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A Novel Hitting Frequency Point Collision Avoidance Method for Wireless Dual-Channel Networks

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Abstract

In dual-channel networks (DCNs), all frequency hopping (FH) sequences used for data channels are chosen from the original FH sequence used for the control channel by shifting different initial phases. As the number of data channels increases, the hitting frequency point problem becomes considerably serious because DCNs is non-orthogonal synchronization network and FH sequences are non-orthogonal. The increasing severity of the hitting frequency point problem consequently reduces the resource utilization efficiency. To solve this problem, we propose a novel hitting frequency point collision avoidance method, which consists of a sequence-selection strategy called sliding correlation (SC) and a collision avoidance strategy called keeping silent on hitting frequency point (KSHF). SC is used to find the optimal phase-shifted FH sequence with the minimum number of hitting frequency points for a new data channel. The hitting frequency points and their locations in this optimal sequence are also derived for KSHF according to SC strategy. In KSHF, the transceivers transmit or receive symbol information not on the hitting frequency point, but on the next frequency point during the next FH period. Analytical and simulation results demonstrate that unlike the traditional method, the proposed method can effectively reduce the number of hitting frequency points and improve the efficiency of the code resource utilization.

Keywords: ad hoc networks, code division networking scheme, hierarchical distributed network structure, frequency hopping sequence, independent hit model, error correction code, packet transmission success probability, data transmission rate

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1. Introduction

In recent years, wireless ad hoc networks that are widely deployed for tactical communication have been mainly constructed by employing de-synchronization or synchronization method [1]. Compared with the de-synchronization network, the synchronization network features network interoperability, large networking scale, strong track interference resistance, and high throughput. Therefore, the synchronization network is mainly used in a large-scale tactical environment. The theoretical networking capacity denotes the theoretical maximum number of subclusters that the network can be divided into under the condition that the network is orthogonal and synchronization. On the battlefield, the number of subnets needed in a common tactical task is far less than the theoretical networking capacity. This condition causes serious code resource wastage. **Fig. 1** illustrates the diagram of idle code resources. The group nets use the frequency division networking method, where the frequency point set in group net no.1 is given by $\{f_0, f_1, f_2, \cdots, f_{n-1}\}$, and the number of frequency points is n. The theoretical networking capacity is n as well given an orthogonal and synchronization network. The number of subnets needed in group net no.1 is m, and is much smaller than n. Hence, the network will have $n-m$ unused sequences, which are defined as idle code resources in this paper.

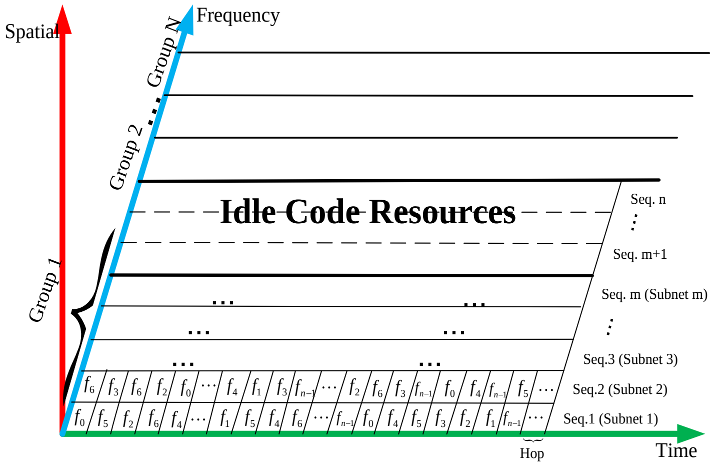


Fig. 1. Idle code resources

In traditional networks, each subcluster can only use a single different frequency hopping (FH) sequence. The unused FH sequences (which represent code resource wastage) can no longer be reused by any node in the network because the nodes in some subclusters can only use the FH sequences assigned to such subclusters. Even though some subcluster do not have communication tasks, the nodes in other subclusters still cannot reuse the sequence of the former. To maximize the utilization efficiency of idle code resources, a novel ad hoc network called dual-channel network (DCN) was proposed; different from traditional networks, DCNs consist of one control channel (CC), which uses one FH sequence, and multiple data channels (DCs), which employ multiple phase-shifted sequences from the former [2]. As a result of a DCN having a single transceiver, its node stays at either the CC or the DC by switching the single transceiver using a time division mechanism. The major merits of DCNs are as follows: 1) the idle code resource can be reused dynamically by any subcluster building multiple DCs between communication radio pairs; 2) different from the complexity realization for the inter-cluster communication of traditional networks with extra convertor equipment, that for the inter-cluster communication of DCNs can be realized by building a DC with a special common FH sequence only for the communication radio pairs.

