-315

Turbo Encoders with Hybrid Concatenated Convolutional Design and Turbo Decoders with Soft Input–Soft Output Design in Unmanned Aerial Systems

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***Abstract*— Nowadays, unmanned aerial systems play a very important role in the economy, environmental protection, research, and military operations. This is accompanied by constantly increasing requirements for the quality and accuracy of the information received and the commands issued. The 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. The conditions for data transfer and command transmission in unmanned aerial systems using channels via communication satellites are particularly difficult. In such channels, the occurrence of single and especially packet errors is a phenomenon with a high degree of probability. The examination and evaluation of the potential capabilities of special class of turbo encoders – with hybrid concatenated convolutional design, to fight against the sever conditions in communication channels in unmanned aerial systems is the main purpose of this research work. Possibilities for optimizing energy consumption and processing time of data flows on board unmanned aerial vehicles through dynamic parameter control of the corresponding turbo decoders with soft input-soft output design are also discussed. Finally, conclusions, recommendations and directions for further research and the application of turbo encoders with hybrid concatenated convolutional design and turbo decoders with soft input and soft output in unmanned aerial systems are made.**

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

I. INTRODUCTION

Communication technologies used as transfer means of data and control commands between main elements of unmanned aerial systems (UAS) – unmanned aerial vehicles (UAV), widely known as drones and the command center (CC) – are critical for effective and safe operation of these systems. Autonomous radio channels; Wi-Fi (IEEE 802.11 family) networks; mobile cellular networks (3G, 4G and 5G) and satellite communication networks are commonly used of them, each of which possess certain advantages and disadvantages. Encoding methods and techniques of data and the control commands strongly depend on conditions in these communication media.

In the satellite communication radio channels data and the control commands are highly susceptible to noise, interference and distortions, which lead to significant amount of single and packet errors in the transmitted information.

Strong methods for coding and decoding to correct errors are required to ensure the reliability and efficiency of the tasks and missions of UAS. An encryption in communications channels of UAS to prevent data and control commands from unauthorized access is necessary, as well.

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, to evaluate the applicability of various turbo codes, as well as approaches for decoding signals damaged by channel noise, in order to correct errors in these channels.

Typical block diagrams of turbo encoders with different internal designs and iterative decoders with soft input and soft output are used to arrive at hypotheses for possibilities

Online ISSN 3044-7771
https://doi.org/10.68302/std2026.vol3.30

for optimizing the use of energy and hardware resources of the equipment, especially that mounted on board the UAV.

A. Satellite Communication Channels

The considerable challenges in ensuring reliable and sustainable operation are reflected in technological complexity, observed in UAVs using cellular and especially satellite communication networks, as shown in Fig. 1.

Satellite communications provide global coverage and are suitable for missions where UAVs operate in remote or hard-to-reach areas – forests, deserts or mountains, and areas without other communication network infrastructure.

However, satellite communication channels suffer from varied and large attenuations due to their large and highly variable physical length. In addition to this, molecular absorption in the Earth's atmosphere, caused primarily by water vapour and oxygen, mismatch between the polarizations of the transmitting and receiving antennas, as well as the inability to use highly directional antennas on board UAVs due to the manoeuvres they perform, lead to an extremely difficult situation regarding to the signal-to-noise ratio (*SNR*).

For constellations of communication satellites (CS) positioned in low Earth orbit (LEO) the physical length of the channel ranges from 400 to about 2000 km. For highly elliptical orbits (HEO), it can reach up to 42000 km and this is the same order of the communication channel length via a communication satellite located in geostationary orbit (GEO), when it is visible at low elevation angles.

This attenuation, caused by the distance D between the transmitter and receiver in the communication line can be estimated by the expression (1):

$$L_0 = 20(1.1 + lgD - lg\lambda), dB \qquad (1)$$

where λ is the wavelength of radio signals.

The molecular absorption of radio signal energy in the Earth's atmosphere is mainly due to oxygen and water dissolved in it, and can be accounted for by expression (2).

