Communication channel management system in mechanical engineering

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Abstract. The article proposes new methods for code-division multiplexing of communication channels and a comparative assessment of spectral efficiency of the proposed methods with the known methods. The analysis of channel multiplexing methods for communication systems is carried out and the possibilities of increasing the interference immunity and security of the signal structure under the operation conditions of communication systems in a busy frequency range are considered.

1. Introduction

The issues of ensuring joint operation of various radio-electronic means are currently very relevant and are solved mainly by organizational measures and strict adherence to frequency regulations. One of the promising directions for increasing spectral efficiency of radio communications in an acute shortage of frequency resource is the direction associated with increasing the efficiency of using the already allocated frequency resource. The main mechanism for achieving this goal in this area is the development of new or improvement of known methods of signal multiplexing.

The following basic methods of signal multiplexing are known: time, frequency, time-frequency and code. Each of these methods has its own advantages and disadvantages.

Along with the requirement for high spectral efficiency, communication systems also have such a requirement as their high noise immunity. In works [1, 2] it is shown that the main method of channel multiplexing for communication systems should be considered the code channel multiplexing method, since this method is associated with the possibility of increasing interference immunity and security of the signal structure, as well as with the possibility of their operation in the occupied frequency range.

It is known that code sequences used for multiplexing channels in a radio communication system must have the orthogonality property [1]. Considering that the code sequences are binary, i.e. the elements of the code sequence are symbols (1; -1) or (1; 0) and each code sequence is associated with one binary symbol of the transmitted information, then the following relations are valid, which will be taken into account when justifying new methods of code multiplexing of channels:
\[ \Delta F = \frac{1}{\tau_{\text{эи}}} = \frac{1}{T_{\text{и}}} = \frac{N}{R} = \frac{N}{R\cdot 2^m} = \frac{F}{T}, \]  

(1)

where \( \Delta F \) - frequency band occupied by the signal spectrum (dedicated frequency band);

\( \tau_{\text{эи}} \) - duration of an elementary pulse in the code sequence;

\( T_{\text{и}} \) - duration of the information pulse;

\( m \) - length of the register that forms code sequences;

\( R_k \) – information transfer rate in the channel;

\( N \) – ensemble of orthogonal code sequences formed by a shift register of width \( m \);

\( F \) – pulse repetition rate of the code sequence.

2. Justification of code sequence types recommended for code multiplexing of channels

Several types (varieties) of orthogonal code sequences are known that can be used in advanced code division multiplex communication systems. These are Legendre, Hall, \( M \) - sequences, Gold sequences and others related to linear recurrent sequences. Shift registers with linear feedback are used to generate these sequences. The listed sequences have a number of remarkable properties, but they also have a significant drawback: low structural security due to a small ensemble of signals and ability to reveal the structure of a linear code with error-free reception of \( 2^m \) consecutive elements [3].

Nonlinear code sequences built on the basis of full code rings [3] have higher security. A complete code ring [ibid.] is a code sequence with a period of \( 2^m \), consisting of zeros and ones, in which each combination of length \( m \) occurs only once in the sequence at any cyclic shift.

De Bruijn showed [4] that the maximum number of sequences \( M \) formed by a register with length \( m \) and that is a complete code ring is estimated by the expression

\[ M = 2^{(2^m-1-m)}, \]  

(2)

and in [3, 5] it is shown that on the basis of a complete code ring it is possible to construct an ensemble of orthogonal codes, the volume of which can be determined from the expression \( N = 2^m \).

The results of investigating the correlation properties of full code rings and code sequences formed on their basis, as well as a comparative assessment of the correlation properties of these codes with Gold sequences are given in [3, 5]. It is shown that the correlation and cross-correlation properties of signals from an ensemble of full code rings are even slightly better than the correlation properties of signals from an ensemble of linear codes.

Taking into account these properties of the code sequences, as well as the possibility of obtaining such an ensemble of orthogonal code sequences based on the complete code rings, which are able to satisfy any practical needs, we can consider them as the optimal codes for multi-channel code division communication systems.

Modern communication systems, including those with code division multiplexing, are characterized by low spectral efficiency, which is estimated by the spectral efficiency coefficient \( \varepsilon \), which is the ratio of the information transmission rate in the system (bandwidth) \( II \) to the frequency band occupied by the spectrum of the used signal \( \Delta F \), i.e.

\[ \varepsilon = \frac{II}{\Delta F}. \]  

(3)

The value of the spectral efficiency coefficient \( \varepsilon \) for modern communication systems does not exceed 0.5.

Thus, it is possible to formulate a general task: to develop new methods of code multiplexing of channels, allowing to increase the spectral efficiency of information transmission systems and, as a consequence, to significantly expand the list of provided telecommunication services that require a high speed of information transmission.
3. Development (justification) of methods for code multiplexing of channels
Formulation of the problem.
It is necessary to ensure the transmission of a large number of independent messages over a single frequency path connecting terminal stations. Each message is transmitted over a separate channel at a rate of $R_c$. A group signal is formed from channel signals by the code multiplexing method, which occupies band $\Delta F_{sc}$. It is believed that frequency band $\Delta F = \Delta F_{sc}$ is allocated for the group signal transmission.

