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Analysis of pseudo noise sequences for multi channel distance measurements

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Introduction

Pseudo noise sequences (PN) now are widely used in telecommunications and for measurement purposes. For example, they have found application in ultrasonic non-destructive testing [1, 2, 3]. Usually the main purpose is to improve signal to noise ratio still keeping a good spatial resolution. In recent years such sequences are also used in code division multiple access telecommunication systems [4-8]. It has been proposed to apply PN sequences for improvement of data acquisition rate in ultrasonic measurement systems [9]. This approach is based on simultaneous measurements in spatially overlapping channels using quasi-orthogonal PN sequences [10]. The main problem, met in employment of this type of signals for distance measurements is the difference of quality requirements between signals used in telecommunications and measurement systems [1, 11]. Therefore it is not clear how well the criteria used for synthesis of PN codes in telecommunications are suitable for measurement purposes.

The main objective of this investigation is a comparative analysis of various optimisation criteria of PN code sequences that could be used in ultrasonic measurement systems. The main goal of such optimisation should be a family of optimal PN sequences fulfilling the requirements listed below. In this paper the results of investigation of four types of PN family codes are presented: Gold, large Kasami, short Kasami and M-sequences. Other well-known code sequences were not analysed due to several reasons: some of them are only used in telecommunications and they are not suitable for distance measurements. Other sequences, such as FEEDFORVARD [5], are difficult to generate.

Optimisation methods and criteria

In this paper requirements to PN code sequences are formulated from the point of view of distance measurements till many reflectors. These measurements may be performed from a few different fixed points. If the measurements are carried out simultaneously, interference in neighbouring channels must be as low as possible. It means that the signals used for this purpose must belong to the family of orthogonal or quasi-orthogonal signals at the same time providing a good spatial resolution.

In order to fulfil these requirements the used quasi-orthogonal signals must possess the following features:

1. Narrow peak of the auto correlation function;
2. Maximum absolute value of sidelobes is close to zero;
3. Cross correlation function between any randomly selected codes is close to zero;
4. Sequences should be as short as possible, but still meeting the listed requirements;

The first two requirements enable to obtain a good spatial resolution. With respect to the width of the main peak of the auto correlation function all environments may be classified into two main types:

1. With dense reflectors;
2. With sparse discrete reflectors.

If the distance between adjacent reflectors is less than the peak width, then the reflectors are dense, in the opposite case they are supposed to be sparse reflectors. As it will be shown later, the performance of the same code sequence may be different in different types of environments.

The third requirement enables to obtain a low level of an interference noise, caused by simultaneously transmitted coded signals.

For multi-channel distance measurements it is necessary to find the set of PN sequences, fulfilling the above-described requirements.

Features of PN sequences depend on the discrete phase hops, which occur in a certain order in the selected sequence. For generation of the PN sequences, which have the above-described features, a few different optimisation criteria may be used.

One common method for selecting codes is to search for a set or a family of sequences in which the maximum absolute values of the side-lobes of the even (periodic) auto correlation function and cross correlation function Q_a, Q_c are relatively small (e.g. Gold codes) with a hope to find a subset in which the maximum values of odd functions Q_a, Q_c are also small. The ultimate goal is to minimize the parameters $\widehat{Q}_a, \widehat{Q}_c$ by finding the best phase – shift combination for each of the K sequences in a set ($\widehat{Q}_a$ and $\widehat{Q}_c$ does not depend on phase shift). In [4] and [5] criteria where proposed to optimise the odd auto correlation function. It is commonly believed that by minimizing the maximal side-lobe value of the odd auto correlation function and the aperiodic side-lobe energy of each sequence for a set of K sequences, the signal to noise ratio is improved.

Let us analyse the auto optimal/least side-lobe energy (AO/LSE) criterion. The main aim of this optimisation criterion is to minimize the maximum absolute value of side-lobes of auto correlation function.

The maximum side-lobe of the odd auto correlation function of sequence x is given by:

$$\widehat{M}(x) = \max\{|\widehat{Q}_x(l)|: \quad 1 \le l < p\} \tag{1}$$

It is desirable to make side- lobes as small as possible. Let us by $\widehat{Q}_{AO}(x)$ denote the minimum value of $\widehat{M}(T^n x)$, where the minimum is over all the phases n of the sequence x, $0 \le n \le p$, and T^n is the discrete phase – shift operator. Typically there exist more that one phase – shift at which the minimum is achieved. Therefore, it is useful to consider the number of times when $\widehat{Q}(T^n x)(l)$ achieves its maximal value, e.g. the number of side-lobe peaks. For a sequence u let $\widehat{L}(u)$ be the number of values l, $1 \le l < p$, for which $\widehat{Q}(u)(l) = \widehat{M}(u)$. A phase n of the sequence x is an auto optimal (AO) phase, if $\widehat{M}(T^n x) = \widehat{Q}_{AO}(x)$ and if $\widehat{L}(T^n x) \le \widehat{L}(T^k x)$ for all phases k for which $\widehat{M}(T^k x) = \widehat{Q}_{AO}(x)$. In order to determine $\widehat{Q}_{AO}(x)$ for a given sequence x, the odd auto correlation function for $T^n x$, $0 \le n < p$, must be computed for each n. Since, in general, the auto optimal phase is not unique, auto optimality can be further refined by considering those auto optimal phases of the odd auto correlation function which corresponds to the least side-lobe energy (LSE) of the aperiodic auto correlation function. Eq.2 means that the odd sidelobe energy reaches its minimum when the aperiodic sidelobe energy reaches its minimum:

$$\sum_{k=1}^{p-1} |Q_i(k)|^2 + \sum_{k=1}^{p-1} |\widehat{Q}_i(k)|^2 = 4\sum_{k=1}^{p-1} |C_i(k)|^2 \tag{2}$$

where $\widehat{Q}_i(k)$ is the odd auto correlation function, $Q_i(k)$ is the even auto correlation function and $C_i(k)$ is the aperiodic cross correlation function.

The phase n of a sequence x is optimal with a least side-lobe energy (AO/LSE) if it is auto optimal and if the side-lobe energy $S_x(T^n x) \le S_x(T^m x)$ for all auto optimal phases m. In contrast to the non-uniqueness of auto optimal phases, the AO/LSE phase is, in most cases, unique.

The average interference parameter $r_{i,j}$

$$r_{i,j} \le 4p^2 + 6\sqrt{S_i S_j} \tag{3}$$

is minimised if the sidelobe energies of sequences i and j are minimised also. Here:

$$S_i = \sum_{k=1}^{p-1} C_i^2(k) \tag{4}$$

is the aperiodic auto correlation function of the sequence i,

$$S_j = \sum_{k=1}^{p-1} C_j^2(k) \tag{5}$$

is the aperiodic auto correlation function of the sequence j.

That's why it is reasonable to emphasize the sidelobe energy parameter instead of the peak sidelobe [10].

Hence, it is of interest to determine, at first, the least aperiodic sidelobe energy phases of a sequence x. The search for some sequences with phases n and m which fulfil the requirement $S_x(T^n x) = S_x(T^m x) \le S_x(T^k x)$ for all k is performed. Only those LSE phases, for which the minimum level of side-lobes $\widehat{M}(x)$ is obtained, are considered and these are referred to as being auto optimal among the set of least sidelobe energy phases.

If the order of the above mentioned optimisation steps is reversed then another criterion LSE/AO is obtained. The main aim of this criterion is to minimize the maximum absolute value of sidelobes of autocorrelation function.

More than ten years ago after definition of AO/LSE and LSE/AO criteria, a third optimisation rule called the maximum sidelobe energy auto optimal (MSE/AO) criterion was proposed [10]. It is based on the observation that the lower bound in

$$p^2 - 2\sqrt{S_i S_j} \le \mu_{i,j}(0) \le p^2 + 2\sqrt{S_i S_j} \tag{6}$$

where:

$$\mu_{i,j}(n) = \sum_{k=1-p}^{p-1} C_i(k) C_j(k+n) \tag{7}$$

is minimized if the aperiodic sidelobe energy possesses its maximum value. The exact definition of the MSE/AO criterion is analogous to the definition of the LSE/AO criterion, except that the minimization of the sidelobe energy is replaced by maximization. The MSE/AO rule, although auto optimal, produces an odd auto correlation function with large sidelobes. The main aim of this optimisation criterion is to maximize the maximum absolute value of sidelobes of autocorrelation function.

The basic problem in the use of inequalities Eq.3 and Eq.6 is that it cannot be guaranteed that the LSE/AO AND MSE/AO criteria really results in a minimized average interference parameter value. It is known that the auto correlation and cross correlation parameters are not independent [5]. Better auto correlation properties can be obtained at the expense of worse cross correlation properties, and vice versa. From the academic point of view, it is interesting to know how much advantage in the signal to noise ratio could be obtained, compared with the criteria discussed in the preceding section, if the mean square cross correlation (MSQCC) values between the reference code and the remaining codes in a set are minimized in addition to the maximum magnitudes of the odd cross correlation function [5].

There are two options for optimisation, namely, the cross optimal mean square cross correlation (CO/MSQCC) and mean square cross correlation cross optimal (MSQCC/CO) criteria.

The main aim of the CO/MSQCC optimisation criterion is to minimize the maximum absolute value of cross correlation function.