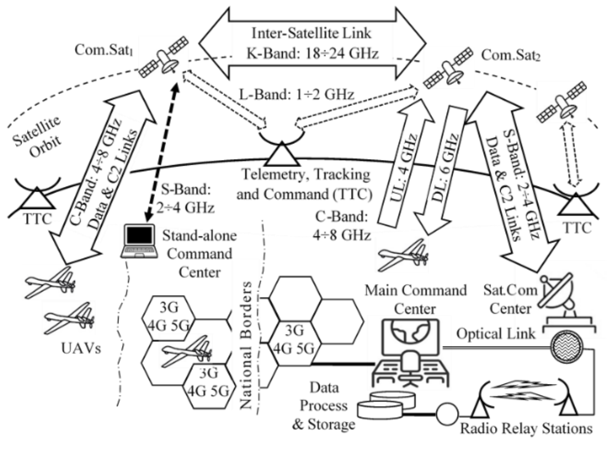

Fig. 1. UAS on cellular and satellite communication networks.

$$L_a = \frac{[L_{O2}(h_{O2} - h_s) + L_{H2O}(h_{H2O} - h_s)]}{sin\theta}, dB \qquad (2)$$

where L_{O2} [*dB/m*] is the specific absorption coefficient and h_{O2} [m] is equivalent atmospheric height for oxygen, L_{H2O} and h_{H2O} are the same ones for water dissolved in the air, h_S is the altitude of the 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, buildings and others.

The accurate assessment of these additional losses (L_d) is a complex problem of a stochastic nature, in the solution of which the climate model of Crane is often used [1].

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

$$L_\Sigma = L_0 + L_a + L_d, dB \qquad (3)$$

Therefore, it is very difficult to predict accurately the total attenuation in satellite communication channels, which is why some redundancy in terms of signal power is mandatory.

Another aggravating circumstance is that antennas with high gain, i.e. with sharp directivity diagrams, are not used on board UAVs to ensure their manoeuvrability. This gives a result in an even worse *SNR* compared to the lines between a communications satellite and a fixed earth station. At the same time, it remains 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.

In the satellite communication channels is observed Doppler shift F_D and signal spectrum broadening with significant values and fluctuations, especially at CS on LEO**.** 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 of the signals in this case can be represented 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. $F_D(H_S, i, B, t)$. [2]. The Doppler shift in one communication system is a result of the radial velocity $V_R(t)$ between the transmitter and the receiver communicating:

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

where $c = 2,998.10^8$ *m/s* is speed of light.

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

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

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, 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 [3]. Thus, it is possible to compensate for the Doppler shift of the signals if the UAV is equipped with a receiver of a global positioning system. Then by an appropriate control of the heterodyne frequency in the super-heterodyne receiver, the intermediate frequency can be stabilized, despite the Doppler shift.

TABLE 1. DOPPLER SHIFT IN GLOBALSTAR SATCOM SYSTEM.

H_S=1414 *km* (LEO), ***i***=52° ; f_0=2,5 *GHz* (Down Link XIII ch.) Absolute Doppler shift, kHz			
Maximum elevation, θ_{max}	30°	60°	90°
Latitude of UAV *B*=42° N	± 37,75	± 44,75	± 45,75
Latitude of UAV *B*=0° (equatorial position)	± 37,25	± 44,63	± 45,75

In addition to the large and highly variable attenuations and Doppler shifts, the control and data transfer between CC and UAVs in UAS*s* using communication satellites is characterized by significant latency due to the large distances that signals must overcome in such systems. Signal processing (encoding and decoding) with powerful error correction codes in systems with communication channels suffering from low level of *SNR* leads to an additional increase in this latency. As a result, control commands arrive at the UAVs with a noticeable delay.

However, UAVs are extremely fast and highly maneuverable flying vehicles due to the absence on board of a human. If, during a complex task, the UAV needs to abruptly change its flight mode and the command for this is not recognized correctly, then retransmission of commands or automatic repeat request (ARQ) mode are not suitable precisely because of this latency.

