Intelligent data processing methods in sensor networks of mobile and autonomous objects

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Abstract. In the near term, tasks related to monitoring mobile geographically distributed objects with the aim of efficiently managing them are acquiring great importance. An example of such tasks is the monitoring the state of given number of vehicles of agricultural enterprise, when it becomes necessary to promptly transfer given amount of data with high requirements for the level of their reliability. The use of the infrastructure of cellular mobile networks for this is not suitable for a number of reasons for rural areas. The paper proposes an approach based on the use of high-speed dynamic sensor networks. This makes it possible to carry out relay transmission of data between objects, including mobile ones. However, the issues of building flexible data transfer protocols in networks of this kind, providing a significant data transfer rate and taking into account the priority of the transmitted information and its features, still remain open. At the same time, for mobile objects in conditions of non-stationarity of the parameters of communication channels, the problems of ensuring the required reliability of data are of particular importance. To solve the last problem, it is proposed to use the permutation decoding method based on the cognitive metaphor.

1. Introduction

The analysis of the subject area related to the development and improvement of modern network technologies in the agricultural sector shows that they cover digital equipment of agricultural enterprises, their vehicles, unmanned aerial vehicles, numerous sensors and sensors, and in the near future they provide for the use of artificial intelligence systems [1-5].

In modern conditions, the tasks of monitoring and automatic control of various moving objects: cars, agricultural machinery, unmanned aerial vehicles are of particular relevance. This is due to the fact that the listed objects are sources of various operational information (current coordinates, speed, status of paired devices, current errors, etc.). Timely receipt and processing of this information is the key to the successful operation of mobile objects and can significantly reduce the costs of transport and agricultural companies.

Usually, the task of monitoring mobile objects is solved using cellular mobile networks. However, the use of such technologies in agriculture is associated with a number of disadvantages, including: lack of widespread coverage, low bandwidth (14-150 Kbps for GSM networks), rather high delays, additional costs for using the infrastructure of cellular operators.
Therefore, to date, the existing commercially successful monitoring and control solutions are limited only to transmitting to the server a minimum set of data separately from each mobile object when they reach the coverage area. If its route passes through regions with poor quality coverage, then adequate monitoring and remote control becomes impossible. At the same time, if the cost of services for the use of mobile channels does not consist of the volume of transmitted traffic, but by subscription, which is very popular today, then the financial effect of using the monitoring and control system can be negative for a particular facility.

It should be noted that this problem is not acute for all regions, for example, in Europe, according to rough estimates, cellular coverage is more than 80%, and this number falls on broadband networks of the third generation and above (3G, UMTC, LTE). The situation is similar in North America. In other regions, the territorial coverage barely reaches 40% [4,5]. To overcome these limitations and expand the functionality in recent years, much attention has been paid to the development of so-called mobile sensor networks.

For areas with widespread coverage of mobile operators, for example, Europe, North America, the eastern part of China, the presented family of technologies allows you to reduce the load from the basic cellular infrastructure. This is achieved by creating a separate special wireless data transmission infrastructure, which, unlike traditional wireless communication networks, requires low radiation power. At the same time, such an approach solves the urgent problem of energy saving of autonomous power sources at high speed and reliability of transmitting small amounts of data (telemetry) with low requirements for their delay. Taking into account the high dynamics of the growth of the number of sensors and manipulators connected to the network, the gain from the use of sensor network technologies for these regions is expected to be significant.

Obviously, an objective change in the topology of such networks and the pronounced uncertainty of the influence of destructive factors forces the use of anti-noise coding means in such network structures.

The purpose of the work is to substantiate technical solutions for the organization of sensor networks in a group of mobile objects that perform a common task.

