Construction of Control Sequence Set for Access Control in Data Link

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Abstract

Time slots are the valuable channel resource in the data link network with time division multiple access architecture. The need for finding a secure and efficient way to meet the requirements of large access capacity, maximum utilization of time slot resource and strong anti-eavesdropping ability in data link network is well motivated. In this paper, a sequence-based access control scheme is proposed to prevent eavesdropping and improve the average usage of time slot resource in data link network by using the sequence called control sequence. Based on the scheme, a new family of control sequences with zero cross correlation and long period is constructed in this paper. By our construction, the terminal user in data link can achieve random access and transmits data packet during its own hopping time slots of the successive frames. It is shown that the control sequences possess properties that make them suitable candidates for designing random access protocols for data link networks to prevent eavesdropping while maintaining high throughput.

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1 Introduction

The data link with the time division multiple access (TDMA) mode is the fundamental communication architecture for the vehicle network and some military applications. With the development of information technology, the data link network will develop toward high-speed, large capacity, security, anti-jamming and anti-eavesdropping to meet the need of future applications [1, 2, 3]. The network time is divided into epochs, frames, and time slots in the TDMA architecture of data link. Time slot is the basic unit of access to the data link network. Figure 1 illustrates the TDMA framework of the data link.

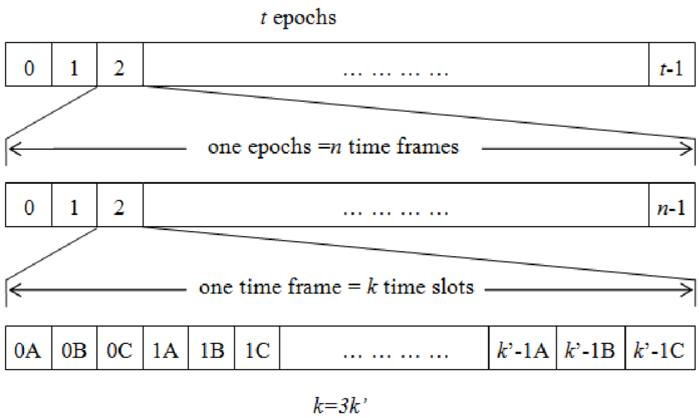

Figure 1: The TDMA framework of the data link

The data packet in data link network are transmitted over multiple slotted, Time Division Duplex (TDD) channels. The TDD assumption implies that each user at any time slot can either receive or transmit a packet over a channel but not both. Time slots are allocated to terminal users in the network. A terminal user transmits a burst sequence encoded with information during its own time slot and the certain slots of the successive frames. All other users listen during this period, and they may or may not receive the transmission [3, 4]. Thus all the users can share the limited time slots and will not experience a collided time slot.

How to access the network randomly and make fully and flexibly use of the limited time slots during the operation of the network has always been one of the key issues in research of data link. There is a necessity for an efficient random access method to improve users anti-eavesdropping ability and make fully and flexibly use of the time slots during the operation of the network[4]. The sequence-based controllable MAC scheme can not only make balanced use of slot resources evenly to achieve the maximum access capacity and improve user's anti-eavesdropping ability, but also not require channel monitoring, back off algorithm or packet retransmission[4]. Hence, the controllable MAC scheme can be used to prevent eavesdropping while maintaining high throughput, which is more suitable for data link network.

The idea of using sequences as a deterministic MAC scheme to achieve its channel capacity can be traced back to the seminal work of Massey and Mathys [5, 6]. The sequence-based controllable Media Access Control (MAC) scheme had been used to solve different types of access control problems in different applications. The sequences have been applied to different applications which call for different sequence design criteria, such as protocol sequences (wobbling sequence[8], CRT sequence[9], schedule sequences[10], conflict-avoiding codes[11]), hopping sequences[12], control sequences[13], et.al.

