

Method of Generating a Frequency-Hopping
Sequence Using Concatenated Codes, as well as Radio
Facility and Radio Communication System Therefor

This invention relates to a method of generating a frequency-hopping sequence wherein different codes are concatenated, and to radio facilities which are in radio communication with one another within a radio communication system and which periodically change between a plurality of different carrier frequencies in accordance with such a frequency-hopping sequence. Such radio communication systems are known, for example, from public mobile radio, where radio transmission is carried out using frequency-hopping techniques to improve the quality and interference immunity of the radio transmission.

In a paper by D. V. Sarwate entitled "Optimum PN Sequences for CDMA Systems", published on pages 53-78 of the book "Code Division Multiple Access Communications", edited by S. G. Glisic and P. A. Leppänen, 1995, Kluwer Academic Publishers, Boston/Dordrecht/London, it is described that by a concatenation of two codes, namely a Lempel-Greenberger code and a Reed-Solomon code, a frequency-hopping sequence with optimal Hamming correlation properties is obtained. By this known method, however, only few different sequences can be generated, namely only as many different sequences as corresponds to the number of code elements. If, for example, a code with

$n=8$ elements is chosen, only 8 different sequences can be generated. In addition, the alphabet size (number of carrier frequencies) must be a power of 2, i.e., the alphabet size can take on the values 2, 4, 8, 26, etc.

The Lempel-Greenberger code is known per se from an article by A. Lempel and H. Greenberger entitled "Families of Sequences with Optimal Hamming Correlation Properties", published in the journal "IEEE Transactions on Information Theory", Vol. IT-20, No. 1, January 1974. There it is stated that the Lempel-Greenberger code can be generated by means of a linear feedback shift register in which outputs are taken successively from all shift-register elements in the feedback loop to generate a pseudorandom sequence with favorable Hamming correlation properties. However, if a Lempel-Greenberger code is used to generate a frequency-hopping sequence, sections may occur within the frequency-hopping sequence in which one and the same carrier frequency appears several times in succession. This means that prolonged sections may occur which do not contain any "hops", which counteracts the effect of the hopping, namely the constant change between the carrier frequencies.

It is an object of the invention to improve the above method such that a frequency-hopping sequence is generated which causes a constant change between the carrier frequencies, with the above disadvantages being eliminated.

Other objects are to provide a radio facility using the method and a radio communication system comprising

such a radio facility.

These objects are attained by a method with the features according to claim 1 and by a radio facility and a radio communication system with the features according to the respective independent claims.

In the method according to the invention, first, elements of a pseudorandom sequence are calculated according to the first code; then, for the plurality of carrier frequencies, all possible sequences in which each of these carrier frequencies is contained only once are calculated according to the second code; thereafter, the two codes are concatenated by mapping each element of the pseudorandom sequence to one of the possible sequences; and finally, the frequency-hopping sequence is generated by joining the sequences according to the order in which the elements of the pseudorandom sequence are generated.

The radio facility according to the invention and the radio communication system equipped therewith comprise means for concatenating the at least two codes to generate the frequency-hopping sequence by calculating the elements of a pseudorandom sequence according to a first code and calculating for the plurality of carrier frequencies according to the second code all possible sequences in which each of these carrier frequencies is contained only once, said means concatenating the two codes by mapping each element of the pseudorandom sequence to one of the possible sequences, and generating the frequency-hopping sequence by joining the sequences according to the order in which the elements of the pseudorandom sequence occur.

This has the advantage that within the generated frequency-hopping sequence, all usable carrier frequencies occur equally frequently and are uniformly distributed over each time range being considered. This reduces the interference between the radio facilities according to the invention and those of a conventional radio communications network. This means that the radio communication system according to the invention hardly interferes with a neighboring radio communication system, such as a so-called overlay network. Therefore, the invention is particularly suited for the construction of a private radio communication system in the neighborhood of a public mobile radio system.