It should be noted that the rate of information transmission in the channels of the communication system affects the choice of the method of code multiplexing of the channels. Below two methods of code multiplexing are considered depending on the ratio of the rates in the system channels.

The first method.
Let us assume that the information transfer rate in all channels is the same, i.e. $R_{ci} = R_{cs}$, where $i = 1 \ldots I$; $I$ is the total number of channels in the system.

Using expression (1), we define the parameters that we will take into account when developing a new method of code multiplexing of channels (when creating a new signal-code structure), namely:

- length of nonlinear orthogonal code sequence $N$ is $N = \Delta F/R_c$;
- this sequence can be formed by a shift register with length $m$, $m = \log_2 N$;
- clock frequency of forming a nonlinear orthogonal code sequence $F_t = NR_c$;
- duration of an information pulse of code sequence $T_n = 1/R_c$;
- duration of an elementary pulse in code sequence $\tau = T_n/N$.

The method is as follows (Figure 1):

1. We will divide all used channels into groups. Each group should have no more than $m$ channels, where $m = \log_2 (\Delta F/R_c)$. (4)

2. Let us choose an orthogonal code generator (OCG): the generator should generate $2^m$ orthogonal code sequences; the length of each orthogonal code sequence must include $N$ elementary pulses, the duration of each is $\tau = T_n/N$, $N = 2^m$, and the register capacity must be equal to $m$.

3. Information from the outputs of all information channels of each group at a rate of $R_c$ is fed to the corresponding information inputs of the modulator.

4. Orthogonal code sequences formed by the generator of orthogonal codes are fed from its $2^m$ outputs to the corresponding inputs of the modulator.

5. In the modulator, each code combination consisting of ‘1’ and ‘0’ formed from information pulses is uniquely associated with one of the $2^m$ orthogonal code sequences formed by OCG, depending on the combination of binary symbols at the information inputs, provides a choice and transmitting to its outputs one of $2^m$ orthogonal code sequences.

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**Figure 1.** Block diagram of a device that implements the first method of channel multiplexing
6. Information from the output of the modulator enters the input of the channel group signal spectrum shaper (CGSSS), where it is converted into a signal, the spectrum width of which is $\Delta F$.

7. From the CGSSS output, the signal occupying the $\Delta F$ band is fed to one of the inputs of the channel group signal summarizer (CGSS).

8. In CGSS there is a linear addition of signals from all channel groups in the band $\Delta F$. A new signal-code structure is formed.

The spectral efficiency of the proposed method will be evaluated in the absence of external interference and taking into account expression (3). In the general case, the throughput of known devices $\Pi$ can be defined as the sum of the information transmission rates on all channels, and at the same information transmission rate in each channel, equal to $R_k$, the device capacity is equal to the product of the information transmission rate in one channel $R_k$ by the number of used communication channels $L$. In this case, expression (3) takes the following form

$$\varepsilon = \frac{R_k L}{\Delta F}.$$  \hfill (5)

Taking into account that for the considered devices the signal spectrum width $\Delta F$ is taken equal to the clock frequency of the code sequence formation of signal $F_t$ (see (1)), the value of the signal spectrum width can be written in the following form

$$\Delta F = F_t = L R_k / r,$$  \hfill (6)

where $r$ – code speed.

Then expression (5) considering (6) will have the form

$$\varepsilon = \frac{R_k L}{\Delta F} = R_k L / LR = r.$$  \hfill (7)

That is, in prior art code division multiplex systems, the spectral efficiency is determined by the code rate.

For the proposed code method for multiplexing channels, their number in the system can be determined as [2, 3]

$$L = mL^* = m \left[ \frac{2\Delta F}{\delta h R_k} - \frac{2\Delta F}{\delta h R_k} + 1 \right] \frac{1}{m},$$  \hfill (8)

where $L^* = \lceil x \rceil$, - means the integer nearest part of the number $x$, less than $x$;

$m = 1, 2, \ldots$ - code base (determined by the number of channels in the group), which has the length $l = 2^{i+m-1}$;

$i$ - number of repetitions of the encoder sequence;

$\delta$ - variance of lateral emissions of the normalized cross-correlation function of signals (codes);

$h$ – given signal-to-noise ratio per bit, determined by the required quality of the transmitted information.

Considering that $\Delta F = F_t = l \cdot \frac{R_k}{2 \cdot r}$, a $l = 2^{i+m-1}$, then

$$\Delta F = 2^{i+m-2} \frac{R_k}{r}.$$  \hfill (9)

Taking into account (9), expression (8) will have the following form
Then expression (5) for determining the spectral efficiency of the proposed code multiplexing method, taking into account (9) and (10), will have the following form

\[
\epsilon = \frac{L R_k}{\Delta F} = L \frac{r}{2^{i+m-2}}.
\]  

Let us determine the numerical value of the spectral efficiency coefficient \( \epsilon \) for the known methods and the proposed method for certain values of the variables \( \delta, h, i, m, r \).