Protocol sequence which is a binary sequence with cross-correlation characteristics, is suitable for defining random access protocol without feedback. The design goal for protocol sequences is to guarantee that any transmitter-receiver pair can hop to a common channel and complete a collision-free transmission at least once within the shortest possible period, no matter what the delay offsets of the nodes are. However, the utilization of time slot resource can not achieve maximum due to experience some collided time slots. Moreover, a practical limitation of such a scheme is that the period of the sequences which also determines the period of collision-free transmission between transmitter-receiver pair, will be inevitably long. In the worst case, the only one collision-free transmission between transmitter-receiver pair would be delayed to the end of the period of sequence. Therefore, the protocol sequence can not be used to the data link network directly.

Hopping sequences are also used in other networks with TDMA architecture. A variety of different set-based q-ary channel hopping sequences have been proposed for the rendezvous problem in cognitive radio networks [12]. The design goal of the hopping sequences is to ensure that any transmitter-receiver pair can rendezvous on a common channel within a period, for all delay offsets. The idea of the hopping sequences is similar to the frequency/time hopping sequences [14, 15, 16, 17, 18] which have been used in frequency/time hopping communication systems. However, such class of hopping sequences also cannot ensure the collision free property required by the data link network.

In 2018, control sequence was firstly proposed to solve access control problems in data link network [13]. For the sequence-based MAC scheme in data link network, the hopping time slots of the successive frame used by every terminal user are chosen pseudo-randomly by a q-ary sequence called control sequence (CS). By using the CS sets, the time slots which are allocated evenly to each user will not overlap at a frame. Moreover, the time slot position of each user changes randomly with the frame goes on. The control sequence can well meet the requirements of large access capacity, maximum utilization of time slot resource and strong anti-eavesdropping ability in data link network. Therefore, it is necessary to design a control sequence to enable terminal users in data link network to choose the hopping slots in the successive frame randomly and evenly to maximize the utilization rate of resources while achieving collision free transmission in each frame.

In this paper, we propose a random access control mode in data link network based on the design and application of control sequences. We investigate the design problem for control sequence set which is a class of hopping sequences with zero crosscorrelation that take values from a q-ary finite set. The investigation is motivated by a random and security MAC problem of data link network which can make fully and flexibly use of the limited time slots while improving user's anti-eavesdropping ability. The rest of this paper is organized in the following manner: in Section 2, we describe the CS-based model for TDMA framework of data link; in Section 3, we give the definition and some notations of CS sets; in Section 4, we propose a new construction of control sequence set and analyse the properties of access control scheme based on CS set; Finally, we conclude the paper in Section 5.

2 Access Control Model Based on Control Sequence

For the CS-based secure MAC scheme in data link network with TDMA architecture, the time slots are used by every terminal user in successive time frame randomly and evenly. The control sequence can maximize the utilization rate of resources while preventing eavesdropping, which meet the requirements of large access capacity, maximum utilization of time slot resource and strong anti-eavesdropping ability in data link network.

Every elements in the CS are used to determine the time slot position in successive frame as the Figure 2. In Figure 2, we define a control sequence, $\mathbf{s} = (s(1), s(2), s(3), \cdots)$, to be a q-ary hopping sequence. An active terminal user is said to transmit according to a control sequence $\mathbf{s}$ if the user transmit at time slot $s(i)$ in the $\sharp i$ frame. The time slot position in successive frame for a terminal user is hopping randomly.

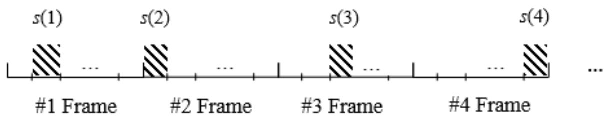

Figure 2: The time slot changes by the control sequence

Different terminal users will be assigned different CSs in the CS set. In order to discuss the TDMA framework of data link based on CS set, we suppose that a period of time is divided into n time frames, each time frame includes k time slots. Therefore, the system can accommodate up to k users at the same time frame. Suppose that there are M CSs can be chosen by the users in data link network, where $M \leq k$. We define a q-ary control sequence set $\mathcal{S} = \{\mathbf{s}_i = (s_i(1), s_i(2), \cdots, s_i(n)) : 1 \leq i \leq M\}$. Based on the CS set $\mathcal{S}$, the access control model of data link can be simplified as Figure 3. The work of the system require a control center to assign the corresponding CS $\mathbf{s}_i$ to terminal user requesting access to the network. Thus, the frame of all the terminal user is synchronized. For practical considerations, one would like to remove the assumption that the time frames are synchronized. It is, in fact, possible to do so and to allow the users to be unsynchronized. However, this more general scenario is not considered in this paper.