Further advantages are apparent from the subclaims:

Particularly advantageously, the pseudorandom sequence is calculated using a code with a function corresponding to the function of a linear feedback shift register in which outputs are taken both from the shift-register elements in the feedback loop and from the shift-register elements in the feedforward loop, the outputs being taken from only a minority of the shift-register elements. In this manner, a pseudorandom sequence is generated which is variable because access to the shift-register elements is variable. This means that both the code length and the density of the elements can be varied.

It is also particularly advantageous to use for the first code a Lempel-Greenberger code which is assigned a variable input vector with elements arranged in a freely selectable configuration which correspond to

the values of the outputs taken from the shift-register elements. In this manner, the variability of the generated pseudorandom sequence is added to the advantages of the Lempel-Greenberger code. Preferably, the first code forms the external code and the second code the internal code, which is achieved by choosing the number of elements of the pseudorandom sequence to be greater than the plurality of carrier frequencies.

The radio facilities advantageously comprise means for calculating pseudorandom sequences which generate different frequency-hopping sequences by determining their input vectors for the Lempel-Greenberger code differently from each other. This reduces the interference between the radio facilities, which are preferably mobile stations. Preferably, the respective means determines the input vector based on a device code assigned to the mobile station or on a user identification assigned to the user of the mobile station.

The invention will become more apparent from the following description of an embodiment when taken in conjunction with the accompanying drawings, in which:

- Fig. 1 is a schematic block diagram of a linear feedback shift register for generating a conventional Lempel-Greenberger code;
- Fig. 2 is a schematic block diagram of a linear feedback shift register for generating a modified Lempel-Greenberger code in accordance with the invention;

- Fig. 3 is a flowchart showing the steps of the method in accordance with the invention;
- Fig. 4 shows schematically the concatenation of a modified Lempel-Greenberger code and a nonrepeating sequence in accordance with the invention; and
- Fig. 5 shows a radio communication system in accordance with the invention, comprising a fixed radio facility and several mobile radio facilities.

Fig. 1 shows a schematic block diagram of a linear feedback shift register for generating a conventional Lempel-Greenberger code. The shift register consists of 17 elements $b_1 - b_{16}$ connected in series, with the output of the last element b_{16} fed back to the input of the first element b_1 . In addition, the output of the 14th shift-register element b_{13} is tapped and fed to a summing element contained in the feedback loop. To form a conventional Lempel-Greenberger code, outputs are taken from several adjacent shift-register elements, here the last three elements $b_{14} - b_{16}$. These outputs are fed in this predetermined order to three logic elements where they are combined with the three-valued code v by an XOR operation, i.e., a modulo-2 addition. The code has three digits v_0, v_1 , and v_2 and can thus represent $2^3=8$ different code words, which in combination with the values from the shift-register elements form the input vector of the Lempel-Greenberger code $LG(n)$. With the arrangement shown in Fig. 1, i.e., a linear feedback shift register having $n=17$ elements, a Lempel-Greenberger code with a length of $2^{n-1} = 2^{16}$ elements can be implemented.

In contrast to the generation of a Lempel-Greenberger code of the conventional type, Fig. 2 shows a linear feedback shift register according to the invention for generating a modified Lempel-Greenberger code. The shift register contains 17 elements connected in series, with the output of the last element fed back to the input of the first element. In addition, the output of the 14th shift-register element b_{n13} is tapped and fed to a summing element (adding stage) contained in the feedback loop. Unlike the conventional Lempel-Greenberger approach, outputs are taken from shift-register elements which need not be adjacent to each other. In the embodiment of Fig. 2, outputs are taken from the 8th element b_{n7} , the last element b_{n16} , and the third last element b_{n14} , the order being freely selectable. This means that the outputs from the shift-register elements need not be taken in a predetermined order, but that the order can be changed. Through this modification alone, 960 different Lempel-Greenberger sequences could be generated in this example. Through the subsequent concatenation which will be described in detail below, even 115,200 different sequences can be generated.