In DCNs, the FH sequences, which are chosen for DCs, are parts of the original sequence and have different shifted phases. Given that all nodes in a DCN use the same frequency point set, multiple non-orthogonal sequences existing in the DCN will cause hitting frequency point problem to decrease the probability of packet transmission success. The traditional method for solving this problem is to use interleaving technology to randomly and uniformly disperse error symbols on the hitting frequency point; an error correction code (ECC) is then used to correct these error symbols [3]. However, this method introduces redundant symbols into the channel when used to check and correct error symbols. This condition results in a relatively low data transmission rate. In addition, this method cannot provide a satisfactory performance when it is applied to DCN because the hitting frequency point problem existing in a DCN is more serious than that existing in the traditional network. Thus, the present study focuses on determining the ways to choose the optimal FH sequences with the minimum number of hitting frequency points and to avoid collisions caused by hitting frequency points.

In this paper, we propose a novel hitting frequency point collision avoidance method, which consists of a sequence-selection strategy called sliding correlation (SC) and a collision avoidance strategy called keeping silent on hitting frequency point (KSHF). SC is used to find the optimal FH sequence with the minimum number of hitting frequency points, and to subsequently derive the locations of these hitting frequency points for collision avoidance. The KSHF strategy requires the transceivers to transmit or receive symbol information not on the hitting frequency point, but on the next frequency point during the next FH period. We also present performance analytical models for a slow frequency hopping (SFH) system and a fast frequency hopping (FFH) system. The method aims to increase the packet transmission success probability of the FH system. Compared with the traditional method, the proposed method has higher packet transmission probability, higher data transmission rate, and greater capability of enhancing resource utilization efficiency.

The rest of paper is organized as follows. Section 2 describes related works. Section 3 proposes the hitting frequency point collision avoidance method. Section 4 provides the performance analytical models for the SFH and FFH system. The analytical and simulation results are given in Section 5 to demonstrate the performance of packet transmission success and data transmission rate of the proposed method in comparison with the traditional method. Finally, in Section 6, we discuss the conclusion of the research.

2. Related Works

2.1 Dual-Channel Networks

Fig. 2 shows the structure of DCNs. The DCN is designed for a certain radio, which employs a hierarchical distributed network structure based on a fully connected subcluster [4, 5]. For simplicity, we hereafter refer to the fully connected subcluster as cluster. As shown in **Fig. 2**, all nodes are divided into multiple, fully connected clusters. Hence, any intra-cluster node can directly communicate with others in only one hop distance. Meanwhile, a virtual back-bone network is composed of all the cluster-head nodes and gateway nodes in the DCN for inter-cluster communication. Every node in the DCN uses a dual-channel structure that consists of one single CC and multiple DCs. All nodes in the DCN use the same CC to exchange network management and route control messages, and the CC employs the same FH sequence assigned before the networking phase. When a node pair has the data transmission request and route, all nodes in the route will establish a DC by using the same idle FH sequence chosen from idle code resource pool, which contains all the unused FH sequences in the network.

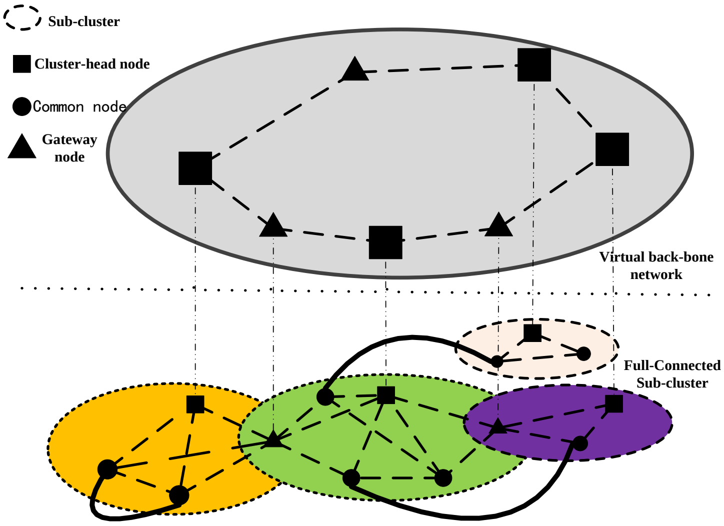


Fig. 2. DCN structure

Any node can stay at a negotiation status (NS) when exchanging management messages, or at a data-transmission status (DTS) when transmitting data packets. Under the NS, the node will switch its half-duplex transceiver to the CC. Once a node proceeds with a data transmission task, it will switch the CC to the DC after finding a route. After ending the transmission task, all nodes in the route will return to the CC to exchange management messages. In sum, every FH sequence is deemed as a frequency-varying channel. Thus, multiple frequency points must be available during each FH slot period in the DCN.