In the CS-based access control model in Figure 3, different users transmit at the hopping time slots controlled by their corresponding CS in successive frames. As the toy example in Figure 3, terminal users A and B are assigned CS $\mathbf{s}_1$ and $\mathbf{s}_M$ respectively to access the network at $\sharp 1$ frame. When any new user C wants to access at $\sharp i - 1$ frame, $0 \leq i \leq n-1$, he will be assigned an idle CS, i.e. $\mathbf{s}_x$ and the exact access time slot $s_x(i)$. User C can access to the network by using time slot $s_x(i)$. The CS $\mathbf{s}_M$ will become the idle CS after user B exits the network at $\sharp i$ frame. Thus, the CS $\mathbf{s}_M$ will be assigned to any new user from $\sharp i + 1$ frame, i.e, user D. Then, user D can access to the network by follow CS $\mathbf{s}_M$ at accurate time slot $s_M(j), j > i$.

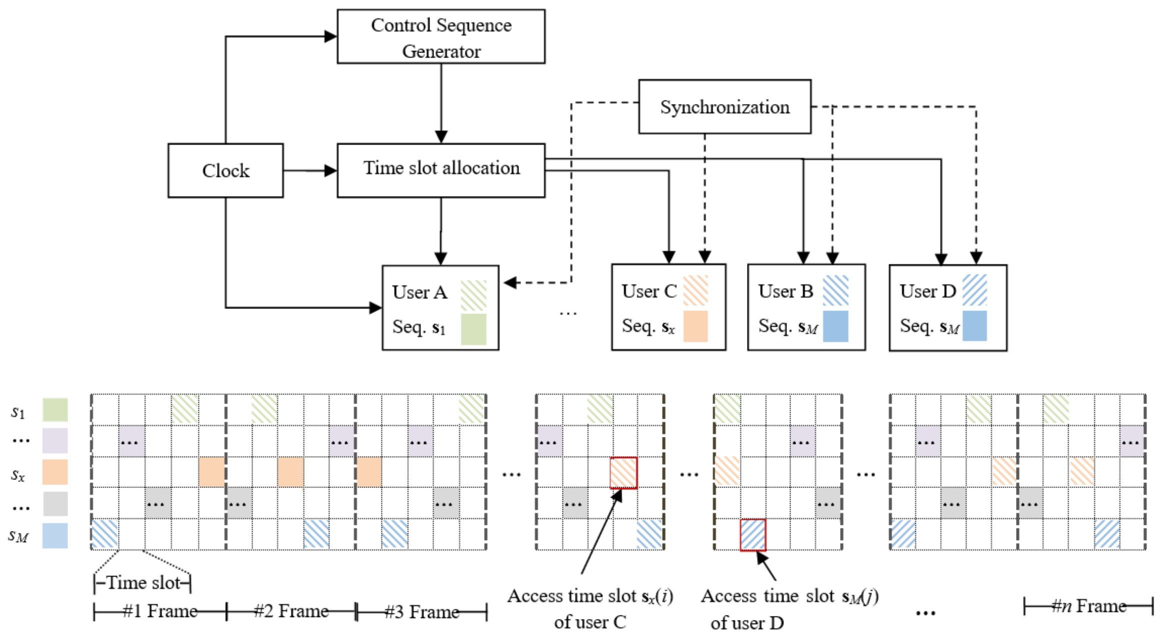

Figure 3: Simplified access control model for TDMA framework of data link

It can be seen from the above access control model that the secure and random MAC scheme can be realized based on the control sequence set. Any authorized terminal user can access randomly and synchronize to the data link network by using an idle control sequence and locating the exact access time slot. On the one hand, in a time frame, different users are randomly allocated different time slots. The time slot used by any user does not overlap with another user's in the same frame. On the other hand, as the time frame goes on, all terminal user can communicate by hopping from one time slot to another by using their own control sequence. The hopping of time slot between different users is irregular. Thus, the main advantages of the CS-based MAC scheme in data link network are as follows:

(1) Improve user's anti-eavesdropping ability

Random access control of time slots makes it difficult for the interceptor to intercept the user by tracking the "fixed" time slots. Especially in the multi-user scenario, access of time slots in a frame can be regard as the unordered access of a group of users. The interceptor cannot distinguish the time slots of different users.

(2) Increase the average usage of time slot

This approach may optimize the system capacity. Especially, it is possible to achieve the maximum usage of time slot resources when the access sequence is sufficiently evenly distributed.

In the following section, we will give the definition and some notations of CS set.

3 Notations and definitions

Let $\mathcal{T} = \{t_0, t_1, \ldots, t_{k-1}\}$ be a time slot set with size $|\mathcal{T}| = k$, $\mathcal{S}$ be a set of M control sequences of length n over $\mathcal{T}$. For any two control sequences $\mathbf{x} = (x(0), x(1), \ldots, x(n-1)), \mathbf{y} = (y(0), y(1), \ldots, y(n-1)) \in \mathcal{S}$, the Hamming correlation function $H(\mathbf{x}, \mathbf{y})$ of $\mathbf{x}$ and $\mathbf{y}$ is defined as follows:

$$H(\mathbf{x}, \mathbf{y}) = \sum_{i=0}^{n-1} h(x(i), y(i)), \tag{1}$$

where $h(a, b) = 1$ if $a = b$, and $h(a, b) = 0$ otherwise.

Definition 1. A hopping sequence set $\mathcal{S}$ is called a (n, M, k) control sequence set over time slot set with size k which includes M sequences of length n if the Hamming correlation $H(\mathbf{x}, \mathbf{y}) = 0$ for any two CSs $\mathbf{x}, \mathbf{y} \in \mathcal{S}$.

Evaluating the performance of control sequence set is a complicated issue and the outcome is dependent to some degree on the nature of the intended application. Nevertheless, the following criteria are commonly considered.

1) The size k of time slot set $\mathcal{T}$ should be equal to the number of time slots in one frame to make sure every time slot in a frame can be used.

2) The length n of CS in $\mathcal{S}$ should be as large as possible to satisfy the number of the time frame.

3) The size M of CS set $\mathcal{S}$ should be as large as possible to ensure the sequences can be allocated to more users. The size M of CS set is upper bounded by k.

4) The number of occurrences of any time slot $t_i \in \mathcal{T}, 0 \leq i \leq k-1$ in the control sequence set should be as uniform as possible.

5) The time slot used by the terminal user should hop randomly in the successive frame to improve the anti-eavesdropping ability.

In order to improve the anti-eavesdropping ability and the utilization of time slots, it is desirable to employ the control sequences with good random access and anti-eavesdropping property. The properties of the control sequence which can achieve access control of data link are quite different from those of the traditional protocol sequences and hopping sequences. Thus, the design of CS set with good random access and anti-eavesdropping property is an important problem.

4 Construction of Control Sequence Set for Access Control

In this section, we present a design of CS set to access randomly and synchronize to the data link network.

Let $\mathcal{T} = \{t_0, t_1, \ldots, t_{k-1}\}$ be a time slot set with size $|\mathcal{T}| = k$. Our procedure of the construction is described as follows.

Construction 1. Construction of Control Sequence Set.

Step 1: Let $k > 1$ be an integer. Define the initial state of the CS set as follows:

$$\mathcal{S}^{(0)} = \left\{ \mathbf{s}_i^{(0)} = (s_{i,0}^{(0)}, s_{i,1}^{(0)}, \cdots, s_{i,k-1}^{(0)}) : 0 \le i \le k-1 \right\}.$$

where $s_{i,b_0}^{(0)} = i + b_0 \mod k, 0 \le b_0 \le k-1,$.