The maximum correlation magnitude of the odd cross correlation function between sequences x and y is defined as :

$$\widehat{M}(x,y) = \max\{|\widehat{Q}_{x,y}(l)|: \quad 0 \le l < p\} \tag{8}$$

In the case of the multi channel distance measurements it is desirable to make the odd cross correlation function value as small as possible. Let by $\hat{Q}_{CO}(x,y)$ denote the minimal value of $\hat{M}(x,T^n y)$, where the minimum is over all relative phase-shifts n between sequences x and y, $0 \le n < p$. The phase of the sequence x is kept fixed and the phase of the sequence y is shifted with respect to x. As in the case of the auto correlation function, there exist more that one phase shift at which the minimum is achieved. Therefore, it is useful to consider the number of times $\hat{Q}(x,T^n y)(l)$ achieves its maximal value. For sequences u and v let $\hat{L}(u,v)$ be the number of values l, $0 \le l < p$, for which $\hat{Q}(u,v)(l) = \hat{M}(u,v)$. The shift n between sequences x and y is the cross-optimal (CO) phase, if $\hat{M}(x,T^n y) = \hat{Q}_{CO}(x,y)$ and if $\hat{L}(x,T^n y) \le \hat{L}(x,T^k y)$ for all phases k for which $\hat{M}(x,T^k y) = \hat{Q}_{CO}(x,y)$. In order to determine $\hat{Q}_{CO}(x,y)$ between sequences x and $T^n y$, the odd cross correlation function must be computed for each n, where $0 \le n < p$. Since the cross optimal phase is not unique, cross-optimality is further refined by considering those cross optimal phases of the odd cross correlation function which correspond to the minimum square sum cross correlation (MSQCC) value of the aperiodic cross correlation function. The following abbreviations are defined:

The phase n between sequences x and y is cross-optimal with a minimum square sum (or mean square) cross correlation value (CO/MSQCC) if it is cross optimal, and it the $S_{ap}(x,T^n y) \le S_{ap}(x,T^m y)$ for all cross optimal phases m. The $S_{ap}(x,y)$ and $S_{od}(x,y)$ are given by

$$S_{ap}(x,y) = \sum_{k=1-p}^{p-1} C_{x,y}^2(k) \quad , \quad S_{od}(x,y) = \sum_{k=0}^{p-1} \hat{Q}_{x,y}^2(k) \tag{9}$$

In contrast to the non-uniqueness of cross-optimal phases, the CO/MSQCC phase is in most cases unique.

The CO/MSQCC criterion emphasizes more the peak correlation value that the mean square value. It can be concluded that the emphasis of the mean square cross correlation parameter instead of the peak correlation might be beneficial in order to reduce the total amount of interference parameter [7]. Hence, at first, it is of interest to determine the phase corresponding to the minimum square sum cross correlation value between sequences x and y. As before, there may appear links with some sequence pairs (i.e. phases n and m for which $S_{ap}(x,T^n y) = S_{ap}(x,T^m y) \le S_{ap}(x,T^k y)$ for all k). Therefore, only those MSQCC phases that have the minimal $\hat{M}(x,y)$ are considered and these are referred to as being cross-optimal among the minimum square sum cross correlation phases. If the order of the above mentioned optimisation steps is reversed then another criterion MSQCC/C is obtained.

Description of the modelling tool

Two computer programs have been developed for analysis of the synthesised PN sequences. The first program performs the optimisation of PN and places the optimised PN sequence into a database. For optimisation the criteria discussed above were used. The second program uploads the PN sequence from the database and performs its analysis according to the tasks described below. The structure of modelling software is shown in Fig.1. This program was written using Matlab 5.3.

In the first stage the family group of PN sequences must be selected according to the given length of the sequence and the optimisation method. During the next step the analysis of the PN sequences is performed. There are several ways for performing PN analysis:

1. Analysis of auto correlation functions of PN sequences. The purpose of this analysis was determination of the shape and evaluation of the maximal level of side-lobes of the auto correlation function.
2. Analysis of cross correlation functions of different PN codes in the family of synthesised sequences. The purpose of this procedure is to find the set of the PN codes with the lowest cross correlation.
3. Estimation of the possibility of extraction of the specified PN sequence from the mixture of a few partially or completely overlapping received coded signals.

The low cross correlation between different codes in the selected family is essential for obtaining a low interference noise. Analysis of cross correlation functions enables to judge about suitability of the synthesised codes for multi-channel measurements. Extraction of the necessary code from the mixture of the signals was analysed for a few different situations:

- Extraction of the required code from a mixture of PN sequences randomly distributed in the given time interval. The amplitudes of all signals are the same.
- Extraction of the required code from a mixture of PN sequences randomly distributed in the given time interval with random amplitudes.

These two cases were modelled adding the selected number of PN sequences, which were randomly allotted in the time domain. The case with random amplitudes is very close to the situation, characteristic for a sonar used for navigation of mobile robots.

