Scientific editor's foreword

The increasing use of information flow generation and processing systems, as well as storage, recovery, maintenance and transmission through various communication channels, is the basis for the accelerated development of our technological digital civilization.

Like any branch of science and technology, digital informatics develops more and more wide areas of modern technologies, actively introduces in production cycles of the enterprises, in various systems of monitoring, including systems of remote sensing of the Earth, and also it becomes a basis of essentially new approaches in scientific activity. Such comprehensive penetration of digital ideology in all aspects of modern society is accompanied by the emergence of a fairly large set difficult scientific and technical problems in the information theory itself.

The main problems of informatics, as it may seem strange, lie in the very foundations of the information theory and in the most complex and, of course, interesting (!) parts, which are the theory, technology, methods and algorithms of noise-resistant coding. This is determined by the fact that the transmission of large amounts of data in digital networks of different levels and their use, storage and recovery is possible only at a high level of these data reliability. But they are useless if the proportion of errors in the digital data will be too noticeable. In this case most of the transmission protocols, software modules with errors, and many other services will not work.

Provision the necessary level of reliability of digital data is engaged in the theory of noise-resistant coding, the achievements of which over the passed 70 years of its development are very significant. For decades, coding already has become a must in digital communication systems in many technologically advanced countries, allowing to increase strongly the speed of data transmission and reliability, and also reduce the size of expensive antennas. Powerful codes were used in the last Millennium in the NASA "Cassini" project for Saturn studies, which was successfully completed in September 2017. A variety of codes are widely used in computer memory systems, mobile communications, home appliances, as well as many other important systems of the digital world and our technocratic society.

However, until recently, the potential of many very expensive discrete channels and various digital networks have not been used fully enough because of the still very low efficiency of many error correction algorithms, decoders, the creation of which is the most difficult information theory problem and noiseproof coding theory.

Of course, concrete advances in coding theory and technology are vast and undeniable. But the unresolved problems of this essentially important science of the digital world until recently, were too much. It is largely determined by the commitment a very large number of scientists working in this field, to the algebraic foundations of this theory.

Nevertheless, as it is well known, the optimal decision, i.e. the best minimal probability of undetected error after decoding error-correcting code in many cases can be achieved at the base of the very simple searching the global extremum of the functional (SGEF) in discrete spaces. It may be done even for exponentially growing number of possible decisions if the code length increases. And such an optimal decision, but only for carefully selected codes, can be found even for a very high noise level of the channel, which one, of course, is especially valuable.

These results were the starting point of fifty years of researches by this monograph's author, who received patent of such an unexpected solution for the problem of noise-resistant coding almost half a century ago. So algebraic coding theory was an excellent starting point in the early researches stages for error correction algorithms. It allowed the scientific community to undestand the codes at the first stage through multidimensional discrete fields and other special mathematical structures. This created in the 60s of the last century conditions for solving some start problems of achieving the required reliability of digital flows for different channels.

The works of the monograph's author and his scientific school showed that the achievements of their Optimization Theory (OT) for noise-resistant coding are the basis of particularly simple algorithms of global searching extremum of functionals that decode correctly the accepted messages directly near the Shannon boundary, which is the ultimate goal of coding theory. This monograph is devoted to the presentation of these results on a completely new ideological level.

Let us to remind that the veracity and the reliability of communications and the effectiveness of communication channels usage depend on the error correcting algorithms, i.e. decoders. But the most of the known algorithms of this type until recently were still unreasonably slow or too complex. The problem of simple and highly reliable decoding at large noise level when the channels are used with maximal efficiency, i.e. when they work in close proximity to the channel capacity
was always implied as existing. But in fact for a long time this task was not put at the forefront. It was due to the presence of only rather weak or too slow algorithms. Even significant progress in the microelectronics of recent decades has not accelerate the searching for solution of this digital communication main problem formulated 70 years ago by Claude Shannon. Known achievements of the coding theory based on algebraic and a number of similar algorithms in recent decades have not improved the real possibilities of this classical theory applied methods and did not indicate new ways for the successful technological development of decoding systems.

Just in these conditions during many decades the Optimization Theory (OT) of noise-resistant decoding is developing in Russia. It successfully solves the problems of optimal decoding, providing the best possible decoding reliability at very high noise levels. Extremely important, that our researchers do it with theoretically minimal linear increasing complexity with growth of the code length. This minimum possible theoretical complexity just also allows to do simple and very fast decoders

for very long codes. And only these codes allow to reach the vicinity of communication channel capacity .

The author and the other undisputed pioneers in this field in their, of course, very unconventional in style and results books and articles over these decades have shown very special features and long-known methods such as a wonderful Viterbi algorithm (VA), for which they have received a patent recently, and new iterative methods of error correction on the multithreshold decoders (MTD) basis. These methods implement very effective procedures for global search also.

A key theme that determines the value of this monograph, are a variety of results convincingly demonstrating quite technological solutions of Shannon's problem of simple high-precision decoding near the channel capacity posed 70 years ago. They are based on the Optimization Theory of noise-resistant coding.