Step 2: Choose $g \in \mathbb{Z}_k^*$ such that g has the largest multiplicative order in $\mathbb{Z}_k^*$. Assume that ord(g) = d, note that d is upper bounded by $\phi(k)$, where ϕ is the Euler function. In general, we have $d = \Omega(k)$.

Step 3: By the first round iteration, we can construct the set $\mathcal{S}^{(1)} = \{\mathbf{s}_i^{(1)} : 0 \le i \le k-1\}$, such as

$$\mathbf{s}_i^{(1)} = (g^0 \cdot \mathbf{s}_i^{(0)}, g^1 \cdot \mathbf{s}_{<i+1>_k}^{(0)}, g^2 \cdot \mathbf{s}_{<i+2>_k}^{(0)}, \cdots, g^{d-1} \cdot \mathbf{s}_{<i+d-1>_k}^{(0)}).$$

Step 4: Construct the desired CS set $\mathcal{S}^{(j)} = \{\mathbf{s}_i^{(j)} : 0 \le i \le k-1, j \ge 2\}$ by j-round iterations,

$$\mathbf{s}_i^{(j)} = (g^0 \cdot \mathbf{s}_i^{(j-1)}, g^1 \cdot \mathbf{s}_i^{(j-1)}, g^2 \cdot \mathbf{s}_i^{(j-1)}, \cdots, g^{d-1} \cdot \mathbf{s}_i^{(j-1)}).$$

After j rounds of iterative operation, any $s_{i,b_j}^{(j)}$ in sequence $\mathbf{s}_i^{(j)}$ can be written as

$$s_{i,b_j}^{(j)} = g^{a_j} g^{a_{j-1}} \cdots g^{a_1} s_{<i+a_1>_k, b_0}^{(0)} \mod k,$$

where $b_j = a_j \cdot d^{j-1}k + b_{j-1}, 0 \le a_j \le d-1, 0 \le b_j \le d^j k - 1$.

Theorem 2. *The CS set $\mathcal{S}$ obtained by Construction 1 is a $(d^j k, k, k)$ CS set.*

Proof. It can be obtained from the above Construction 1 that the CS set $\mathcal{S}$ is with k sequences of length $d^j k$ over a time slot set of size k. In the above construction, the size M of CS set $\mathcal{S}$ takes the maximum $M = k$. Then, we will prove the Hamming correlation $H(\mathcal{S}^{(j)}) = 0$.

For any two CSs $\mathbf{s}_{i_1}^{(j)}, \mathbf{s}_{i_2}^{(j)} \in \mathcal{S}$, suppose $H(\mathbf{s}_{i_1}^{(j)}, \mathbf{s}_{i_2}^{(j)}) \ne 0$, so there exist any $0 \le i_1 \ne i_2 \le k-1$, and $0 \le b_j \le d^j k - 1$ satisfy that $s_{<i_1+a_1>_k, b_j}^{(j)} = s_{<i_2+a_1>_k, b_j}^{(j)} \mod k$. So, we have

$$g^{a_j} g^{a_{j-1}} \cdots g^{a_1} (i_1 + a_1 + b_0) \equiv g^{a_j} g^{a_{j-1}} \cdots g^{a_1} (i_2 + a_1 + b_0) \mod k.$$

This gives

$$g^{<a_j + a_{j-1} + \cdots + a_1>_d} (i_1 + a_1 - i_2 + a_1) \equiv 0 \mod k.$$

Then we obtain $i_1 + a_1 \equiv i_2 + a_1 \mod k$ for $g^{<a_j + a_{j-1} + \cdots + a_1>_d} \in \mathbb{Z}_k^*$.
A contradiction. The proof is completed. □

Theorem 3. *Each time slot t_i ($t_i \in \mathcal{T}, 0 \le i \le k-1$) appears d^j times in $\mathbf{s}_i^{(j)}$.*