A traditional synchronization network consists of multiple subnets as a result of using different FH sequences with the same set of frequency points. Compared with this traditional network, a DCN demonstrates better interoperability performance and higher resource utilization efficiency.

2.2 Phase-shifted FH Sequence for DCNs

FH sequence families with optimal hamming- correlation property are often used in traditional synchronization networks to distinguish subnets. Therefore, the hitting frequency point problem depends on the correlation property of these sequences existing in the network. Orthogonal sequences indicate a correlation value of zero, in which case the hitting frequency point problem does not exist. By contrast, non-orthogonal sequences denote that the hitting frequency point problem depends on the number of sequences existing in the network [6]. However, traditional synchronization networks rarely use different phase-shifted sequences obtained from the same FH sequence by shifting different phases.

Phase-shifted sequences for DCNs are selected because of the following reasons:

1) the same FH generator that generates phase-shifted sequences is applied to all nodes in DCNs for easy interoperability. Hence, any node pair only needs to generate the same FH

sequence with the same FH generator by shifting the same phase to realize data transmission.

2) phase-shifted sequences generated by the same FH sequence generator are auto-correlated, which features the optimal hamming- correlation needed for networking. Hence, when using different phase-shifted FH sequences, all nodes in the DCN only need to employ the same FH sequence generator and identify the sequence phase of the related DC. Compared with the use of different cross-correlation sequences generated by different sequence generators, the use of phase-shifted sequence is a better way to make the nodes in the DCN switch easily between the CC and DC. In addition, the hitting frequency point problem of a synchronization network using phase-shifted sequences depends on the auto-correlation performance of the original FH sequence.

Related works [7-9] prove that the common sequences such as the *m* sequence, M sequence, and Gold sequence, demonstrate the optimal partial auto-correlation performance. Thus, we use the *m* sequence for DCNs in establishing DCs. However, the use of phase-shifted sequences for networking is not available in existing literature.

2.3 Avoiding Collision Caused by Hitting Frequency Point

In considering the ways to eliminate the impacts of the hitting frequency point problem on packet transmission, we need to discuss this topic in relation to SFH and FFH system. An SFH system transmits multiple symbols on each frequency point during one FH period; thus, multiple error symbols could occur if this frequency point is hitting one of other sequences [10]. The traditional method for an SFH system is to use de-interleaving technology to disperse these error symbols and then use an ECC to check and recover them. However, this traditional method introduces redundant bits for checking and correcting errors. This condition decreases the resource utilization efficiency and reduces the data transmission rate when the channel capacity is constant.

With the transmission of one symbol on multiple frequency points, an FFH system has additional frequency diversity gain to resist multi-path fading and external interference; such capability depends on the ratios of hop rate and channel transmission rate [11]. In addition, the frequency diversity gain can effectively reduce the impacts of the hitting frequency point problem on symbol transmission. However, the capability of solving the hitting frequency point problem depends on the frequency diversity gain of the FFH system. Hence, improving this capability will require either a relatively high hop rate restricted by the hardware of the FFH system or a relatively low channel transmission rate that may reduce resource utilization efficiency. In this study, we propose a novel collision avoidance method for SFH and FFH systems from a different perspective.

3. Hitting Frequency Point Collision Avoidance Method

3.1 Choosing the Optimal Phase-shifted FH sequence

Fig. 3 illustrates the diagram of multiple partial phase-shifted sequences overlaying in a DCN. It is observed that, there are one CC and DCs in the DCN. The sequence used for the CC is the original one, and the sequences used for the DCs are derived from the original one by shifting different phases. Take the reference partial phase-shifted sequence in **Fig. 3** for example. Determining the partial sequence length (which denotes the hop number of the partial sequence) and phase is the key to finding the optimal partial FH sequence. In general, the general size of communication data flows is approximately a few hundred KB. Thus, we can derive the partial sequence length by obtaining parameters such as information transmission rate and hop rate.