2. Capabilities of well-known network solutions for transport monitoring tasks
Two approaches are possible. The first approach is to create a group of communication protocols of the first and second layers of OSI to achieve maximum coverage, minimum power consumption of end nodes and the ability to connect a large number of devices to the network. This is achieved mainly through the use of more noise-immune modulation methods (BPSK, LoRa, DSSS, FSK, UNB, DBPSK and others) and the sub-GHz frequency range. The scheme of interaction between the base station and end devices is simplified as much as possible. At the same time, mechanisms for ensuring quality of service (QoS) are sacrificed, such as handshaking, profiling, reservation, etc. Access to the transmission medium is provided not by complex code (CDMA) and time division (TDMA) mechanisms, but by simpler approaches, such as ALOHA, slotted ALOHA, LBT (Listen before talk), CSMA/CA and others. To reduce the level of interference when sharing the same frequency channel, restrictions are introduced on the downlink (from the base station to the end device). Thus, asymmetry of the communication channel is formed or the channel becomes completely unidirectional [6]. Networks built on these principles are called LPWAN (Low Power Wide Area Network). The most popular and commercially successful ones include the following LPWA wireless technologies: LoRaWAN, Sigfox, Igenu, Telensa, Weighless-SIG, NB-IoT, EC-GSM, and others [6].

Depending on the specifics of the monitoring / control system, LPWAN can be deployed as a local network for the exchange of telemetry data between mobile objects, or as a network with an Internet access point. Expansion of coverage and provision of mobility is provided by placing additional communication equipment, which is much cheaper than base stations of cellular operators and requires less costs for their deployment. In addition, the overwhelming majority of LPWA technologies operate in the free ISM band, which allows them to be freely used.
In terms of its topology, LPWA networks do not differ in any way from classical wireless networks (GSM, UMTS, LTE, 802.11, etc.) and are built according to the “star” scheme, and assume the presence of an operator that ensures the functioning of the base station infrastructure. As an exception, the Igenu protocol can be noted, which supports a tree topology. Mesh networks have not found widespread use in LPWAN due to the need to implement complex routing algorithms on end devices, which does not allow end devices to provide long-term operation (on the order of several years) on battery power [7]. The analysis shows that at present LPWAN solutions are practically inapplicable for monitoring and managing transport facilities, since they provide extremely low data transfer rates (up to several tens of bytes per second). In addition, the coverage area of LPWAN networks is currently significantly inferior to the coverage area of cellular mobile communication networks.

The second approach involves using the mobility of the devices themselves to transfer information between geographically distributed devices or networks in the absence of radio accessibility. Such networks are commonly referred to as mobile wireless sensor networks MWSN. At the same time, there are three types of mobile sensor networks: single-level, two-level and three-level.

Single-layer MWSNs unite a group of dissimilar devices that communicate with each other without any control device (access point, base station, router), using special routing algorithms to transfer data through available devices located in the receiving area.

Two-layer MWSNs consist of stationary devices transmitting data and mobile devices that receive data from stationary devices on one network and transmit it to recipients on another network when they reach their broadcasting area. Popular smartwatch applications are a simple example of such an architecture. A “smart watch” and a smartphone usually work in pairs, but there are times when there is no way to take your phone with you. In this case, the data received from GPS satellites, infrared sensors and a pedometer are saved in the watch's memory.

Three-layer networks consist of a group of stationary devices transmitting data, mobile devices that provide data transportation from one broadcasting zone to another, and a group of access points in the networks of which the recipient is located. An example of such an organization is a parking control system in a covered parking lot. The sensor network collects data on free parking spaces and broadcasts a data packet, which is received by a mobile device compatible with this communication system, for example, a smartphone.

The above approach requires significantly more computational resources and energy consumption than the first approach, but it allows for significantly greater coverage. In addition, it becomes possible to control the coverage, providing communication with the necessary areas in a certain period of time [8].

The above approaches to organizing sensor networks for monitoring systems are not mutually exclusive and can be used within a single system. Their successful implementation turns out to be especially convenient for transport monitoring tasks in conditions of weak or absent cellular mobile network coverage. A large number of mobile carriers of radio devices make it possible to form relay micro-coverage over large areas, providing the ability to transfer data within dynamically created radio networks. This makes it possible to implement many different scenarios for joint data processing, including the direct reaction of one or many radio devices to events occurring in a given fragment of the radio network.