Proof. Let α be an element of $\mathbb{Z}_k$. We count the number of indices b_j such that $s_{i,b_j}^{(j)} = \alpha$, i.e, $g^{a_j} g^{a_{j-1}} \cdots g^{a_1}(< i + a_1 >_k + b_0) \equiv \alpha \mod k$, where $0 \le a_j \le d-1, 0 \le b_j \le d^j k - 1$. Thus, we have $b_0 \equiv \alpha \cdot g^{<-(a_j + a_{j-1} \cdots + a_1)>_d} \mod k$. For each $0 \le a_j \le d-1$, there exists a unique b_0 with $0 \le b_0 \le k-1$ such that $b_0 \equiv \alpha \cdot g^{<-(a_j + a_{j-1} \cdots + a_1)>_d} - (i + a_1) \mod k$, this implies that there are exactly n^j indices b_j such that $s_{i,b_j}^{(j)} = \alpha$. The proof is completed. □

Therefore, by our construction, the design principle of control sequence can be well satisfied. Firstly, the size k of time slot set $\mathcal{T}$ equal to the number of time slots in one frame. Secondly, the length n of CS in $\mathcal{S}$ will reach infinite when the number of iteration rounds j tends to be infinite. Thirdly, the size M of CS set $\mathcal{S}$ reaches the upper bound $M = k$. Moreover, the number of occurrences of any time slot $t_i \in \mathcal{T}, 0 \le i \le k-1$ is uniform. Lastly, any terminal user transmit data packet during the random hopping slots of the successive frames.

Example 4. Construction of $(2560, 10, 10)$ Control Sequence Set.

Step 1: We select an initial state of the CS set $\mathcal{S}^{(0)} = \{\mathbf{s}_i^{(0)} : 0 \le i \le 9\}$, such that

$$\begin{aligned} \mathbf{s}_0^{(0)} &= \{0,1,2,3,4,5,6,7,8,9\}, \\ \mathbf{s}_1^{(0)} &= \{1,2,3,4,5,6,7,8,9,0\}, \\ &\vdots \\ \mathbf{s}_9^{(0)} &= \{9,0,1,2,3,4,5,6,7,8\}. \end{aligned}$$

Step 2: Choose $g = 3 \in \mathbb{Z}_{10}^*$ such that $g = 3$ has the largest multiplicative order ord(g) $= 4$ in $\mathbb{Z}_{10}^*$.

Step 3: By the first round iteration, we can construct the CS set $\mathcal{S}^{(1)}$ as,

$$\mathcal{S}^{(1)} = \{\mathbf{s}_i^{(1)} = (3^0 \cdot \mathbf{s}_i^{(0)}, 3^1 \cdot \mathbf{s}_{<i+1>_{10}}^{(0)}, \cdots, 3^3 \cdot \mathbf{s}_{<i+3>_{10}}^{(0)}) : 0 \le i \le 9\},$$

where

$$\begin{aligned} \mathbf{s}_0^{(1)} &= \{0,1,2,3,4,5,6,7,8,9,3,6,9,2,5,8,1,\ldots,9,6,3,0,7,4\}, \\ \mathbf{s}_1^{(1)} &= \{1,2,3,4,5,6,7,8,9,0,6,9,2,5,8,1,4,\ldots,6,3,0,7,4,1\}, \\ &\vdots \\ \mathbf{s}_9^{(1)} &= \{9,0,1,2,3,4,5,6,7,8,0,3,6,9,2,5,8,\ldots,2,9,6,3,0,7\}. \end{aligned}$$