In the embodiment shown in Fig. 2, a first output is taken from the 15th shift-register element b_{n14} , a second output from the last shift-register element b_{n16} , and a third output from the 8th shift-register element b_{n7} . The values of these outputs form the input vector for the Lempel-Greenberger code. In this example, 115,200 different sequences can be generated with the aid of the modified Lempel-Greenberger code and the concatenation.

Fig. 3 is a flowchart showing the steps of the method 100 according to the invention. The method serves to generate a frequency-hopping sequence and contains the steps 110 to 130.

In a first step 110, the elements of a pseudorandom sequence are calculated with the aid of the modified Lempel-Greenberger code described with reference to Fig. 2. The rule for calculating an element is:

$$LG(n) = v_0 \bmod b_{n-a_0} + p(v_1 \bmod b_{n-a_1}) + p^2(v_2 \bmod b_{n-a_2}) + \dots \\ \dots + p^{k-1}(v_{k-1} \bmod b_{n-a_{(k-1)}}),$$

where the selected code word is denoted by $v_0, v_1, v_2, \dots$, etc., and the output values of the tapped shift-register elements are denoted by $b_{n-a_0}, b_{n-a_1}, b_{n-a_2}, \dots$, etc.. The subscript a corresponds to a vector with the elements $a_0, a_1, a_2, \dots$, etc.. This vector a is freely selectable and indicates in which order the shift-register elements are tapped. The number p is a prime number, which is preferably set equal to 2 ($p=2$: binary case).

In this concrete case and in agreement with Fig. 2, the following equation is obtained:

$$LG(n) = v_0 \bmod b_{n-14} + 2(v_1 \bmod b_{n-16}) + 2^2(v_2 \bmod b_{n-7}).$$

In a subsequent step 120, all those possible sequences are calculated for the plurality of carrier frequencies in which each of these carrier frequencies is contained only once, i.e., nonrepeating sequences are formed which each comprise all usable carrier frequencies, each frequency occurring only once within

any one of the sequences. The sequences are determined according to the following equation, where I is the index for the I th variant of the base sequence c^0 :

$$c^I = \{ (C_0 + I) \bmod N, (C_1 + I) \bmod N, \dots (C_{N-1} + I) \bmod N \}.$$

In the example where $c^0 = \{3, 2, 0, 5, 1\}$, the base sequence has $N=6$ elements (carrier frequencies), and the third variant is calculated as follows:

$$\begin{aligned} c^3 &= \{ (3 + 3) \bmod 6, (2 + 3) \bmod 6, \dots, (1 + 3) \bmod 6 \} \\ &= \{ 0, 5, 3, 2, 1, 4 \}. \end{aligned}$$

As is illustrated by this example, unlike the conventional Lempel-Greenberger approach, a number N can now be taken into account which need not be a multiple of 2. The method according to the invention is thus applicable to any number N of carrier frequencies.

In a next step 130, the frequency-hopping sequence $s[i]$ is generated by joining the previously calculated sequences; the order in which the sequences occur is determined by the previously calculated elements of the pseudorandom sequence. The rule for the calculation is:

$$s(i) = (LG(i \bmod N) + i \bmod N + C_{i \bmod N}) \bmod N$$

The method 100 will now be explained in more detail with reference to Fig. 4.

Fig. 4 shows a part of a frequency-hopping sequence $s[i]$ which is generated by the method illustrated in

Fig. 3. The method is carried out with the aid of a count variable n , which is counted here from 0 to 6, for example. First, a Lempel-Greenberger code is calculated for $n=0$ by the method just described, the result being equal to 3. By adding this result to the current count variable, i.e., $0 + 3$, the index I for the required sequence c^1 is obtained. Thus, in this case, the index becomes $I=3$, so that the sequence c^3 is generated as a first part of the frequency-hopping sequence.

The sequence c^3 as well as all other conceivable sequences follow from a freely selectable base sequence c^0 with the elements 3, 2, 0, 5, 4, 1. This means that this base sequence specifies all carrier frequencies 0-5 in a predeterminable order and is the basis for the variants resulting therefrom, such as the sequences c^1 , c^2 , c^3 , etc. The sequence c^3 contains, for example, the elements for specifying the carrier frequencies in the following order: 0, 5, 3, 2, 1, 4.