Modelling results

Auto correlation properties of PN sequences:

Modelling results for the Gold and large Kasami sequences are presented in Fig.2-7. It is very difficult to say that some optimisation methods are better than other. As an example, the auto correlation functions of PN sequences optimised by the same metho (MSQCC/CO) and within the same family group (Gold) are presented in Fig. 2, 3 and 4. It is easy to see that they are significantly different. The level of side-lobes is different, even if their energy is on the same level. Auto correlation function, shown in Fig.4, illustrates that optimisation of the same PN family by the same method can give significantly different results. Fig. 5 shows the correlation functions of the same family group PN sequences, but optimised by the different method (MSE/AO). This method gives a much higher level of side-lobes than in the previous three cases.

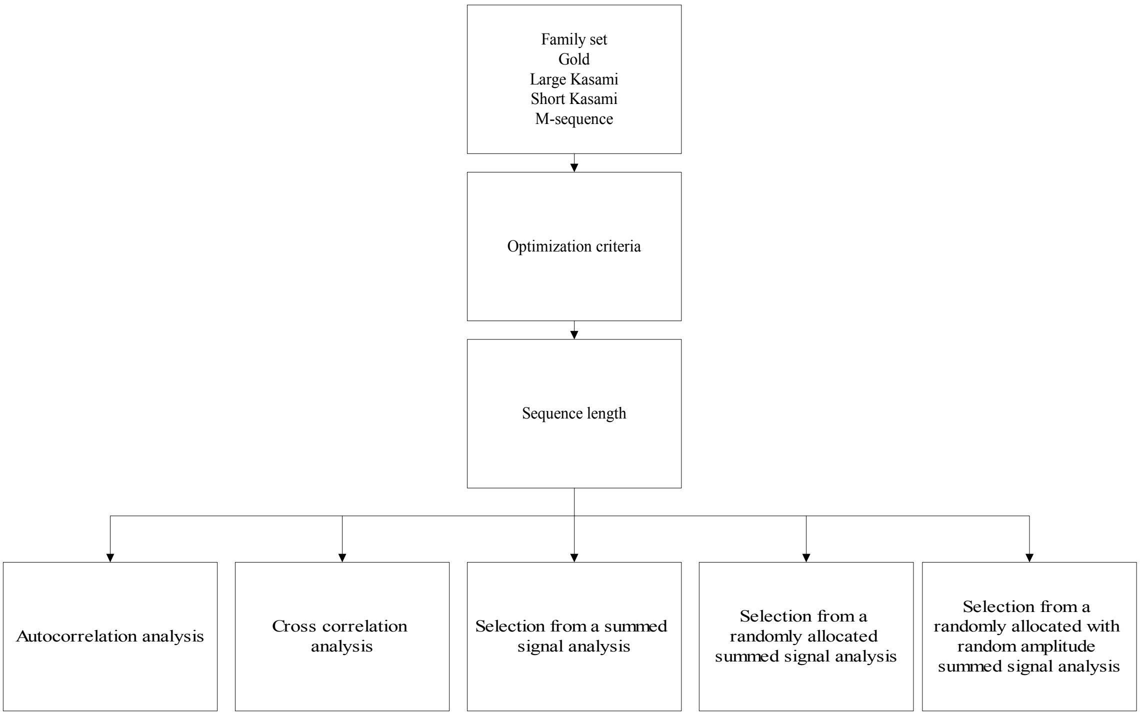


Fig. 1**. Structure of the modelling program**

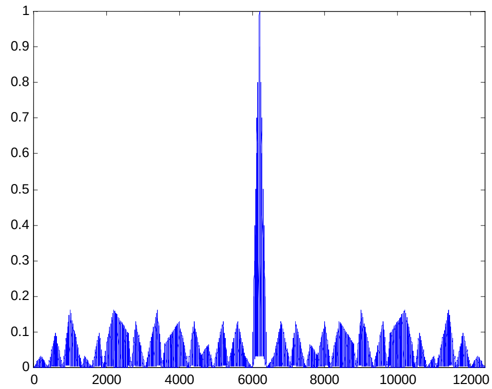


Fig. 2 **Auto correlations function of the Gold PN sequence Nr. 33 (Optimisation criterion MSQCC/CO, the sequence length 31**)