Since the overwhelming majority of wireless sensor network technologies are based on the unlicensed ISM band, in which countless systems coexist at the same time, creating a lot of interference, anti-interference coding methods play a key role in maintaining a reliable connection. Indeed, a distinctive feature of mobile sensor networks is a dynamic over time change in data transmission conditions, which leads not only to a change in the network topology, but also to the emergence of network sections with a weak signal at the reception of the next link in the network. In this case, the increase in the energy efficiency of the communication system is one of the main conditions for the operability of the system in general.
3. The principle of permutation decoding based on a clear cognitive map

The main criterion for the effectiveness of the use of a redundant code in a communication system is the indicator called the energy code gain (ECG). In a channel with Gaussian noise, to reveal the asymptotic boundaries of the ECG exponent, it is assumed that the ratio \( E_b / N_0 \to \infty \), in which the value \( E_b \) – signal energy per bit, \( N_0 \) – spectral density of Gaussian noise, in the case of hard decisions and implementation of the S-erasure correction algorithm ECG, is estimated by the expression:

\[
D_s = 10 \log(Rd_{\text{min}}) \text{ dB}
\]

(1)

Here \( d_{\text{min}} \) – minimum code distance, \( R = k/n \) – relative code rate, \( k \) – the number of information characters in the length code vector \( n \).

Known methods for decoding error-correcting codes, which implement the maximum use of the redundancy introduced into the code and provide a higher indicator ECG [9]. In this case, the asymptotic estimate ECG from the use of a block binary code can be the expression:

\[
D_m(k) = 10 \log \left((1 - R + n^{-1})^{\frac{1}{k}}\right) \text{ dB}
\]

(2)

The classical estimate for the extremum of a function of the form \( D_m'(k) = 0 \) results in the expression:

\[
n = 2k - 1
\]

(3)

Therefore, the optimal ratio for \( k \) is the value \( n = 2k \). Then for each symbol from \( k \) there is a replacement for him from \( n-k=r \) symbols, as in the double data transfer. The transition to error-correcting coding inevitably leads to a relation of the form \( k > r \) due to the appearance of algebraic dependencies. In the case when \( k \gg r \), the efficiency of redundant coding is reduced. Thus, in order to achieve simplicity in the implementation of receiver processors to achieve the required level of data reliability under the conditions of using sensor networks, we can admit data repetition or triple repetition. In this case, the maximum effect from the use of a redundant code should not be expected [10].

The synthesis of control system elements, using the principles of remote command transmission, should undoubtedly be based on effective solutions in the field of data transmission over channels of arbitrary physical nature. The most important elements of Diversity Control Systems (DCS) are the forward and backward links. In this case, such DCS are created as interconnected systems of information flow of control signals and telecommunications using a new generation of element base.

Permutation decoding (PD) of \( n \) symbols of the code vector, fixed by the receiver, are selected \( k \) symbols that were least affected by interfering factors. The degree of influence of interfering factors on the symbols of the adopted code combination is determined by soft decisions, which are used to form the reliability assessment. The receiving device encodes these \( k \) symbols by the equivalent code (EC), which is generated on the basis of the main code in accordance with the permutation accepted for production based on the results of sorting and selection. The vector formed in this way is only affected by internal failures of the receive processor, the probability of which is very low.

Therefore, the reliability of the permuted code combination is higher than the reliability of the vector received from the communication channel. A symbol-by-symbol comparison of these vectors leads to the identification of the error vector operating in the DCS link. Obviously, the use of PD makes it possible to use the redundancy introduced into the code with the greatest effect, since it makes it possible to correct errors whose multiplicity is equal to the value \( r \). The PD method is based on the well-known linear properties of block systematic codes [11].

To implement a permutation decoder, an optimized permutation decoding algorithm is proposed in the following form:
• Step 1. There is a fixation of rigid solutions of the reception vector \( V_r \), which in the communication channel was affected by the error vector \( V_e \). The symbol acceptance reliability is estimated using symbol soft decision (SSS) values.

• Step 2. SSS values are sorted in descending order. The symbols corresponding to the SSS values are arranged so that the symbols with the highest values appear in place of the information bits \( \lambda \). Such an arrangement of the most reliable symbols is due to the fact that for group codes the generating matrices in a systematic form have in their composition the identity matrix located on the left.

• Step 3. After ranking the symbols in accordance with the decreasing SSS, bijective transformations are performed \( f: V_r \rightarrow V_p \), where \( V_p \) is a rearranged vector. On their basis, a permutation matrix \( P \) is formed.

• Step 4. In vector \( V_p \), stand out left \( k \) the most reliable symbols and are fixed in the form of a new information vector \( V_{inf}' \).