After the first sequence has been generated for the frequency-hopping pattern $s[i]$, the next one is generated. To do this, the count variable n is increased by 1. For $n=1$, a Lempel-Greenberger code is then calculated with the result $LG=6$. By adding this result to n , the index for the next sequence is obtained, namely $I = 1 + 6 = 7$. Accordingly, the next sequence is c^7 with the following elements: 4, 3, 1, 0, 5, 2. This sequence is joined to the previously calculated sequence. The count variable is then again increased by 1 and a further sequence is calculated. As shown in Fig. 4, for $n=2$, a Lempel-Greenberger code with the result $LG=5$ is obtained, which means that the

sequence c^7 is adjoined. The generation of the frequency-hopping pattern is then carried out successively as described, i.e.: For $n=3$, $LG=0$ and $c^1=c^3$; for $n=4$, $LG=4$ and $c^1=c^8$; for $n=5$, $LG=7$ and $c^1=c^{12}$; for $n=6$, $LG=7$ and $c^1=c^{13}$, and so forth.

As shown by way of example with the aid of Fig. 4, the frequency-hopping pattern $s[i]$ is formed from joined sequences c^3 , c^7 , c^7 , c^3 , c^8 , and so forth. Since the carrier frequencies occur only once within each of the sequences, the possibility of a repetition of the same carrier frequency is excluded. Only at the transitions from one sequence to the next can one and the same carrier frequency occur twice in succession. For example, the carrier frequency 4 occurs twice in succession at the transition from the sequence c^3 to the sequence c^7 . For the transition from the sequence c^8 to the sequence c^{12} , a repetition of the carrier frequency 3 is obtained. However, as a result of the modified Lampel-Greenberger code according to the invention, such repetitions are very rare. The method described has the advantage that a very large number of different sequences (here 115,200) can be generated.

Fig. 5 shows by way of example the structure of a radio communication system CTS according to the invention which is located in the neighborhood of a public mobile radio system GSM. The radio communication system CTS has a fixed radio facility, namely a base station BS, and several mobile radio facilities, namely mobile stations MS, MS', and MS". The radio communication system CTS is to serve as a private communication system. The radio facilities

shown transmit their radio signals by the frequency-hopping method presented herein. As a result, the possibility of interference between the radio facilities and with the neighboring mobile radio system GSM is nearly excluded. Within the neighboring radio system, a conventional frequency-hopping technique is used between a base trasceiver station BTS and mobile stations M.

The invention has been described in terms of a mobile radio communication system. It is also possible to use the method in a radio communication system with predominantly fixed radio facilities, such as for wireless office communication. The invention is also particularly suited for use in tactical mobile radio systems, which generally contain exclusively mobile facilities.



Claims

1. A method (100) of generating a frequency-hopping sequence ($s[i]$) for radio communication between radio facilities (BS, MS) which periodically change between a plurality (I) of different carrier frequencies (0, 1, ..., 5), wherein at least two codes ($LG[n]$, c^l) are concatenated, said method comprising the steps of:
 - calculating elements of a pseudorandom sequence according to the first code ($LG[n]$) (step 110);
 - calculating for the plurality of carrier frequencies according to the second code (c^l) all possible sequences in which each of these carrier frequencies is contained only once (step 120);
 - concatenating the two codes ($LG[n]$, c^l) by mapping each element ($n=3$) of the pseudorandom sequence to one of the possible sequences (c^3), and generating the frequency-hopping sequence ($s[i]$) by joining the sequences (c^3 , c^7 , ..., c^8 , ...) according to the order ($n = 3, 6, \dots, 4, \dots$) in which the elements of the pseudorandom sequence are generated (step 130).
2. A method (100) as claimed in claim 1 wherein the pseudorandom sequence is calculated using a code with a function corresponding to the function of a linear feedback shift register in which outputs are taken from only part of the shift-register elements (b_{n-7} , b_{n-14} , b_{n-16}) in a freely selectable order.