Step 4: Then, choose $j = 4$, construct the desired $(2560, 10, 10)$ CS set $\mathcal{S}^{(4)} = \{\mathbf{s}_i^{(4)} : 0 \le i \le 9\}$ by 4-round iterations,

$$\begin{aligned} \mathbf{s}_i^{(4)} &= (3^0 \cdot \mathbf{s}_i^{(3)}, 3^1 \cdot \mathbf{s}_i^{(3)}, 3^2 \cdot \mathbf{s}_i^{(3)}, 3^3 \cdot \mathbf{s}_i^{(3)}) \\ &= (3^{<0+0>_4} \cdot \mathbf{s}_i^{(2)}, 3^{<0+1>_4} \cdot \mathbf{s}_i^{(2)}, \ldots, 3^{<3+3>_4} \cdot \mathbf{s}_i^{(2)}) \\ &= (3^{<0+0+0>_4} \cdot \mathbf{s}_i^{(1)}, 3^{<0+0+1>_4} \cdot \mathbf{s}_i^{(1)}, \ldots, 3^{<3+3+3>_4} \cdot \mathbf{s}_i^{(1)}) \end{aligned}$$

It can be verified that there are 10 sequences in CS set $\mathcal{S}^{(4)}$ with the Hamming correlation $H(\mathcal{S}^{(4)}) = 0$, and the length $4^4 \cdot 10 = 2560$. Thus, $\mathcal{S}^{(4)}$ is a $(2560, 10, 10)$ CS set, the sequences in S are cyclically distinct. It should be noted that the family size of CS set $\mathcal{S}^{(4)}$ reaches maximum $M = k = 10$, and the length of CS will reach infinite when the number of iteration rounds j is large enough. Moreover, the time slots in different sequence hop randomly according to different rules.

Based on the control sequence sets, the random and secure MAC scheme in data link can be realized. Thus, the users in data link can access asynchronously by using their own synchronizing CS. Terminal user who wants to access randomly need to apply to the control center. The control center will assign an idle control sequence and the exact access time slot to the user to access. Any authorized terminal user can access randomly and synchronize to the data link network by using the idle control sequence and locating the exact access time slot.

In the following, we will use the $(2560, 10, 10)$ control sequence set in Example 4 to illustrate the random access control mode based on CS.

Example 5. Assume that there are two terminal users named A and B in the current network using the CSs $\mathbf{s}_\alpha^{(4)}, \mathbf{s}_\beta^{(4)}$ respectively. The current time slots they used are $s_\alpha^{(4)}(t-1), s_\beta^{(4)}(t-1)$ respectively when the new user X ask to access to the network.

Then, for some $i, 1 \leq i \leq 10, i \neq \beta, i \neq \alpha$, extra control sequences $\mathbf{s}_i^{(4)}$ and the exact access time slot $s_i^{(4)}(t)$ will be assigned to user X. In the following time frame, the time slots of user X hop randomly according to the CS $\mathbf{s}_i^{(4)}$.

Thus, the new user can access randomly to synchronize with the users in the network after the time slot that he make the request. In the same time frame, different users are randomly allocated to different time slots. The time slot used by any user does not overlap with another user's time slot in the same frame. As the time frame goes on, all terminal user can transmit data packet by hopping from one time slot to another by using their own control sequence. The time slot position allocated to a certain user changes randomly.

5 Conclusion

The CS-based controllable MAC scheme can be used to prevent eavesdropping while maintaining high throughput in data link network. The control sequence can well meet the requirements of large access capacity, maximum utilization of time slot resource and strong anti-eavesdropping ability in data link network. By using control sequence, terminal users in data link network can choose a certain slot in successive frame randomly and evenly to maximize the utilization rate of resources while achieving collision free transmission in each frame. In this paper, a new secure random access control mode in data link network was proposed based on the design and application of control sequences. Then, a class of control sequence was constructed. Based on our construction, the terminal user can access randomly by using an idle control sequence and locating the exact access time slot.

It is shown that the terminal unit can access to the network and change their time slot randomly as the frame go on.

It is worth noting that the property of CS-based MAC scheme provide the network with the ability to defend against the eavesdropping attacks and time-slot tracking attacks. Moreover, the random secure MAC scheme in this paper makes the balanced use of time slots in each time frame, which makes it possible to maximize the utilization of time slots resources in data link network. Thus, the new CS-based MAC scheme can be used to the communication system which employ TDMA architecture. In order to further evaluate the anti-eavesdropping ability of this scheme, the statistical evaluation of randomness and linear complexity of the long-period control sequences will be considered in the future work.

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