• Step 5. New information vector \( V_{inf}' \), obtained in the course of the procedures of the fourth step, is multiplied by the generating matrix permuted and reduced to a systematic form \( G'_{sis} \), and the EC vector \( V_{eq} \) is calculated.

• Step 6. The EC vector \( V_{eq} \) is multiplied by the transposed permutation matrix \( P^T \). After this, a reverse bijection is found \( f: V_p \rightarrow V_r \), and an equivalent rearranged vector is obtained \( V_{p}^{eq} \) is obtained.

• Step 7. To calculate the vector \( V_e \), characterizing the impact of errors in the communication channel during the development of rigid vector decisions \( V_r \), the vectors \( V_r \) и \( V_{p}^{eq} \) are summarised.

In the course of the analysis of the classical procedure of permutation decoding, it turns out that the performance of the decoder is significantly reduced due to the performance of matrix calculations. The main disadvantage of the classical permutation decoding procedure is the need to carry it out even when the same permutations are repeated during data processing.

It is possible to eliminate this drawback by optimizing the classical permutation decoding algorithm, which consists in carrying out a cognitive procedure for memorizing the permutations of the columns of the main generating matrix \( G \) group code that form linearly independent key matrices \( Q \). In addition, it is necessary to memorize the corresponding rearranged matrices in a systematic form \( G'_{sis} \).

Such optimization will make it possible to carry out preliminary “training” of the decoder to recognize repeated permutations and, thus, to realize its cognitive functions, which will be executed in the form of the formation of a cognitive map of matrix permutations \( G \). The cognitive map will allow, after the fourth step, to determine if there is a positive decision when decoding \( V_r \) and in its absence, refuse decoding.

To exclude such matrix transformations, during the operational operation of the decoder, each of the possible ordered tuples into its cognitive map \( Z_i \) symbols are assigned its own matrix of the form \( G'_{sis} \) and dimensions \( n \times k \). There can be multiplicity \( \{A\} = C_n^k \times (n-k)k! \) such matrices. In [11], it is proved that the structure of matrices from obeys the laws that make it possible for reference samples (matrices) \( G_p \in G'_{sis} \) using trivial transformations, which are moving rows and columns from \( G_p \), form subsets of the required EC matrices so that \( \{A\} = \{A_1, A_2, ..., A_M\} \). In principle, this allows to
reduce the memory capacity of the cognitive decoder card (CDC) to the number $C^n_k$ reference matrices, while, taking into account the presence of the left identity matrix $E$ in the structure $G_p$, dimension of stored test parts $H$ such matrices becomes equal $(n-k)×k$.

Studies have shown that samples of reference matrices $G_p$ for group codes have a cyclic property that allows you to reduce the CDC volume to a value $R = C^n_k/k$ matrices. Such matrices are called in combinatorics generators of permutation cycles (GPC). Thus, the procedure for reducing the amount of required CDC memory is replaced by the process of sorting the rows and columns of the check part of the matrix GPC. For the Hamming code $(7,4,3)$, the set of all permutations of character numerators combined into cycles is shown in figure 1. The cycle number is indicated by the last digit after the dash in each permutation. Combinations from the number of GPC natrunke are highlighted in bold.

![Figure 1](image_url) Samples of reference matrix numbers in lexicographic format.

It is easy to see that the entries in table 1 are cyclic shifts of combinations, for example, 1234, 2345,...,7123 or in lexicographic format (1237). The reference matrix for all these combinations is the source code matrix $G$. These combinations form an orbit. Our code has five orbits. The forming combination of the orbit is the combination in which the sum of the substitution numerators forms the minimum value.

Each orbit has its own parity check matrix. Checking this condition is required to present the check elements of the ranked code vector in a given cyclic sequence. The cycle orbit number in table 1 for each permutation is shown with a prefix. In this case, there is its own initial check matrix, the structure of which is shown below. Zero orbit EC does not form.

Thus, instead of 28 reference matrices, the cognitive map contains only four types of forming matrices, which, due to elementary permutations, turn into the full set of permuted matrices required for a given code.