It is known that for orthogonal sequences the numerical value \( \delta \approx 0.44 \) [3, 5], and the signal-to-noise ratio \( h \) for the biorthogonal code (16, 5, 8), provided the probability of error per bit is equal to \( 10^{-3} \), should be equal to 2.6 [7, 8]. The value of \( r \) for the selected code for the proposed method is 6/32, and for the known ones - 0.5. Let’s take \( i = 1 \) and \( m = 6 \).

Then the value of the coefficient of spectral efficiency \( \epsilon \) with these data for the proposed method will be equal to 1.65, and for the known methods 0.5. That is, the spectral efficiency of the claimed method is 3.3 times higher.

Second method. Let the information transfer rate in the channels be different and equal to \( R_{k1}, R_{k2}, R_{k3} \). Moreover, let \( R_{k1} > R_{k2} > R_{k3} \).

The method is as follows (Figure 2):

1. All available information channels (IC) are divided into groups. Moreover, the group is combined into channels only with the same information transfer rate.
2. Determine the clock frequency of the generators of orthogonal codes of channel groups \( F = \Delta F \).
3. Determine the length of the nonlinear orthogonal code sequence of the orthogonal code generator for each channel group \( N \):
   - for a group of channels with speed \( R_{k1}, N_{k1} = F_s / R_{k1} \);
   - for a group of channels with speed \( R_{k2}, N_{k2} = F_s / R_{k2} \);
   - for a group of channels with speed \( R_{k3}, N_{k3} = F_s / R_{k3} \).

**Figure 2.** Block diagram of a device that implements the second method of channel multiplexing.
4. Determine the capacity of the orthogonal code generator register for each channel group $m$:

- for a group of channels with speed $R_{k1}$, $m_{k1} = \log_2 N_{k1}$;
- for a group of channels with speed $R_{k2}$, $m_{k2} = \log_2 N_{k2}$;
- for a group of channels with speed $R_{k3}$, $m_{k3} = \log_2 N_{k3}$.

5. Determine the maximum possible number of channels in each group $L = 2^{m_{k1}}$.

6. We determine the number of groups of channels $P$, which can be organized in the proposed way. According to works [2, 3], one can write

$$ P = \left\lfloor \frac{L}{\delta rh} \right\rfloor + \left\lfloor \frac{L}{\delta rh} \right\rfloor + 1, $$

(12)

where $[x]$ - means the integer nearest part of the number $x$, less than $x$;

- $L$ – maximum number of channels in a group;

- $h$ – given signal-to-noise ratio per bit, determined by the required quality of the transmitted information;

- $\delta$ - variance of lateral emissions of the normalized cross-correlation function of signals (codes).

7. Information from the output of each information channel (in each channel group with its own rate $R_k$) is fed to its own (channel) signal spectrum shaper (SSS), which converts it into a signal that occupies $\Delta F$ spectrum.

8. From the output of SSS channel, the signal occupying band $\Delta F$ is fed to one of the inputs of the channel signal summarizer (CSS). In CSS there is a linear addition of all signals of the channels of the channel group in band $\Delta F$.

9. From the CSS output, signals of the channel group are fed to one of the inputs of the channel group signal summarizer (CGSS). In CGSS there is a linear addition of the signals of all channel groups in the frequency band $\Delta F$. A new signal-code structure is formed.

Let us assess the spectral efficiency of the proposed method in comparison with the known ones. Let’s make an assessment in the absence of external interference.

1. It has been established above that in the known systems with code division multiplexing the spectral efficiency of the system is determined by the code rate $r$ (see expression (7)).

2. For the proposed method, the expression for assessing spectral efficiency has the form [6]

$$ \varepsilon = \frac{2}{\Delta F} = 2r \cdot \left( \frac{2}{\delta rh} + \frac{2}{\delta rhL} \right) + 1. $$

(13)

Let us determine the numerical value of the spectral efficiency coefficient $\varepsilon$ for the proposed device at certain values of the variables $h, r, L, \delta$.

It is known [3, 5] that for orthogonal sequences the numerical value $\delta \approx 0.44$. Let us take $L = 64$, and the signal-to-noise ratio for the biorthogonal code (16, 5, 8) with the provision of the error probability per bit equal to $10^{-3}$, according to [7] $h = 2.84$. The rate of the selected code $r = 5/16$. Then the value of the coefficient of spectral efficiency $\varepsilon$ with these data will be equal to 1.875. Comparing the values of the spectral efficiency coefficients of the above method and the known methods, it is easy to establish that the considered method is 3.75 times superior in efficiency.

4. Conclusions

1. In communication systems of mechanical engineering in conditions of acute shortage of frequency resource, it is advisable to use the method of code multiplexing of channels based on nonlinear code sequences obtained based on full code rings.
2. The proposed methods for code multiplexing of channels based on nonlinear code sequences obtained based on full code rings make it possible to increase the spectral efficiency of promising communication systems in comparison with the known ones by more than 3 times.

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