3. A method (100) as claimed in claim 2 wherein the pseudorandom sequence is calculated using a Lempel-Greenberger code which is assigned a variable input vector with elements arranged in a freely selectable configuration which correspond to the values of the outputs taken from the shift-register elements (b_{n-7} , b_{n-14} , b_{n-16}).

4. A method (100) as claimed in claim 1 wherein the first code ($LG[n]$) forms the external code and the second code (c^1) the internal code, this being achieved by choosing the number (n) of elements of the pseudorandom sequence to be greater than the plurality (I) of carrier frequencies.

5. A radio facility (MS) for a radio communication system (CTS) wherein said radio facility (MS) and other radio facilities (BS, MS') periodically change between a plurality (I) of different carrier frequencies (0, 1, ..., 5) in accordance with a frequency-hopping sequence ($s[i]$), comprising a means for calculating the frequency-hopping sequence ($s[i]$) which concatenates at least two codes ($LG[n]$, c^1) to generate the frequency-hopping sequence ($s[i]$) by calculating elements of a pseudorandom sequence according to the first code ($LG[n]$) and calculating for the plurality of carrier frequencies according to the second code (c^1) all possible sequences in which each of these carrier frequencies is contained only once, said means concatenating the two codes ($LG[n]$, c^1) by mapping each element ($n=3$) of the pseudorandom sequence to one of the possible sequences (c^3), and generating the frequency-hopping sequence ($s[i]$) by



joining the sequences ($c^3, c^7, \dots, c^8, \dots$) according to the order ($n = 3, 6, \dots, 4, \dots$) in which the elements of the pseudorandom sequence occur.

6. A radio communication system (CTS) comprising at least two intercommunicating radio facilities (BS, MS, MS'; MS'') which periodically change between a plurality (I) of different carrier frequencies (0, 1, ..., 5) according to a frequency-hopping sequence ($s[i]$), comprising a means for calculating the frequency-hopping sequence ($s[i]$) which concatenates at least two codes ($LG[n], c^1$) to generate the frequency-hopping sequence ($s[i]$) by calculating elements of a pseudorandom sequence for the plurality of carrier frequencies according to the first code ($LG[n]$) and calculating for the plurality of carrier frequencies according to the second code (c^1) all possible sequences in which each of these carrier frequencies is contained only once, said means concatenating the two codes ($LG[n], c^1$) by mapping each element ($n=3$) of the pseudorandom sequence to one of the possible sequences (c^3), and generating the frequency-hopping sequence ($s[i]$) by joining the sequences ($c^3, c^7, \dots, c^8, \dots$) according to the order ($n = 3, 6, \dots, 4, \dots$) in which the elements of the pseudorandom sequence occur.

7. A radio communication system (CTS) as claimed in claim 6 wherein the intercommunicating radio facilities are at least one base station (BS) and two mobile stations (MS, MS', MS'') whose means for calculating the pseudorandom sequence use a code with a function corresponding to the function of a linear feedback shift register in which outputs are taken





from only part of the shift-register elements (b_{n-7} , b_{n-14} , b_{n-16}) in a freely selectable order.

8. A radio communication system (CTS) as claimed in claim 7 wherein the means for calculating the pseudorandom sequence use a Lempel-Greenberger code which is assigned a variable input vector with elements arranged in a freely selectable configuration which correspond to the values of the outputs taken from the shift-register elements (b_{n-7} , b_{n-14} , b_{n-16}), and wherein the means in the mobile stations (MS, MS', MS'') generate different frequency-hopping sequences by determining their input vectors differently from each other.

9. A radio communication system (CTS) as claimed in claim 8 wherein the means in each of the mobile stations (MS) determines the input vector based on a device code assigned to the mobile station.

10. A radio communication system (CTS) as claimed in claim 8 wherein the means in each of the mobile stations (MS) determines the input vector based on a user identification assigned to the user of the mobile station (MS).

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