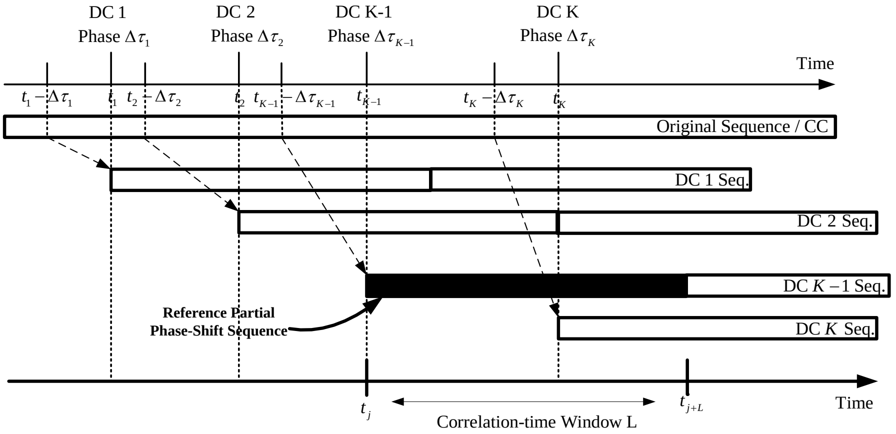


Fig. 3. Diagram of multiple phase-shifted sequences overlaying in the DCN

The sequence-selection strategy called SC is proposed to determine the phase of the optimal partial FH sequence. We assume that the nodes of DCNs use a typical FH sequence generator called L-G model based on *m* sequence [12]. As a result of the major inputs of the L-G model such as net ID, key, and time clock, the node can search any frequency point of the original sequence by changing its time clock and time-clock frequency. Hence, we propose SC as a hitting frequency point optimization method. **Fig. 4** illustrates the flow of the SC method. The specified steps of SC method are described as follows:

Step 1. When a new DC needs to be established, the source node obtains the phases of existing CC and DCs in the DCN from its sequence phase register.

Step 2. The source node determines the search range.

Step 3. Except for the known phases of existing sequences, the node compares the probable new DC sequence with the existing sequences starting from the first phase of the search range to the end; the node then derives the number of hitting frequency points by sliding phase.

Step 4. At the end of search range, the node will obtain the new DC sequence with the minimum number of hitting frequency points and the locations of these hitting frequency points.

Step 5. The source node transmits the message containing the phase used for the new DC sequence and the locations of these hitting frequency points to other nodes in the CC.

Step 6. All nodes, along with the new DC, switch their sequence generators to the new phase at a certain time to establish the DC; they then store the locations of the hitting frequency points in their own location registers.

Step 7. Other intra-cluster nodes, which have received the message containing the new DC phase, store the phase information and DC ID in their own sequence phase registers but discard the locations of the hitting frequency points.

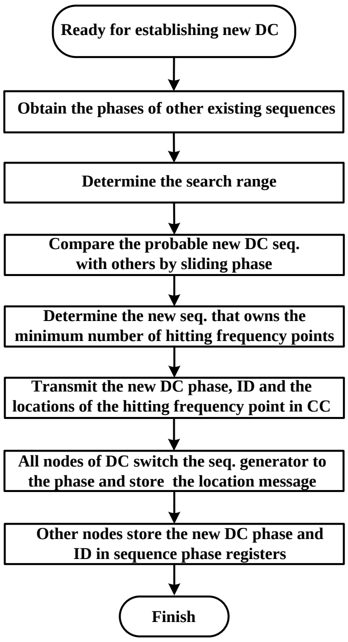


Fig. 4. The flow of the SC strategy

3.2 KSHF

Based on the location of the hitting frequency points in the location register of a source node and a target node, the KSHF strategy for an SFH system will stop the frequency synthesizer of the transmitter generating the carrier signal of the hitting frequency point. At the same time, the KSHF strategy stops using a digital up converter to mix the symbols with the carrier until the next FH period begins and requires the receiver to stop receiving messages that correspond to the hitting frequency points in this FH period. At the next FH period, the transceiver begins to transmit or receive the delayed symbol messages.

The primary procedure of the KSHF strategy for an FFH system is similar to that for an SFH system. The difference lies in the fact that because the frequency diversity gains of an FFH system can partially solve the hitting frequency point problem, KSHF is only effective when the number of the hitting frequency points in a symbol period exceeds the capability of the frequency diversity gains of the FFH system. The condition indicates that the number of non-hitting frequency points is below the threshold used for judging whether the symbol is recovered successfully. Hence, at the beginning of KSHF, the FFH transceivers both check and judge whether the incoming symbol will be recovered successfully according to the number of hitting frequency points in its period. Only when the frequency diversity gain does not works the transceivers operates the rest of KSHF just as the SFH transceivers do.

Obviously, KSHF only reduces the data transmission rate of the DC using the latest partial FH sequence joining the network to achieve a high packet transmission probability and consequently improve system reliability during this sequence period. Both SC and KSHF will add computation complexity for system, which mainly depending on the search process of the FH generator.

4. Performance Analysis

In this section, we present the analytical performance evaluation model for the SFH and FFH system. We also provide the expressions of the probability of minimum hitting frequency point, packet transmission success probability, data transmission rate, and so on.