The aforementioned characteristics of satellite communication networks as a medium in UAS are a prerequisite for special attention to the reliability and error protection of data and commands transmitted 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 necessary [4]. The accurate choice of Forward Error Correction (FEC) code depends on both the specific requirements of the communication system and the characteristics of the communication channel [5], [6].

Fig. 1 shows the communication channels used to connect between the elements of a complex UAS, passing through communication satellites. The appropriate frequency ranges are indicated, and the principle of comparability of the powers of the receiver inputs is observed in the distribution of the frequency bands between up-link and down-link. This means that when the energy resources of the various elements of the communication system are unequal, and therefore the radiated power capabilities, the higher frequency part of the range is assigned to the element with the greater energy capabilities. The greater attenuation from molecular absorption in these higher frequency bands equalizes the power levels at the receiving points. Elements of the separate Telemetry, Tracking and Command (TTC) system are also shown.

B. Turbo Encoders in UAS– Features and Design

There are several types of error correction codes suitable for use in the harsh conditions in communication channels of UAS using satellite communication networks [7]. Such are Low Density Parity Check (LDPC) codes; Reed-Solomon codes, which are a special case of Bose–Chaudhuri–Hocquenghem (BCH) codes; non-separable continuous codes with a subsequent interleaving process, often in combination with some of the block codes mentioned above, applied as outer ones.

Turbo codes are particularly suitable for application in any kind of systems using satellite communication channels. This relatively young class of FEC codes, which are the first practically usable ones bringing the actual channel capacity very close to its maximum (Shannon limit), have convincingly proven their effectiveness and have found application in 3G (UMTS) and 4G (LTE, IEEE 802.16 – WiMAX) mobile cellular communications, in satellite communications and deep space communications.

The most valuable characteristics of turbo codes are superior error correction performance, enhanced decoding accuracy, robustness in noisy environments, efficiency at low *SNR*, adaptability for different applications, reduced bandwidth requirements, handling burst errors and energy efficiency [8], [9]. These useful properties of turbo codes are achieved at the expense of some certain disadvantages compared to traditional FEC codes. Most of these drawbacks are due to the requirements of the turbo code decoding process. The more significant of them are computational complexity, demands for larger volumes of memory, more energy consumed and more latency at the decoding process, especially when implementing iterations. Other common drawbacks of error protection using turbo codes are the sensitivity to the design of the interleaver (*Π* block) in combating packet errors and lack of universal suitability, because turbo codes are not optimal for short data blocks.

The classic design of turbo encoder, shown in Fig. 2 [10], explains the main idea that allow achieving the unique characteristics of turbo codes.

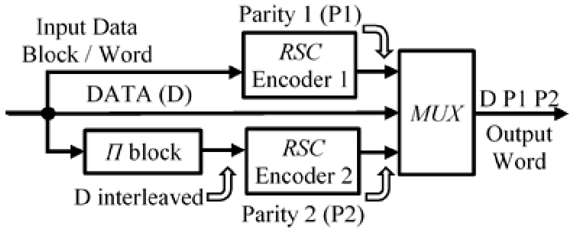

Fig. 2. Classic design of turbo encoder.

Two parity sequences, achieved by working on different arrangements of the same block of data, together with the original data block are sent through noisy channel. The inner encoders in that design, used to obtain parity sequences are recursive systematic convolutional (*RSC*) encoders, which differ from non-recursive ones due to the presence of feedback in their shift-register pattern, making them filters with an infinite impulse response [11], [12].

One *RSC* encoder with constraint length *K* of 4 in form of a chain of memory cells and a feedback, realized by shift-registers (D-Triggers) and Boolean *XOR* function units is shown as an example in Fig. 3. The feedforward polynomial *G(D)*, describing the parity output, is:

$$G(D) = D + D^3 \tag{6}$$

and the polynomial *F(D)*, describing the feedback, is:

$$F(D) = 1 + D^2 + D^3 \tag{7}$$

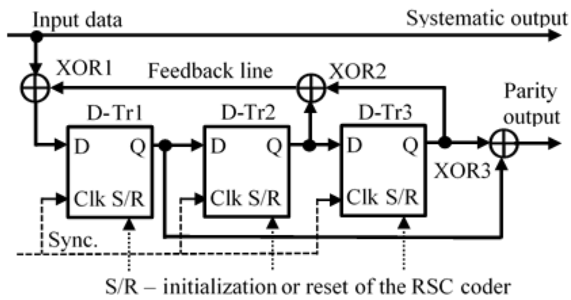

Fig. 3. An example of RSC encoder design.