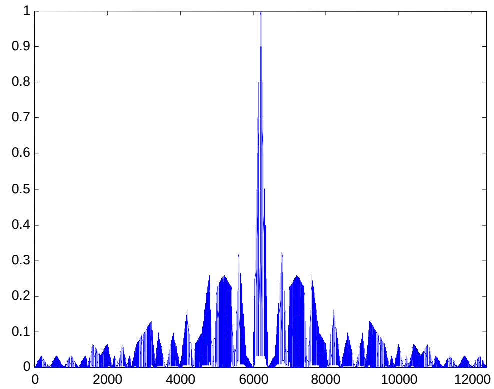
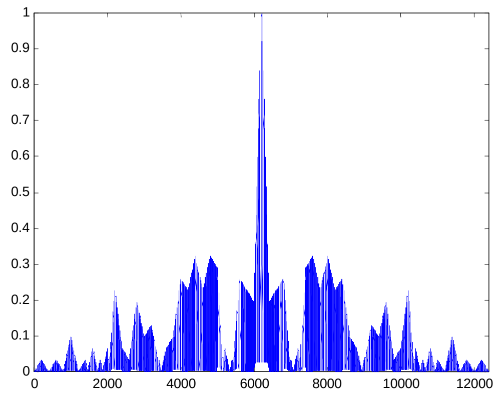


Fig.3 **Auto correlation function of the Gold PN sequence Nr. 31 (Optimisation criterion MSQCC/CO, the sequence length 31)**



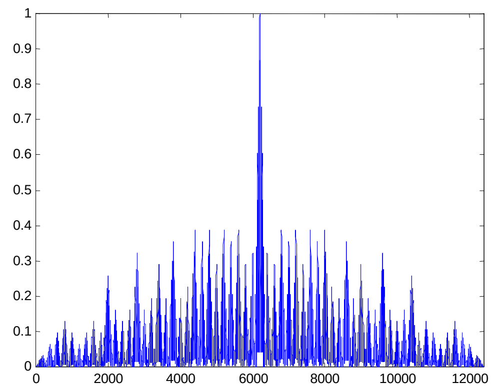


Fig. 4. **Auto correlation function of the Gold sequence Nr. 6 (Optimisation criterion MSQCC/CO, the sequence length 31)**

Fig. 5 **Auto correlation function of the Gold sequence Nr. 21 (Optimisation criterion MSE/AO, the sequence length 31)**

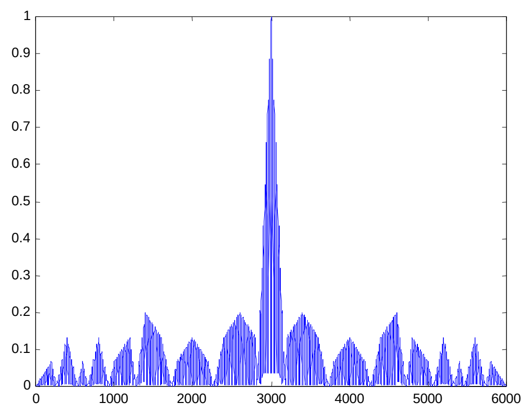


Fig. 6 **Auto correlation function of the Large Kasami PN sequence Nr. 12 (Optimisation criterion MSQCC/CO, the sequence length 15)**

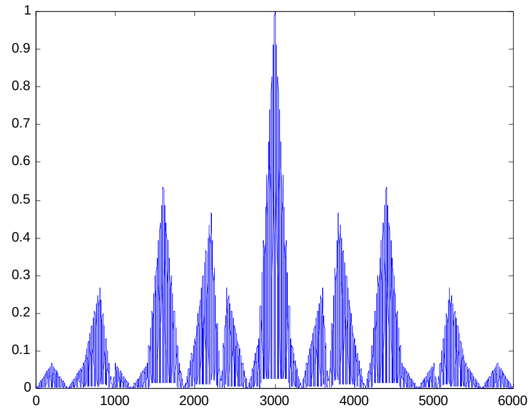


Fig. 7 **Auto correlation function of the Large Kasami PN sequence Nr. 2 (Optimisation criterion MSE/AO, the sequence length 15)**

Actually, the PN sequences shown in Fig. 2 and 3 can be used for distance measurements, because they have quite a low level of sidelobe energy, but they can be exploited for reaching different goals. The first sequence can be used for measurements of the distance to densely located targets. The second sequence can be used for measurements of distance to sparse targets, because the level of the side-lobes in the vicinity of the central peak is quite high, but it is decreasing at further distances from the central peak.

Here we can make a conclusion that it is expedient to analyse not only transmitting, but also receiving part of a distance measurement system, in order to optimise not only the coded signals, but also their reception and filtration. The most efficient would be the smart distance measuring system, which could scan the environment in the first stage and then, depending upon the location of targets, could choose the most suitable PN signal.

The auto correlation functions of the large Kasami PN family-signals are shown in Fig. 6 and 7. They significantly differ not only from the above mentioned functions, but also between themselves.

In other words, the analysis of auto correlation functions of the PN sequences optimised by different methods shows that it is really difficult to decide which method is better or worse. Actually, the PN optimisation method MSE/AO is not suitable for achieving above described tasks, because this method generates PN sequences with a maximum energy and at the same time a highest level of side-lobes.