In a real data transmission system, the main disadvantage of the method is the impossibility of realizing all possible permutations of symbols of code vectors for binary codes. Some of the permutations related to zero orbits do not allow the formation of equivalent codes. It is important to identify such combinations in a timely manner so as not to waste time processing them. To do this, the CDC must list such combinations in a lexicographic format.

To calculate such permutations in real systems and for large code lengths, it is productive to use the partition of the code vector space into clusters. A cluster can include all combinations that contain several identical bits indicating the cluster number and accompanying elements of the Galois field of some degree of expansion. The field elements are to the left of the cluster number. An important property of such a configuration of cluster numbers is that permutations that do not provide equivalent
codes exactly coincide with combinations that do not provide for the formation of clusters. Using this property, all combinations of zero orbits can be calculated a priori.

A feature of the clustering method is its adaptability to promising data processing methods based on deep learning neural networks. This is important from the point of view of the full use of the correction capabilities of redundant codes in the systems under consideration.

It was found that the full set of matrices for the implementation of PD requires 7 KB of memory, when using the reference matrices, 52 bytes are required. The cognitive map concept would require only 7.5 bytes for the code (7,4,3). After completing the CDC, it receives the status of a clear cognitive map.

4. Results and discussion

To compare the various modes of data exchange and make final recommendations, we highlight four main modes of DCS operation. For convenience, we estimate all modes under conditions when the block of information bits $k = 4$.

First, let's evaluate a system with regular data repetition. It is known that to correct one error, the data must be repeated at least three times. In this case, the parameter $d_{\text{min}} = 3$ and the system is capable of fixing one error. Wherein $n = 12$, and the parameter $R = 0.33$. Let's assign this mode number 1.

Secondly, for some increase in the parameter $R$ we apply the usual data repetition and add parity check to the information bits to correct the erasures. Then it is possible to correct one erasure and $n = 10$, and $R = 0.4$. We will assign number 2 to this mode.

For mode 3, we apply the usual Hamming code, for which $d_{\text{min}} = 3$, $n = 7$, and $R = 0.57$. The classical method of syndromic decoding will be used to process code combinations at the reception.

For mode 4, the usual Hamming code with known parameters is applicable, but the decoding method will be permutation decoding based on the cognitive map.

Figure 2. Comparative characteristics of erroneous data decoding for modes 1, 2, and 3. Figure 3. Evaluating the benefits of permutation data decoding.

The results of analytical modeling of the first three modes are presented in figure 2. Analysis shows that no significant difference between these modes has been identified. The best (as expected) indicators have mode 3, the implementation of which is known and will not cause any particular difficulties. However, the ECG turns out to be negligible. Such a mode in the conditions of constantly changing distances between objects and conditions of signal propagation is not able to provide the required level of data reliability in the system being developed. Figure 3 shows graphs of all four analyzed modes.

The advantages of the fourth mode are obvious. Implementing a PD system using CDC is simple. This is because most matrix operations are performed in the system at the decoder training stage and, based on the simplest linear transformations of the test parts of the generating matrices. It is possible to obtain a combination of EC in a short time, with minimal expenditure of the decoder’s computational resource.
5. Conclusion
The use of sensor networks in the system of mobile grouping vehicles in the course of a certain type of work can provide an agricultural enterprise with a certain commercial gain due to the rational management of the forces and means of the enterprise.

Application of the permutation decoding method makes possible to use the redundancy introduced into the error-correcting code to the fullest extent in the data transmission system and to increase the multiplicity of the errors corrected by the code.

The use of a clear CDC reduces computational costs when searching for generating matrices of the required equivalent codes. At the same time, the use of the method of clustering the space of code combinations of the code makes it possible to quite simply a priori calculate the substitutions of the enumerators of the symbols of code combinations that are not capable of obtaining the corresponding EC, which contributes to an increase in the speed of data processing.

As a hidden resource of the PD system, you should specify the possibilities of indirect adaptation. They consist of short distances between interacting objects of the sensor network, the symbols of code combinations accepted reliably and the procedure for their permutation is practically not required but in conditions of critical distances. PD system begins to play a decisive role. For this reason, the proposed method of increasing the reliability of data is useful not only in the conditions of weak coverage of zone of agricultural enterprises by mobile operators, which is typical for certain regions of Russian Federation but also in the conditions of European Union.

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