$F_0(t-1)$	$F_0(t)$	$F_0(t+1)$	$F_0(t+2)$
$F_1(t-1)$	$F_1(t)$	$F_1(t+1)$	$F_1(t+2)$
$F_u(t-1)$	$F_u(t)$	$F_u(t+1)$	$F_u(t+2)$

Fig. 5. Time distribution of frequency points in synchronization DCNs

4.1 Probability of Minimum Hitting Frequency Point

In establishing a new DC, we need to consider how to choose the partial sequence phase that has the minimum number of hitting frequency points. From the perspective of pseudorandom sequence analytical theory, an independent hitting model is often used to analyze sequences [13]. In this case, every single hop of the partial sequence is independent with other hops, and every partial phase-shift sequence is independent with other different phase-shift ones. The time distribution of frequency points in synchronization DCNs is shown in **Fig. 5**. In synchronization networks, the probability P_h of collision between the concurrent frequency point of the reference sequence and those of other sequences is given by

$$P_h = 1-\left(1-q^{-1}\right)^{U-1} \tag{1}$$

Where U denotes the total number of sequences used for the CC and DCs, and q denotes the number of frequency point sets used for the DCN. With regard to the reference partial sequence, the probability $P(n,i)$ of the number i of hitting frequency points among n frequency points follows a Bernoulli distribution; it is calculated as

$$P(n,i) = C_n^i \left(P_h\right)^i \left(1-P_h\right)^{n-i} \tag{2}$$

The expectation number $E(\mathrm{i})$ of hitting frequency points in a partial sequence with the length of n hops is computed as

$$E(i) = nP_h \tag{3}$$

Assuming that a DCN has $U-1$ sequences, we define the original sequence phase as the reference phase, the value of which is zero. Based on the reference phase, τ is the phase value of the newly built DC. Thus, the partial FH sequence no. U is represented as

$$S_{U+1} = \left\{s^1_{0+\tau}, s^1_{1+\tau}, \ldots, s^1_{L-1+\tau}\right\} \tag{4}$$

Where L denotes the hop count of seq. no. U. The number of hitting frequency points between seq. no. U and other existing sequences is represented as

$$X(\tau) = \sum_{l=0}^{L-1} h\left(s_l^1, s_l^2, \ldots, s_l^{U-1}, s^1_{l+\tau}\right) \tag{5}$$

Where the phase value τ satisfies $1 \le \tau \le D$, D represents the search area range, and $h(\bullet)$ denotes the collision between the frequency point no. $l+1$ of seq. no. U and other frequency points of existing sequences at the same location; the latter can be given by

$$h(\bullet) = \begin{cases} 0 & \left(s^1_{l+\tau} \ne s^1_l\right) \cup \left(s^1_{l+\tau} \ne s^2_l\right) \cup \ldots \cup \left(s^1_{l+\tau} \ne s^{U-1}_l\right) \\ 1 & else \end{cases} \tag{6}$$

In the search area range D, the minimum number of frequency point number $x_{\min}$ is given by

$$x_{\min} = \min\left\{X(1), X(2), ..., X(D)\right\} \tag{7}$$

In addition, the sample vector $\mathbf{X}$ of the number of hitting frequency points between seq. no. U and other sequences is represented as

$$\begin{aligned}\mathbf{X} &= \left\{X_0, X_1, ..., X_{L-1}, X_L\right\} \\ &= \left\{0,1,2,...., L-1, L\right\}\end{aligned} \tag{8}$$

According to Equation (8), the minimum number of frequency points $x_{\min}$ between seq. no. U and other existing sequences is 0, and the maximum number of frequency point is L. In addition, the hitting probabilities corresponding to the sample $\mathbf{X}$ are $\mathbf{p} = \left\{p_0, p_1, ..., p_{L-1}, p_L\right\}$, and the elements of vector $\mathbf{p}$ are computed by Equation (2). In the search area range D, the set vector of the number of hitting frequency points $\mathbf{X}_{\mathbf{min}}$ is given by

$$\mathbf{X}_{\mathbf{min}} = \left\{x_{\min} \left| x_{\min} \in \left(X_0, X_1, ..., X_{L-1}, X_L\right)\right.\right\} \tag{9}$$