Cross correlation properties of PN sequences

Analysis of cross correlation functions of PN sequences was performed with the purpose to evaluate interference between two simultaneously received PN signals. Two typical cases are presented in Fig. 8 and 9. In Fig. 8 the maximal cross correlation values between any two coded sequences, arbitrary selected from the 33 Gold sequences, optimised using the MSQCC/CO criterion, are presented. The cross correlation was calculated for each sequence with each sequence in the selected set. The maximal value equal to 1 is obtained when the particular sequence is correlated with itself; e.g., auto correlation function is calculated. In Fig.8 these values are indicated

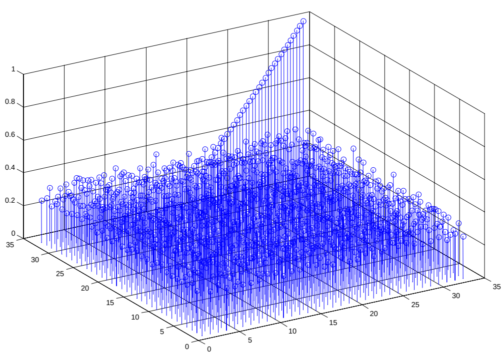


Fig. 8. **Cross correlation of the Gold sequences (Optimisation**

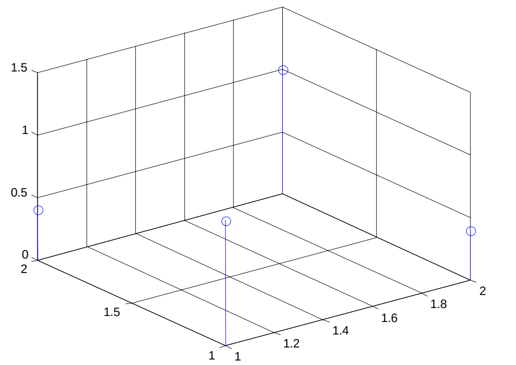


Fig. 9. **Cross correlation of the M sequences (Optimisation**

criterion MSQCC/CO, the sequences length 31)

criterion MSQCC/CO, the sequences length 15)

along a diagonal direction. The average maximum cross correlation value for any other combination is about 0.2.

The cross correlation function between two M-sequences optimised using the MSQCC/CO criterion is presented in Fig. 9. In this case the maximal cross correlation value is close to 0.5.

Hence, it is possible to conclude that for PN family-groups, optimised by the same methods, maximal value of the cross correlation functions is practically the same. The variations are within limits of a few percents, but as it is shown in Fig. 8 and 9, very depends on a sequence family and the sequence length.

Extraction of the PN sequence the mixture of a few signals

During the simultaneous distance measurements in different directions reception of the signals is complicated by other signals, reflected or propagating in other channels. That's why it is important to analyse the situation, in which it is possible to extract the required code from a mixture of a few PN signals.

In this analysis several PN sequences from the same family-group and of the same length were added. Two different composite signals obtained in such a way are shown in Fig. 10 and 11. In Fig. 10 the signal, obtained after adding of two M-sequences is presented. In this case it is possible to select from the composite signal any of these two signals (Fig. 11 and 13).

In Fig. 11 the mixture of fifteen randomly selected PN sequences is presented. It is clear that from such a kind of signal it is impossible to extract any PN. That indicates why it is important not only to optimise the PN sequences, but also to exploit directed transmitters and receivers in order to minimize crosstalks in closely located channels.

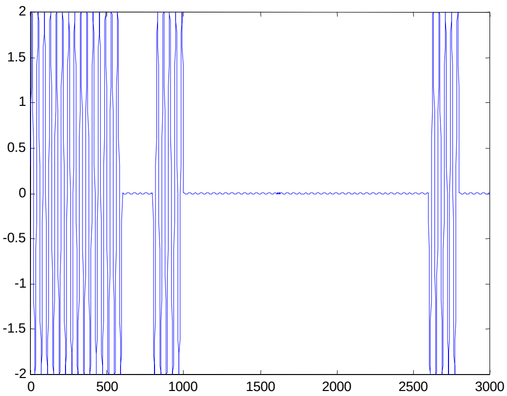


Fig.10. **Summed signal of 2 M sequences (Optimisation criterion CO/MSQCC, the sequences length 15)**

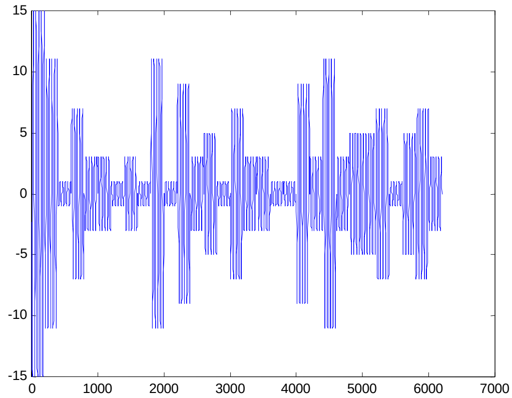


Fig.11**. Summed signal of the 33 Gold sequences (Optimisation criterion MSE/AO, the sequences length 31)**