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. 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 conditions in the communication channel, latency, capabilities for adapting to different speeds and volumes of the processed data blocks, computational complexity, power consumption, etc. [7].

a) Parallel-concatenated convolutional (*PCC*) encoder in which certain number of *RSC* encoders are producing different parity blocks by working in parallel on variants of one and the same data block. Encoder with *PCC* design is shown as an example in Fig. 4.

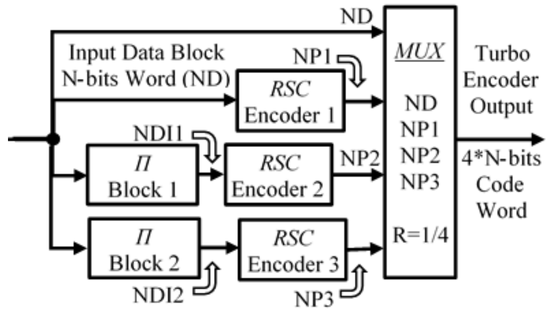

Fig. 4. An example of turbo encoder with PCC design.

The required number of interleavers provides the different variants of the data block. A structure of *PCC* turbo encoder consists of three *RSC* encoders and two interleavers. This turbo encoding has high coding gain and is appropriate to UASs where reliability and low latency are strongly required, e.g. satellite communication lines.

b) 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.

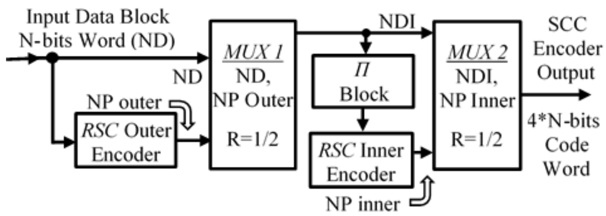

Fig. 5. An example of turbo encoder with SCC design.

Because inclusion of an *RSC* encoder as an inner encoder, turbo codes generated by encoders with *SCC* design have better characteristics compared to codes generated by encoders with *PCC* design around *error floor* – the area after which the trend of decreasing of the bit error ratio (*BER*) with increasing *SNR* decreases significantly.

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

The combining of the two main types of connection between the built-in RSC encoders allows the turbo encoders with the *HCC* design to inherit from *PCC* encoders the high coding gain at low *SNR* and from the *SCC* the low error floor at high *SNR* [13]. Furthermore, the complex *HCC* design allows an adapting the encoder to different coding rates, by puncturing (taking away part of the parity bits according to a certain pattern) at several points in the connection scheme.

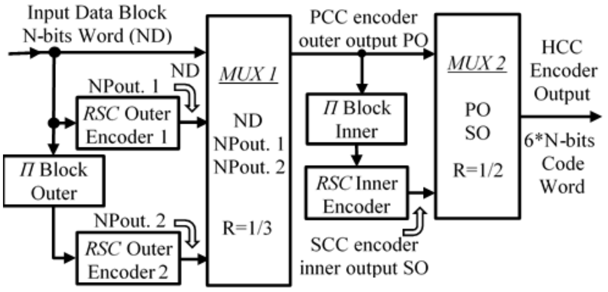

Fig. 6. An example of turbo encoder with HCC design.

It should be borne in mind that 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 network with satellites on *LEO*, is used as the medium between the *UAS* elements. 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, copes with these challenges to a high degree.

The superior performance of codes generated by turbo encoders with *HCC* design over a wide range of *SNR*, as well as the ability to work with different data types makes them extremely suitable for *UAS*.