Furthermore, the probability set vector $\mathbf{q}$ of the set of the number of hitting frequency point has $\mathbf{q} = \left\{q_0, q_1, ..., q_{L-1}, q_L\right\}$, the expression of which is computed as

$$\begin{aligned}& q_0 = P\left(x_{\min} = X_0\right) = 1 - \left(1 - p_0\right)^D \\ & q_1 = P\left(x_{\min} = X_1\right) = \left(1 - p_0\right)^D - \left(1 - p_0 - p_1\right)^D \\ & q_2 = P\left(x_{\min} = X_2\right) = \left(1 - p_0 - p_1\right)^D - \left(1 - p_0 - p_1 - p_2\right)^D \\ & ... \\ & q_L = P\left(x_{\min} = X_L\right) = \left(1 - \sum_{i=0}^{L-1} p_i\right)^D - \left(1 - \sum_{i=0}^{L} p_i\right)^D\end{aligned} \tag{10}$$

Thus, the expectation $E[\mathbf{X}_{\mathbf{min}}]$ of the number of hitting frequency point $\mathbf{X}_{\mathbf{min}}$ of seq. no. U is calculated as

$$\begin{aligned}E[\mathbf{X}_{\mathbf{min}}] &= X_0 q_0 + X_1 q_1 + ... + X_{L-1} q_{L-1} + X_L q_L \\ &= q_1 + ... + \left(L-1\right) q_2 + L q_L\end{aligned} \tag{11}$$

Hence, the probability of the minimum hitting frequency point $P_h^{'}$ is given by

$$P_h^{'} = \frac{E[\mathbf{X}_{\mathbf{min}}]}{L} \tag{12}$$

4.2 Performance Analysis for SFH Systems

In the traditional method, we assume that the SFH system uses BCH $(n_{BCH}, k_{BCH}, t_{BCH})$ (where n_{BCH} denotes the symbol number that the code word owns, k_{BCH} denotes the payload symbol number, and t_{BCH} denotes the error symbol number. Therefore, k_{BCH} / n_{BCH} is the encoding efficiency. According to (2), the probability of packet transmission success P_{ptra} is given by

$$P_{ptrasfh} = \sum_{i=0}^{N_{\max}} C_{N_{hop}}^{i} (P_h)^i (1 - P_h)^{N_{hop} - i} \tag{13}$$

In (13), N_{hop} denotes the hop number of the packet, and $N_{\max}$ denotes the maximum number of hitting frequency points that a packet can tolerate. The data transmission rate R_{btra} can be calculated as

$$R_{btrasfh} = R_c \log_2(M) \frac{k_{BCH}}{n_{BCH}} P_{ptrasfh} \tag{14}$$

Where R_c denotes the channel transmission rate, and M denotes the modulation factor of MFSK.

With regard to the proposed method, for the SFH system, the packet transmission success probability $P_{psfh} = 1$ because the packet is transmitted in a way of avoiding the hitting frequency points. The data transmission rate R_{bsfh} of the SFH system is computed as

$$R_{bsfh} = R_c \log_2(M) \frac{P_{psfh}}{1 + P_h^{'}} \tag{15}$$

4.3 Performance Analysis for FFH Systems

FFH systems use frequency diversity gain to partially solve the hitting frequency point problem. Let N_{syms} denote the symbol number in one packet. In this case, the probability of a packet transmission success $P_{ptraffh} = P_{sym}{}^{N_{sym}}$. According to (2), P_{sym} denotes the probability of a symbol transmission success; it is given by

$$P_{sym} = \sum_{i=0}^{K-N_{thr}-1} C_K^i P_h{}^i (1-P_h)^{(K-i)} \tag{16}$$

Where K is the number of frequency points used for one symbol transmission, and N_{thr} is the threshold for judging whether the symbol transmission is successful. The data transmission rate is calculated as

$$R_{btraffh} = R_c \log_2(M) P_{ptraffh} \tag{17}$$

The proposed method for the FFH system works when the traditional method does not work. Hence, when the symbol transmission is a failure, the KSHF delays this symbol until the next symbol period for transmission. Obviously, the packet transmission success probability for an FFH system is $P_{pffh} = 1$. The data transmission rate R_{bffh} of FFH system is given by

$$R_{bffh} = R_c P_{sym}^{'} \log_2(M) P_{pffh} \tag{18}$$

According to (16), the symbol transmission success probability of the proposed method $P_{sym}^{'}$ is

$$P_{sym}^{'} = \sum_{i=0}^{K-N_{thr}-1} C_K^i (P_h^{'})^i (1-P_h^{'})^{(K-i)} \tag{19}$$

5. Analytical and Simulation Results

Based on previous performance analysis, simulations are performed using MATLAB for packet transmission success probability and data transmission rate respectively. The major parameter settings are specified in **Table 1**.