Starting installation of this new coding theory has become the Main Theorem of multithreshold decoding (MTMTD), which stated that properly organized simple majoritarian iterative algorithms with each change of decoded symbols is strictly closer to the optimal decoder (OD) decision, for achievements which before usually needed to carry out a complete exponentially complex search. In various technical systems, for example, Viterbi algorithm does it.

An exact MTMTD proof has revolutionary changed problems of decoding for all channels with independent distortion. Now it is possible to use MTD decoders for all classes of majority decodable codes. MTD algorithms only at linear (!) complexity with the code length of this algorithm usually achieve OD decisions even at high channel noise. But the author understood clearly, that specially formulated the cornerstones of his science MTMTD theorem did not promise to achieve always the decision of the OD, i.e., the multithreshold algorithm, alas, is not optimal decoder (OD). Exactly therefore, the members of the author's scientific school, who have so far created this full-scale Optimization Theory, all these years have been searching for the conditions that must be fulfilled in order for the process of successful decoding, i.e. the search for the global extremum of the functional, would be as long as possible. It is very important that this search does not stop somewhere at halfway to the optimal decision, which is the code word closest to the message received from the channel. And under this it was necessary always to ensure that the complexity of the corresponding decoder, naturally understood as the number of performed operations, remained theoretically minimal, only linearly increasing with the code length, even at high channel noise levels. The author solved this next very difficult problem with his new theory of error propagation (EP) for majority schemes.

All the obvious and sometimes quite unexpected ways to achieve the decision of OD based on MTD algorithms and a number of others methods just set forth in all their diversity in this book. The author makes it clear that for a large number of channels and codes it is already possible to achieve a very high level of final reliability on the MTD decoders basis and a number of derived methods directly near the Shannon boundary. As it will be seen from the following material, this task is

really in very many cases has been already quite successfully solved by the author and for some code clusters (typical combinations of code parameters and channels) it will be solved by methods already known in the OT. Therefore, the author is certainly a specialist who has the right to declare his Shannon's problem solution for all major types of the digital channels with independent distortions. The task of expansion the list of such code clusters will now be permanently resolved and by already numerous known, and, of course, new methods. The field of OT will rise quickly; all conditions for this the scientific school OT and the author have already created.

The level of the author's achievements in the field of technological accessibility of the algorithms described in this monograph is not less important also, although he is mainly engaged in the fundamental researches. It turns out that he and his scientific school got a number of extremely important results in a variety of technological areas related to the coding theory and technique. The most significant application achievement OT is extending the scope of the MTMTD to virtually the entire set of iterative decoding methods for linear codes — both block and convolutional: concatenating schemes of different types, channels with erasures, ultra-fast hardware and software options decoders, as well as, which is also quite unusual and even unexpected in general for the whole coding theory, his re-opened symbolic codes.

Symbolic codes were known as a nonbinary majority decodable codes. They were invented, as well as usual threshold algorithms, by the founder of this direction, the outstanding American scientist J. Massey in the 60-th of XX century. However, in his analysis of these codes, he has demanded from them such the exceptionally high characteristics, which they could not provide at all. And, as a result of his considerable frustration, he refused further such code structures analysis. And this refusal became the reason that researchers around the world, in fact, certainly believed his opinion. Over the next 50 years they actually did not use the majority algorithms for nonbinary codes. These codes seemed as if they did not exist. But it happened so that all the other nonbinary codes and decoders created by classical algebraic theory during this long period, also did not become outstanding achievements of science, although they were very useful in many technical systems.

But the monograph author and his school were very attentive to the codes, once rejected by J. Massey, clearly separated them from other types of nonbinary codes and called them as the symbolic codes. By now they have created a complete theory for them as well as for especially simple symbolic MTD decoders based on the principles of searching global optimization of functionals, which effectively correct errors in these code structures for a very high noise. And since the main parameters of symbolic codes, i.e. the size of the alphabet and the length are completely independent of each other, then the characteristics of all these symbolic algorithms have become completely and forever unattainable for any other nonbinary code systems that do not use methods of searching the global extremum. But this is not surprising, because the classical coding theory for almost 60 years has not created anything more effective in

a variety of nonbinary codes than very weak Reed-Solomon (RS) codes, because they really still can use only very short versions of this type of codes.

By the way, it is very useful to draw the attention of this book readers to the fact that for a truly triumphant procession of symbolic codes around the world of coding systems, the authors of symbolic algorithms immediately changed and patented the rule of threshold elements work, which ones are the single active nodes in all MTDs, including symbolic decoders. This moment decided the fate of the world contest among nonbinary algorithms. It take place simply, as they say, "due to obvious advantage" of symbolic codes in all respects of the efficiency and complexity. You can verify this by reading the relevant sections of this monograph or previously published books and author's articles on this subject.