C. Iterrative Turbo Decoding

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. Although algorithms based on hard decisions (according to Hamming distance between code words) are significantly easier and more economical to implement, nowadays those based on soft decisions (according to Euclidean distance), iterations and inner information exchange are mainly used.

In radio communication channels, in the presence of Additive White Gaussian Noise (*AWGN*), opposing signals, as Binary Phase Shift Keying (*BPSK*) modulated ones, are best distinguished. In these cases computer data u_k (0 or 1) are mapped as opposite channel symbols x_k (1 or -1) by the rule:

$$x_k = 1 - 2u_k \tag{8}$$

In this case, the *XOR* (*exclusive OR*) operation, often used in computer science, is completely adequately replaced by the "multiplication" operation used in communication technology.

The typical turbo decoder with soft-in soft-out (*SISO*) design is based on the assumption of an independent input sequence and a memoryless channel and its structure and the nature of the processes within it explains some of the shortcomings of turbo codes listed above.

In turbo decoders with built-in *SISO* decoders, soft decisions are presented and processed by Log-Likelihood Ratio (*LLR*), of the evaluated signals. As an example when the received *BPSK* signals are evaluated in channel decoder, the ratio of the conditional probabilities for the transmission of x_k or $-x_k$ is used, given a received signal y_k:

$$LLR = ln\left[\frac{P(x_k/y_k)}{P(-x_k/y_k)}\right] \tag{9}$$

The aim is to obtain large values of |*LLR*|, which means great certainty in making a decision, and the sign in front of the *LLR* indicates which of the two signals (x_k or $-x_k$) is more likely. *LLR* values close to zero indicate serious uncertainty in the decisions and at *LLR*=0 there is complete uncertainty. The value of |*LLR*|=3 corresponds to 95.5% confidence in the estimate for one or the other symbol. The natural logarithm is chosen for convenience in determining the estimate of symbols passed through a communication channel with AWGN, since the nature of this noise assumes a Gaussian (normal) probability distribution of amplitudes.

Other relationships that are valid in this way for probabilistic symbol evaluation are:

$$P(x_k) = (1 + e^{-LLR})^{-1}; \quad P(-x_k) = 1 - P(x_k) \tag{10}$$

If there is only one decoder, it must make a hard and final decision about the meaning of the received symbol. Two or more decoders can participate in a soft decoding scheme, in which the decoders exchange soft information - an estimate of the meaning of a received symbol, with some degree of confidence in that estimate. *LLR* is precisely the format in which these soft-input soft-output decoders exchange such soft information. Turbo coding shows its superior qualities best if, when evaluating a single symbol, the process of exchanging soft information between *SISO* decoders is repeated many times before a final hard decision is made – so called *iterative decoding*.

The *SISO* decoders built into the turbo decoders implement the Bahl-Cocke-Jelinek-Raviv (*BCJR*) algorithm, which is particularly suitable for decoding convolutional codes and provides maximum a posteriori (*MAP*) estimate for defined trellis, i.e. turbo codes with a specific structure, determined by the block diagram and parameters of the turbo encoder. To achieve this, the *BCJR* algorithm calculates and combines three types of metrics (probabilities): forward metric α_{k-1}, backward metric β_{k-1} and branch metric (probability of transition) γ_{k-1}.

Generally speaking, a posteriori information LLR_{post} has the following structure:

$$LLR_{post} = LLR_s + LLR_{apr} + LLR_{ext} \tag{11}$$

where LLR_s is the evaluation of the systematic symbol by the channel decoder, LLR_{apr} is some quantity of a priori information.