Table 1. Configuration of simulation parameters

Parameters	Value	Definitions
q	256	Number of frequency points
S	512 bytes	Packet size
B	8 bits	Byte length
M	2	Modulation factor of MFSK
R_{csfh}	384 k symbol/s	Channel transmission rate for SFH
R_{hsfh}	1000 hop/s	Hop rate for SFH
R_{cffh}	64 k symbol/s	Channel transmission rate for FFH
R_{hffh}	320 k hop/s	Hop rate for FFH
K	5	Frequency diversity gain for FFH

5.1 Probability of Minimum Hitting Frequency Point

In this subsection, we present the analytical and simulation results, which show us the probability curves of the minimum frequency point hitting according to Equation (12). **Fig. 6** illustrates the probability of minimum frequency point hitting for different search area ranges. As shown in **Fig. 6**, the SC strategy can provide a significantly low probability of hitting frequency point in comparison with the method involving the randomly selection of a sequence. This probability depends on the size range of the search area D. In addition, the probability of hitting frequency point P_h' becomes small as the search area range D increases. However, a large search area range increases the searching time. Hence, $D=1000$ is considered most suitable for DCNs in terms of computation complexity and performance improvement.

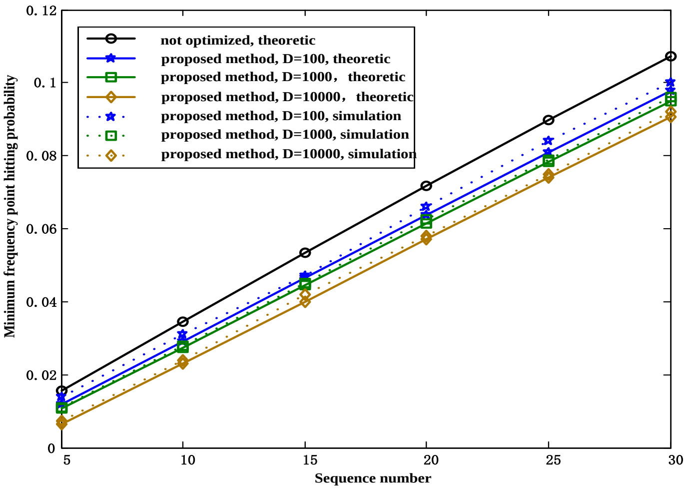
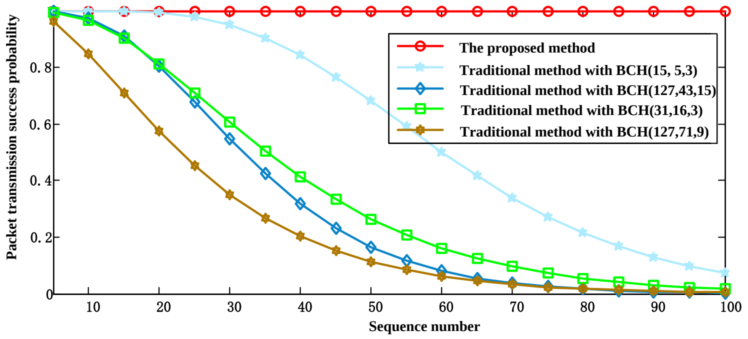


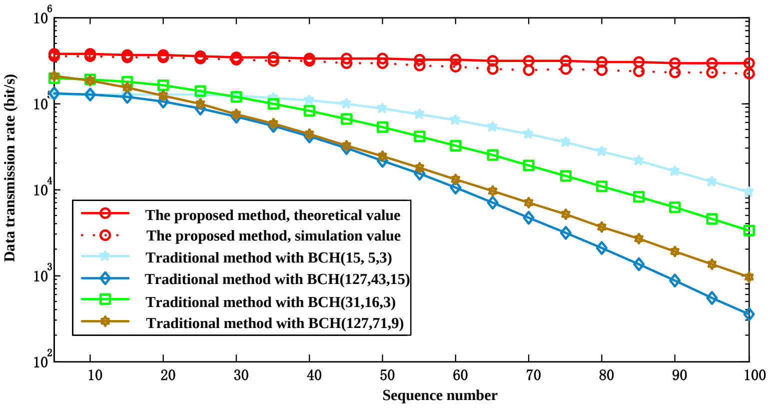
Fig. 6. Probability curves of the minimum hitting frequency point hitting versus the sequence number for different search area ranges

5.2 Performance Analysis for SFH Systems

This subsection describes the comparison of the performance analysis of the proposed method and the traditional method for the SFH system. In this simulation, the partial sequence length $L_{sfh} = 64000$ hops, and the BCH codes are used for the simulation. **Fig. 7** shows the comparison of the performance curves of the proposed method and traditional method for the SFH system. Given that only the traditional method uses BCH codes for the SFH system, its performance depends on the encoding efficiency k_{BCH} / n_{BCH} . By contrast, the proposed method does not introduce the ECC code to the system; thus, its encoding efficiency is higher than that of the traditional method, and it features better system reliability and resource utilization efficiency. Meanwhile, the data transmission rate decreases as the sequence number grows because of the increase in the number of hitting frequency points in a packet. This condition increases the time needed for packet transmission. Therefore, the proposed method has a significantly higher data transmission rate than the traditional method with ECC codes.