The scientific school OT has already published several books on the subject of OT and a reference book on coding. International telecommunication Union (ITU) at its Anniversary 2015, has published a fairly complete monograph on OT in English language. At the same time, it is important to emphasize that in general all MTD algorithms options, despite the inherent not always obvious ideas of effective global search, are extremely simple devices or programs with well-understood principles of operation, which are extremely useful for training students and professionals, and also for development and application.

In the monograph the author gave full attention and many others ideas that emerged in the process of development OT: the principle of divergence, parallel concatenation, codes with selected branches and other systems and organization principles of a new, very unusual decoding style that formed its special vast intellectual space of OT paradigms. All of them really helped in creation, research and implementation of extremely simple decoding methods at high noise level. Note that earlier none of these listed concepts in coding theory were presented. But their role in the OT and in the successful solution of decoding problems proved to be extremely important.

Some of the author's results are discoveries in coding theory.

We must indicate one of the most important methodological results of the author's theory — the selection of decoders with direct metric control (DDMC) into a special group also. This proved to be particularly useful and even absolutely necessary in solving coding problems in channels with extremely high noise levels. The scientific school of the author includes in the group DDMC all methods using MTD and VA, which have the most important property of accurate measurement the distances to be minimized by these algorithms. This approach brings the researches of decoders based on VA and MTD to a higher level, the work at which has already made it possible to obtain an extremely important result - the creation and patenting the block version for Viterbi algorithm (BVA) with a complexity close to that of classical VA for convolutional codes. This result for one of the most important algorithms of the last century is impressive in itself, because the complexity of the classical coding theory for others block versions of BVA actually corresponds to the

doubled exponent of complexity in comparison with convolutional codes. It made them, of course, absolutely unsuitable for application in real systems. The emergence of effective and relatively simple block VA, which is similar to convolutional codes, simplifies the procedures of error correction for all binary block codes and unifies them on a common basis of DDMC methods.

In previous monographs on OT and MTD in order to illustrate many of the results about MTD algorithms network portals **www.mtdbest.ru** and **www.mtdbest.iki.rssi.ru** have been used frequently. They are used by the author's scientific school. The first of them is upgraded frequently. It repeatedly facilitates the correct understanding of the OT results for interested readers. Opportunities to use these portal resources in this monograph are even more diverse and useful.

Members of the scientific school have received almost 20 patents for their methods and algorithms, including abroad.

Completing the presentation Professor's V.V. Zolotarev monograph to the scientific and technical community, it is necessary to note some problems connected with his theory. The development of MTD algorithms during half a century of researching - on majoritarian and similar methods, as well as their support by leading institutes of the communications industry has demonstrated a really wide possibilities in this direction in the technology of decoding and full compliance of created MTD decoders to theoretical positions of the author. This was facilitated by a significant number of patented by the author technical solutions, most of which have been tested by hardware, on models and by other researchers.

Having such a serious and comprehensive support for his work, the author of the monograph quite reasonably claims that his theory turns out to be a new section of the theories of the functionals global extremum searching under specific conditions of discrete spaces. Thus there are all primary necessary conditions for such statement of a problem: the code which increase in length leads to the exponentially rapid growth of admissible decisions number - code words, etc. At the same time, the methods invented by the author make it possible, even with a large channel noise, to find optimal decisions for the codes chosen by him, since in OT there are all necessary criteria of decisions optimality that meet the global minimum the decision distances to the vector taken from the channel.

The situation with OT strongly resembles A. Viterbi case, who actually took for its extremely useful decoding method half a century ago already well known procedure from dynamic programming. His algorithm became one of the main error correction methods in digital communication for many decades .

In this regard, one has to wonder why this monograph's author has not a clear understanding of whether his methods successfully used by him for all types channels with independent distortion, to any standard classes of global optimization procedures. It is possible that successful the OT paradigms development and technologies will prove the belonging of this theories to some standard setting of global searching problems. Then the situation of paradigm shift from one scientific

branch in another, a similar to algorithm Viterbi, will be confirmed. Introduction certainty in this matter will contribute to the application of the whole arsenal of global searching theories to the coding theory problems , which is of particular interest.

If the author can substantiate his theory as the appearance a new class of global search tasks, then his separate contribution to global search theories is also welcome. In any case, the elimination of the obvious uncertainty in the ownership of the OT will create conditions for its further successful development. This question solution should be put as a very actual problem.

I would say that this monograph marks the transition of the applied coding theory to a new phase of development focused on simple effective error correction algorithms creation. It becomes quite understandable and solvable optimization problem in discrete spaces. Many of the algorithms discussed in this book work successfully in close proximity to the Shannon's boundary and achievement for the majority of other algorithms DDMC class neighborhoods of this bound, as follows from OT, stated in this monograph, already seems simply a matter of time.

The special importance of this monograph publication is determined by the fact that 2018 is the coding theory anniversary: 70 years ago Claude Shannon put forward the problem of simple and effective decoding before science and technology in his remarkable article "Mathematical theory of communication". It is gratifying to see its successful solution this jubilee year in the Russian scientist’s monograph .

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