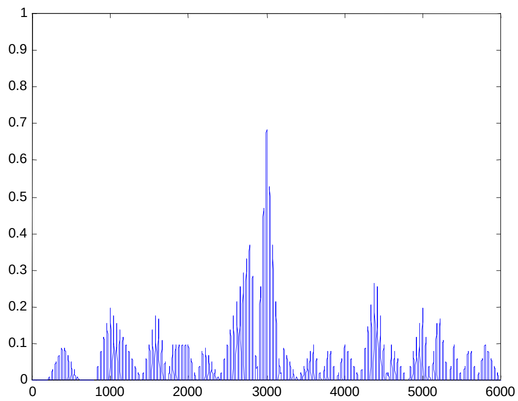


Fig. 12. **M sequence extraction from the summed up signal (Optimisation criterion MSQCC/CO, the sequence length 15)**

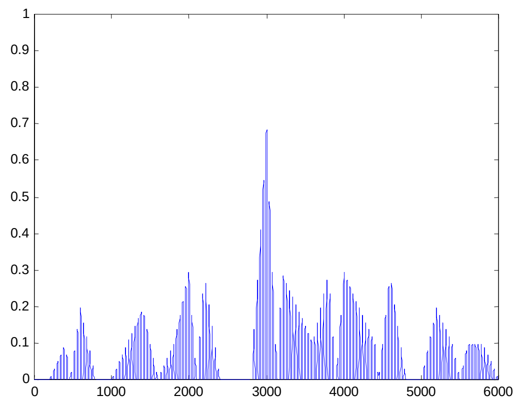


Fig. 13. **M sequence extraction from the summed up signal (Optimisation criterion MSQCC/CO, the sequence length 15)**

Also, it is possible to make a conclusion that it is expedient to determine a limit of number and types of PN signals, which can be simultaneously used in multi-channel measurement systems.

Extraction of the PN sequence from the mixture of a few coded signals.

As it was mentioned earlier, in the process of simultaneous distance measurements till several different targets, the received signal is a sum of several PN sequences. First of all we shall analyse the case when the received signal consists of the different PN sequences with random delays.

Such a signal was simulated in the following way. The time interval used for modelling was chosen a few times longer than the period of PN sequence. Afterwards, the PN sequences of the same type and the same length in a random order were allotted in time and summed. From this mixture we have tried to extract the chosen PN signal by means of the correlation processing.

Two examples of such summed signals are shown in Fig 14 and 15. The same problem as described before is met also in this case. The results of the correlation processing are presented in Fig. 16 and 17. Fig. 16 shows the case, when extraction of the necessary PN sequence from the summed up signal is very good. Fig. 17 illustrates the case, when it is almost impossible to extract the necessary PN sequence from the mixture of the signals. This confirms the conclusion that it is expedient to use in multi-channel distance measuring systems not only optimised PN sequences, but also receivers with high spatial directivity. This allows to avoid the influence of PN signals propagating in adjacent measurement channels and to improve selection of a necessary signal.

It is very difficult to conclude which PN family group is the best from the point of view of their extraction from the mixture of few coded sequences, because it depends very much upon the length and the number of simultaneously received PN sequences.

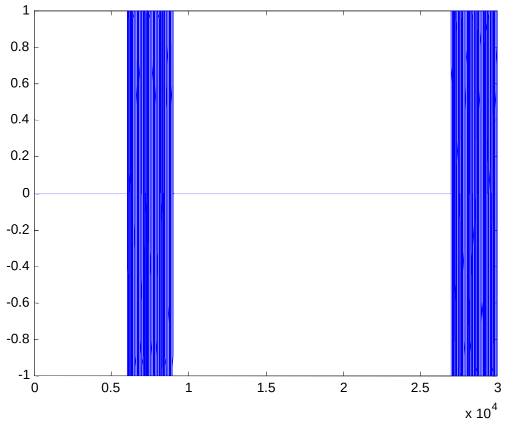


Fig. 14. **Summed signal of the two M sequences (Optimisation criterion CO/MSQCC, the sequences length 15)**