Each *SISO* decoder produces extrinsic information LLR_{ext} that is sent and used by the other *SISO* decoder as a priori information LLR_{apr}. The new produced information is extracted using the parity symbols, which also pass through the noisy channel and therefore the estimate for them is in the form of Log-Likelihood Ratio LLR_{par}. This extrinsic information at the output of any *SISO* decoder does not repeat parts of the information at the input of this *SISO* decoder, thus avoiding overconfidence of the overall turbo decoder:

$$LLR_{ext} = LLR_{post} - LLR_s - LLR_{apr} \tag{12}$$

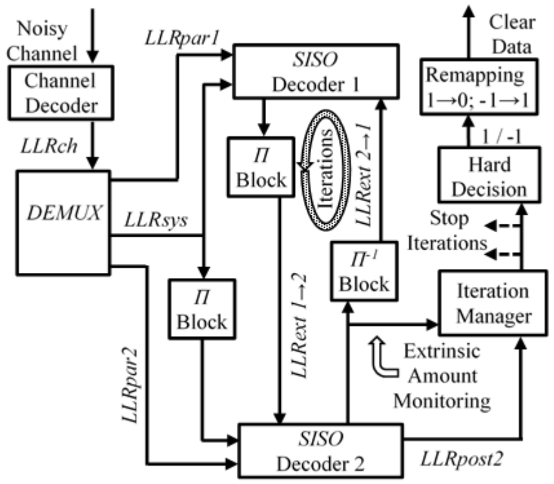

Fig. 7. Turbo decoder with built-in channel and SISO decoders.

A turbo decoder with two embedded SISO decoders iteratively exchanging extrinsic information and controlling the iterations is shown in Fig. 7.

From the internal information exchange algorithm and the sequence of iteration stages, it is clear that each portion of extrinsic information at the output of one SISO decoder is a priori information at the input of the other SISO decoder. The exchange breaks by the iteration manager, which stops the process upon reaching certain criteria.

III. RESULTS AND DISCUSSION

Analysis of the shortcomings of turbo codes shows that they are primarily related to providing more energy resources and hardware complexity and capabilities for decoding processes. Unfortunately, these qualities are lacking in UAV equipment and power supplies.

Given the theoretical and constructive considerations described above, several approaches can be considered for optimal use of the energy and hardware resources of the elements of a UAS using satellite communication channels in its structure. Searching for and finding such solutions is especially important for UAVs, where the limitations of these resources, as well as mass, volume, and aerodynamics and maneuverability requirements, are severe.

One approach to optimizing two-way communications between the UAV, on the one hand, and the ground CC or communication satellite, on the other, is to use asymmetric FEC coding schemes in the opposing channels - Fig. 8

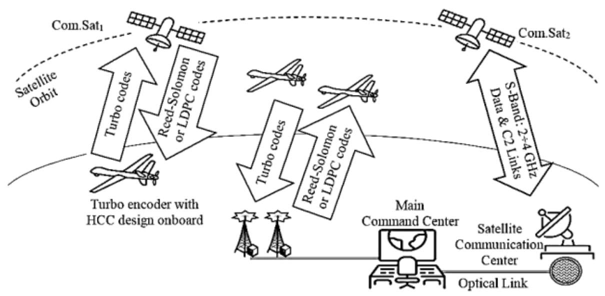

Fig. 8. Asymmetric *FEC* encoding to and from *UAV*.

This means that on board the UAV, blocks of data can be encoded against errors with powerful turbo codes, since on the ground (in the command center) or on board the communication satellite, there are more energy and hardware resources to overcome the higher demands of the turbo code decoding processes. In the communication channels to the UAV, the information flow consists primarily of commands, which are essentially short blocks of data, where turbo codes are not particularly effective anyway.

To protect data from errors in the communication channels towards the UAV, it seems appropriate to use LDPC or Reed-Solomon block codes, which outperform turbo codes when dealing with short data blocks. In addition, protection against errors in these channels can be enhanced by providing a higher level of signal-to-noise ratio at the input of the UAV receiving equipment, since the ground CC or communication satellite, having greater energy resources than those of the UAV, can afford higher transmission power.

Analysis of a typical family of *BER* versus *SNR* characteristics (shown in Fig. 9) of performance of iterative turbo decoder at different number of iterations shows some interesting facts that can be used for an optimization [12].

