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Designing synchronization patterns minimizing the latency and the computational complexity for inaudible sound communication systems

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Abstract: The inaudible sound communication system of our implementation estimates the correct positions of received symbols in its decoding process by calculating the correlations with the pre-defined synchronization patterns. This paper describes that a theoretical approach based on solving Euler graphs taking account of constraint conditions may potentially provide more efficient synchronization patterns, compared with the conventional technique that employs random sequences for designing synchronization patterns.

Keywords: inaudible sound communication, synchronization, de Bruijn sequence, Euler graph

Classification: Fundamental Theories for Communications

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1 Introduction

Smart Solution Technology, Inc. has developed an inaudible sound communication system that enables long distance data exchanges more than 3 meters [1]. This technology aims at check-in services at commercial facilities such as shopping stores for people who use smartphones that receive sound signals with their built-in microphones.

Our implementation adopts an approach that transmits binary symbols simultaneously with a hopping pattern for increasing the stability of sound communications [1]. FSK (frequency shift keying) is employed as a communication protocol to transmit binary symbols. It employs a pair of high and low frequencies to represent a binary symbol in each band [1]. Figure 1 shows a case in which binary symbols defined as [0, 0, 0, 0, 1, 1, 1, 1] are repeatedly transmitted.

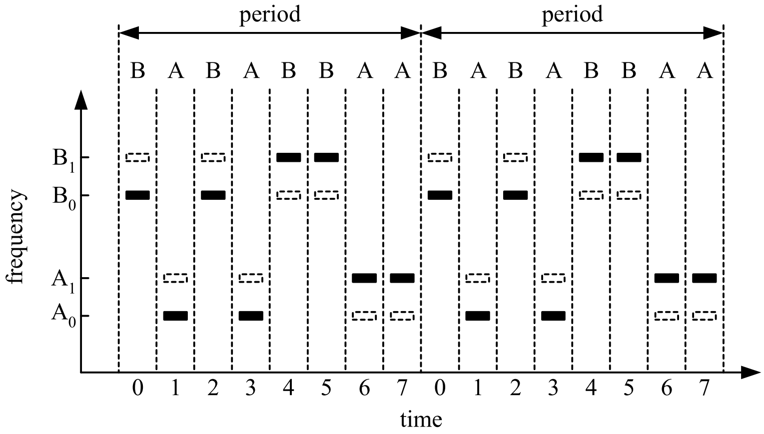

Fig. 1. Time-frequency structure of sound signals in the inaudible sound communication system of our implementation.

The hopping pattern denotes the order in which the frequency bands are selected. The hopping pattern of the case shown in Fig. 1 is defined as [B, A, B, A, B, B, A, A]. The number of bands is 2 in this example. The binary data are repeatedly transmitted according to the hopping pattern. The synchronization process is performed by calculating the correlation between the received symbols with this pre-defined synchronization pattern. The maximum value of the calculation among all the possible combinations provides the correct answer of the synchronization process.

Receiving the whole sequence of a hopping pattern is supposed to be desirable for maximizing the stability of the synchronization process in principle. However, the latency of the process inevitably increases as the period of a hopping pattern is lengthened. Our implementation chooses 24 bps (bit per second) for decreasing transmission errors. In this condition, for example, it takes 5 seconds to receive the whole sequence of a hopping pattern, if its length is chosen 120. It may cause inconvenience in the services due to its too long latency.

In addition, the computational complexity also becomes another problem. The correlation calculation requires n multiplications and $n - 1$ additions for each band where n denotes the length of a hopping pattern. Since all the possible combinations

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must be considered in the synchronization process, the hopping pattern is required to be circularly rotated n times along the time axis. The correlation calculation is performed for each rotation. Accordingly, the total amount of the calculation is defined as $(2n-1)nb$ where b denotes the number of bands. Consequently, the order of the computational complexity is regarded as $O(n^2)$.