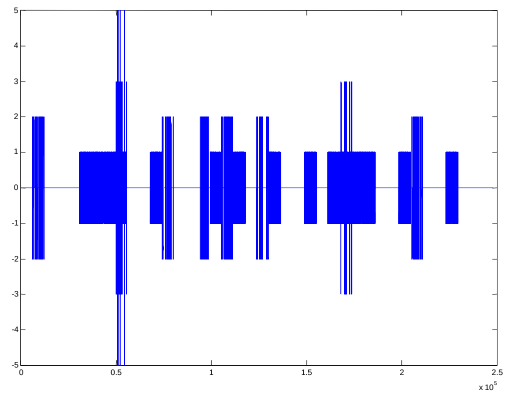


Fig. 15. **Summed signal of the 31 Gold PN sequences (Optimisation criterion MSQCC/CO, the sequences length 31)**

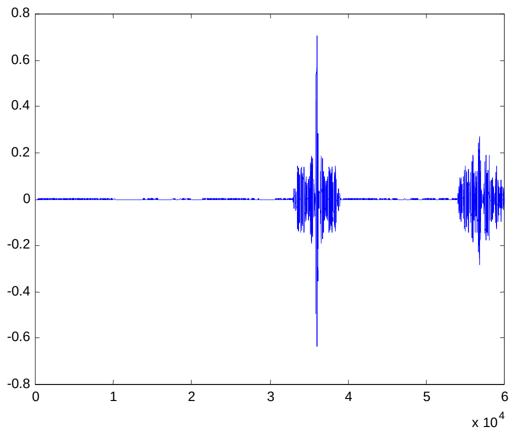


Fig. 16. **Cross correlation between M-sequence and the summed signal (Optimisation criterion MSQCC/CO, the sequence length 15)**

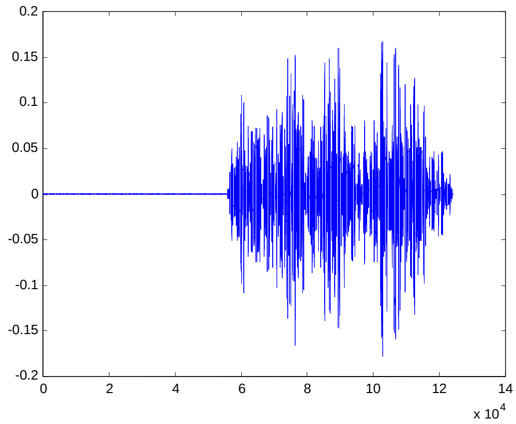


Fig. 17. **Cross correlation between Gold PN sequence and the summed signal (Optimisation criterion CO/MSQCC, the equence length 31)**

Conclusions

In this investigation several thousands of different coded sequences were analysed. From the computer modelling follows that it is quite complicated to answer which optimisation method and which PN family group is the best because of a big spill of PN parameters. However, it is clear that the optimisation method MSE/AO is not suitable for achieving the above-mentioned targets.

It is not worth to optimise the PN sequences, which have number of elements more than 255, because a computation burden is too big. On the other hand, such PN sequences, practically cannot be used in ultrasonic distance measurement systems.

The optimisation results very depend on the type of the chosen sequence family and its length.

The minimal absolute value of side-lobes of auto correlation function is achieved using the MSQCC/CO and AO/LSE optimisation criteria. Minimal absolute value of a cross correlation function between randomly selected codes is obtained by means of the CO/MSQCC optimisation criterion.

The minimal absolute value of side-lobes of an auto correlation function is obtained for the Gold and the Large Kasami sequences. Correspondingly, the minimal absolute value of a cross correlation function is achieved using the Gold and the Small Kasami sequences.

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Pseudotriukšminių kodinių sekų, skirtų daugiakanaliams atstumo matavimams, analizė

Reziumė

Daugiakanalėse atstumo matavimo sistemose naudojant kodines sekas, galima tuo pat metu atlikti atstumo matavimus daugeliu krypčių. Tai gerokai supaprastina daugiakanalę atstumo matavimo sistemą ir paspartina matavimus. Šiose sistemose naudojamoms kodinėms sekoms taikomi tokie kokybiniai kriterijai kaip siaura autokoreliacinė funkcija, žemas šoninių lapelių lygis, tarpusavio koreliacijos funkcija artima nuliui, kiek įmanoma trumpesnės sekos. Matavimams reikalingas kvaziortogonaliųjų kodinių sekų rinkinys, tenkinantis išvardytus reikalavimus. Kodinių sekų analizei sudaryta kompiuterinė programa, kuri leidžia parinkti kodines sekas, atitinkančias nurodytus kokybinius kriterijus, ir analizuoti gautus sekų parametrus. Šia programa atlikto kompiuterinio modeliavimo rezultatai rodo, kad ne visi optimizavimo kriterijai duoda siekiamą rezultatą. Beveik visada gaunama gana didelė rezultatų sklaida, o kai kurie optimizavimo kriterijai visiškai netinka kodinėms sekoms, tinkamoms daugiakanalėms atstumo matavimo sistemoms, optimizuoti.

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