First of all, it is noticeable that a drastic drop in BER occurs in the first few iterations. For example, at an *SNR* of around 1.5 dB, the *BER* drop between the first and third iteration is almost three orders of magnitude (1000 times). At the same time, for the same *SNR*, the *BER* drop from the sixth to the eighteenth iteration is insignificant.

Next, it is seen that this disproportionality in the significance of the first and subsequent iterations for *BER* reduction increases with increasing *SNR*. Furthermore, it is evident that the presence of an error floor makes it meaningless to increase the number of iterations above a certain reasonable limit, which remains adequate for a wide range of *SNR*.

Since in satellite communication lines the distance between the communication satellite and the UAV is very variable, and as a result the *SNR* fluctuates within large limits, maintaining a given *BER* level requires a significant reserve of computing power, for the sake of energy resources. In addition to distance, the position of the opposing equipment relative to the antenna's directional pattern also matters. This can be avoided by setting a certain *BER* threshold, which is different for different data types, and then applying a variable number of iterations required to bring the *BER* below this threshold. Thus, the number of iterations, and thus the consumption of energy resources, is set depending on the *SNR* in the channel or the distance between the communication satellite and the UAV, without unnecessary losses.

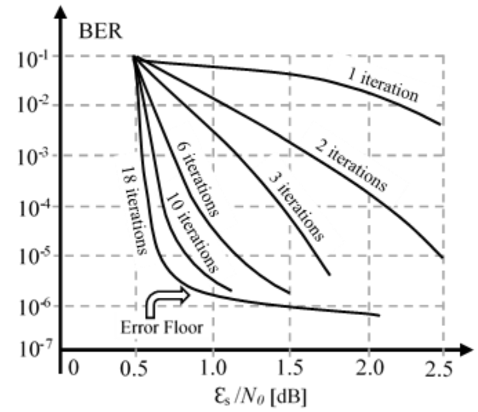

Fig. 9. Typical iteration family of characteristics BER vs. SNR.

Instead of the distance between the communication satellite and the UAV, a more accurate criterion can be the extrinsic information exchanged between the *SISO* decoders during turbo decoding. When the amount of such information falls below a certain level, set by the required *BER*, the iteration manager that monitors it stops the iterations and issues a command to make a hard decision based on the a posteriori information at the output of the second *SISO* decoder, reached up to that point.

IV. Conclusions

The conditions in the communication channels for data and control commands transfer in UAS are extremely difficult, especially if communication satellites are used.

Therefore, a few key points need to be considered:

• Different types of digital data in communication channels have different sensitivity to errors occurring during their transmission. Command and control 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. Turbo codes are not optimal for short blocks, where LDPC and BCH codes are more effective. The possible solution is in asymmetric encoding – the FEC codes used in the direction from CC or communication satellite to UAV and in the opposite direction are of different types and characteristics.

• Turbo codes have superior performance at low *SNR*. However, they require more power and hardware resources, especially during decoding. In the channels to the UAV, a higher *SNR* can be achieved at the expense of the capabilities of the ground and satellite equipment to transmit signals with higher power, i.e. this is another argument for using asymmetric FEC coding. In addition, ground and satellite stations can afford to use directional antennas in the channels to UAVs, which further improves the *SNR* at the inputs of the receiving equipment.

• Turbo encoders with *HCC* design cover a wide range of requirements and characteristics of the satellite communication channels. In addition, they contain in their complex structure all the necessary blocks and connections to switch on command and as needed, thereby becoming encoders with *PCC* or *SCC* design. This makes them applicable to UAS, which use satellite communication networks for control and data transfer to and from UAVs.

• Optimization of the use of energy and hardware resources can also be achieved through the development and research of more complex and intelligent algorithms for managing iterations and other processes in turbo code decoders. This would lead to opportunities for energy and hardware, with their attendant mass and volume, to be allocated to improving other mission characteristics and the effectiveness of UAS in general.

Acknowledgments

This work was supported by the NSP SD program, which has received funding from the Ministry of Education and Science of the Republic of Bulgaria under the grant agreement no. Д01-74/19.05.2022.

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