Therefore, a part of a hopping pattern should be employed for the synchronization process instead of the whole sequence of a hopping pattern in order to minimize the latency and the computational complexity of the synchronization process. However, the relationship between the number of symbols and the correctness of the synchronization process is a trade-off. Hence, the most important point for designing hopping patterns is to enable correct synchronization with a shorter latency and a smaller computational complexity as much as possible.

2 Proposed technique

This study has discussed an efficient approach to generate hopping patterns that may be regarded as theoretically the best solutions. The proposed technique takes account of the characteristics of de Bruijn sequences [2]. Adopting a de Bruijn sequence as a hopping pattern enables correct synchronization if the number of received symbols is at least equal to its order, which is less than the length of a hopping pattern. Consequently, it decreases the number of symbols required for the synchronization process [3].

However, some modification is required for practical use that includes constraint conditions in which the same symbols must not be selected consecutively [4]. This prohibition rule takes account of a multi-path echo problem that may lengthen sound signals. It causes undesirable interferences back and forth in transmitting sound signals in indoor environments. So, the problem that this study attempts to solve is summarized as to find a finite sequence of n symbols for designing a hopping pattern such that any symbol does not appear consecutively, and any partial sequences appear only at once per period when the whole sequence is repeated.

This study has discussed that such a hopping pattern may be generated by solving an Euler graph, which defines a trail that visits every edge exactly once. This approach is actually the same way as de Bruijn sequences are generated [5]. However, instead of generating ordinary de Bruijn sequences, the proposed technique in this study solves an Euler graph that includes the constraint conditions to generate a hopping pattern that takes account of the constraint conditions. This graph simply excludes the prohibited edges corresponding to the constraint conditions from a graph that generates ordinary de Bruijn sequences.

According to the number of bands, the order of sequence, and the length of prohibition determined by the constraint conditions, the proposed technique defines the adjacency matrix of an Euler graph consisting of all the possible edges. The matrix may yield hopping patterns if the numbers of input and output edges in each node are the same [6].

The length of such an Euler graph sequence is defined as follows.

$$n = {}_bP_{r+1} \cdot (b-r)^{k-(r+1)} \tag{1}$$

where b is the number of bands, k is the order of the sequence, and r is the length of prohibition.

The computational complexity is therefore defined as $(2k-1)nb$, since correct synchronization may be sufficiently performed if the number of received symbols is at least equal to its order. Consequently, the order of the computational complexity becomes $O(n \log n)$ since $k \propto \log n$. It decreases drastically compared with the straightforward approach that employs the whole sequence of a hopping pattern.

3 Experiment

To evaluate the proposed technique, a hopping pattern consisting of 24 symbols was generated, where the number of bands was 4, the order of sequence was 3, and the length of prohibition was 2. Figure 2 shows the adjacency matrix of an Euler graph for generating a hopping pattern that follows these conditions. The columns and rows of this matrix define input and output edges, respectively. For example, the first column of this matrix defines the input edges indicating that band B must be selected after band A that follows band C or D. On the other hand, the first row of this matrix defines the output edges indicating that band C or D must be selected after band B that follows band A. These selections follows the constraint condition in which every symbol must take two consecutive breaks once it is selected.

	AB	AC	AD	BA	BC	BD	CA	CB	CD	DA	DB	DC
AB	0	0	0	0	1	1	0	0	0	0	0	0
AC	0	0	0	0	0	0	0	1	1	0	0	0
AD	0	0	0	0	0	0	0	0	0	0	1	1
BA	0	1	1	0	0	0	0	0	0	0	0	0
BC	0	0	0	0	0	0	1	0	1	0	0	0
BD	0	0	0	0	0	0	0	0	0	1	0	1
CA	1	0	1	0	0	0	0	0	0	0	0	0
CB	0	0	0	1	0	1	0	0	0	0	0	0
CD	0	0	0	0	0	0	0	0	0	1	1	0
DA	1	1	0	0	0	0	0	0	0	0	0	0
DB	0	0	0	1	1	0	0	0	0	0	0	0
DC	0	0	0	0	0	0	1	1	0	0	0	0

Fig. 2. Adjacency matrix of an Euler graph for generating a hopping pattern that takes account of a constraint condition.