（a）Packet transmission success probability Versus sequence number

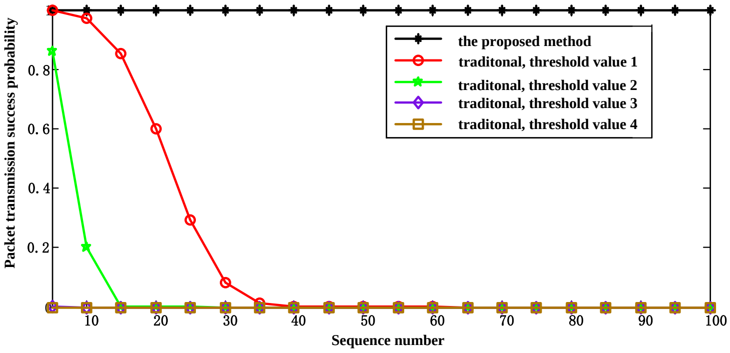


（b）Data transmission rate Versus sequence number

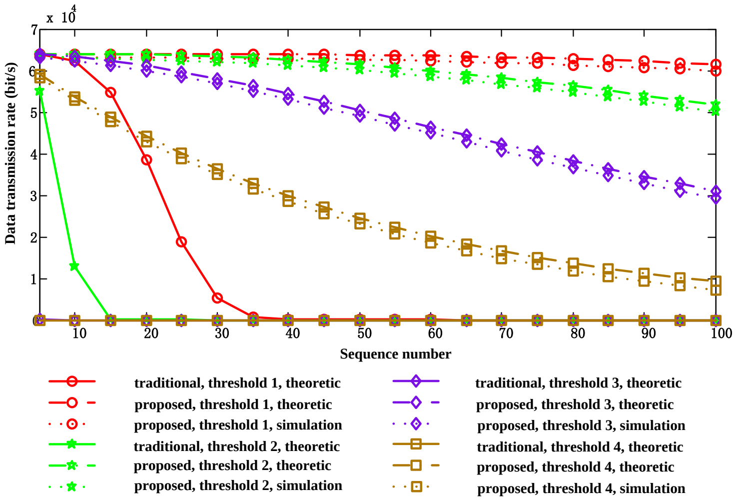
Fig. 7. Performance comparison curves of SFH system with the proposed method and the traditional method

5.3 Performance Analysis for FFH Systems

The analysis comparison of the proposed method and the traditional method for the FFH system is descried in this subsection. The major parameters in this simulation are as follows: the partial sequence length $L_{ffh} = 4096000$ hops, and the symbol judgment thresholds $N_{thr}=1,2,3,4$. The proposed method only works when the frequency diversity gain of the FFH system cannot handle the symbol suffering from the hitting collision. **Fig. 8** shows the comparison of performance curves of the proposed method and traditional method for the FFH system. Obviously, the packet transmission success probability of the proposed method is 1, which is far higher than that of the traditional method. Furthermore, the packet transmission success probability of traditional method increases as the symbol judgment grows and decreases rapidly as the sequence number increases. Hence, in **Fig. 8 (b)**, the data transmission rate of the proposed method is significantly better than that of the traditional method and decreases slowly as sequence number grows. In addition, the data transmission rate of the proposed method with a lower symbol judgment threshold is higher than that of the method with a higher threshold. This condition can be explained by the fact that a higher symbol threshold reduces the impacts of the frequency diversity gain on the hitting frequency point problem.



(a) Packet transmission success probability versus sequence number



(b) Data transmission rate versus sequence number

Fig. 8. Comparison of performance curves of the proposed method and traditional method for the FFH system under different symbol judgment thresholds

6. Conclusions

In this paper, we present a novel hitting frequency point collision avoidance method for DCNs. This method is aimed at improving the efficiency of code utilization through the SC strategy and the KSHF strategy. We also provide the procedure and performance analysis of the method for the SFH and FFH systems. The performance of the proposed method and traditional method is compared by using MATLAB simulation. The analytical and simulation results reveal that the proposed method can provide a significant performance improvement in comparison with the traditional methods.

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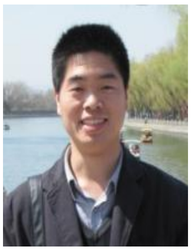

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