The numbers of input and output edges in each node are the same so that this Euler graph has solutions that correspond to one-stroke trails. One of such trails was solved to generate a hopping pattern for the evaluation. It consisted of 24 symbols denoted as [A, B, D, C, B, D, A, C, D, B, C, D, A, B, C, A, D, B, A, C, B, A, D, C]. Since the order of the sequence is 3, only 3 consecutive symbols are theoretically sufficient to estimate their correct positions with this hopping pattern.

In addition, a hopping pattern of the conventional technique was also generated for the comparison. It is basically a random sequence, although the constraint

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condition is taken into account. It consisted of 24 symbols denoted as [A, B, D, C, B, D, C, B, A, C, B, D, C, B, D, A, B, C, A, B, C, A, B, D].

Figure 3 shows the result of the evaluation. When there was no noise, the synchronization pattern designed with the proposed technique required only 3 consecutive symbols, although the conventional technique required 6. When the SNR (signal-to-noise ratio) of the received symbols decreased, the number of the received symbols required for the correct estimation increased. Nevertheless, the proposed technique required only about half as many symbols as the conventional technique.

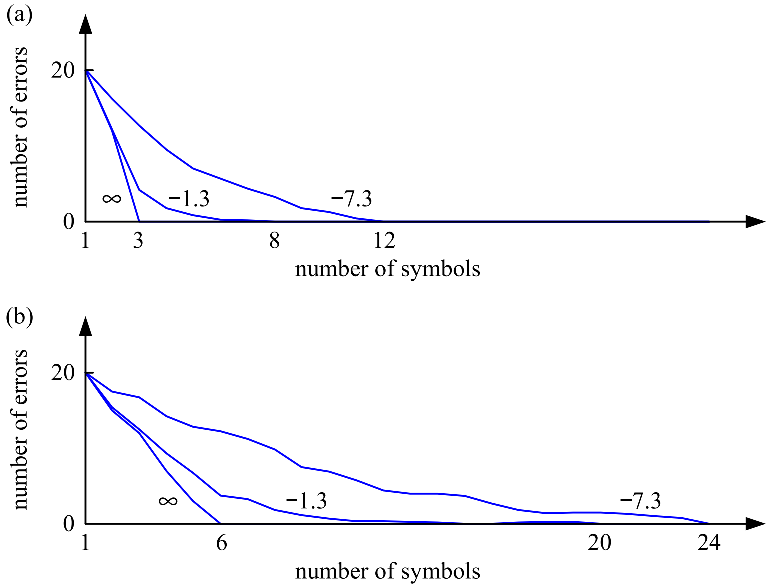

Fig. 3. The relationship between the number of symbols employed in the synchronization process and the number of errors simulated with (a) the proposed and (b) the conventional technique. The numbers inside the graphs indicate the SNR of the received symbols.

The probability of selecting each band is equal in the proposed technique. On the other hand, it is not in the conventional technique. Therefore, the correctness of the synchronization process may change if the frequency distribution of the noise is biased. However, it was assumed to be uniform in this evaluation in order to simplify the condition. Also, this evaluation examined a case in which the length of a hopping pattern was 24, even though the correctness of the synchronization process may change if the period of a hopping pattern is lengthened. The results shown in the figure is just a case that examined the basic advantage of the proposed technique compared with the conventional technique. Further investigation taking account of other conditions including practical situations is needed to prove fully the potential of the proposed technique.

4 Conclusions

The experimental result indicates that the proposed technique may outperform the conventional technique for improving the efficiency of the synchronization process.

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The proposed technique generates hopping patterns that may be regarded as theoretically the best solutions. It enables correct synchronization with a shorter latency and a smaller computational complexity than the conventional technique. Further investigation considering practical situations remains as a future work.

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