IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received July 12, 2021, accepted July 29, 2021, date of publication July 30, 2021, date of current version August 6, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3101553

A Time-Varying Chaotic Multitone Communication Method Based on OFDM for Low Detection Probability of Eavesdroppers

SHENGNAN GUO AND YONGQING FU

College of Information and Communication Engineering, Harbin Engineering University, Harbin 150001, China

Corresponding author: Shengnan Guo (guoshengnan@hrbeu.edu.cn)

This work was supported in part by the Fundamental Research Funds for the Central Universities.

ABSTRACT Due to the rapid development of modern communication technology and the substantial improvement of the processing capacity of communication equipment, it has become a challenging and meaningful research direction to realize the covert transmission of information by ensuring the low probability of detection (LPD) performance of the communication signals. The disadvantage of traditional fixed-parameter signal in LPD gradually appears. The paper proposes a time-varying chaotic multitone communication method to accomplish the LPD for the eavesdroppers. The method gets rid of the conventional LPD communication method whose performance improvement is exchanged at the expense of its reliability loss or sacrificing more resources. Based on the original chaotic multitone (CMT) communication method, the time-varying parameter is introduced to improve the randomness of the waveform and thus reduce the detection probability of eavesdroppers to the single tones in the multitone group (MTG). Meanwhile, to improve spectrum efficiency and reduce system complexity, the corresponding communication system model is designed based on orthogonal frequency division multiplexing (OFDM) technology. After given the corresponding detection and demodulation scheme based on the diversity and combination, the influence of time-varying parameters on the reliability for the cooperative receiver is analyzed. The LPD contribution of this method is evaluated by analyzing the detection probability of the eavesdropper. The experimental results show that the proposed method not only maintains the original reliability but also reduces the detection probability of eavesdroppers under the constant false alarm probability detection scheme.

INDEX TERMS LPD, time-varying chaotic multitone communication method, communication reliability, constant false-alarm rate, OFDM.

I. INTRODUCTION

With the development of current sensing and detection technologies, in the complex wireless communication environment, high requirements are put forward for the low probability of detection (LPD) of eavesdroppers to ensure the security of communication. The goal of LPD technology is to maximize the energy required for eavesdroppers to detect signals while maintaining the original communication reliability [1], [2]. At present, the commonly used technologies include spread spectrum and short-term burst technology, which introduce uncertainty and randomness to make the signal characteristics less obvious [3]–[5]. The randomness and uncertainty are mainly divided into the system itself and artificially introduced which have been confirmed the feasibility [6]. However, the method using the uncertainty of the system itself often sacrifices the reliability with the cooperative receiver [7]. In the literature, a joint data and interference transmission scheme based on a new distributed asynchronous cyclic delay diversity scheme is proposed for cooperative communication systems which can achieve the maximum diversity gain at the legitimate user, while degrading the receive signal-to-interference-Maximize diversity gain at the legitimate user while reducing the received signal to interference and noise ratio at eavesdropper [8]. Artificially introduced uncertainties generally require relay or other assistance measures, resulting in a waste of energy and spectrum resources [9], [10]. Therefore,

The associate editor coordinating the review of this manuscript and approving it for publication was Barbara Masini.

a communication method that can maintain reliability and improve concealment with uncertainty and randomness has become a hot research topic.

A chaotic multitone (CMT) communication method proposed in [11] is different from the conventional multi-carrier modulation communication method. There is no fixed correspondence between baseband data and multi-carrier in this scheme, and its transformation law is chaotic, so it is called chaotic multitone modulation. The anti-interception performance is guaranteed by one-to-many chaotic mapping between baseband data and multitone group (MTG). In addition, the encryption modulation method based on chaotic cryptography is studied to meet the randomness and security requirements of the modulation and coding scheme level [12]. But the frequency diversity method in CMT based on frequency division multiplexing (FDM) causes the waste of spectrum resources. Besides, when the number of single tone in the MTG is fixed, the multitone signal features are easily exposed to the eavesdroppers who have the detection ability of multi-filter banks detection and signal energy is high enough, even if the characteristics of the signal are unknown [15], [16]. Based on the above analysis, to raise the energy threshold for eavesdroppers to find signals and decrease the waste of spectrum resources based on FDM, the paper introduces the time-varying parameter to design Time-varying CMT (T-CMT) communication method. It can improve the randomness of the waveform and achieve LPD for eavesdroppers by allocating power uncertainty at every single tone. Then, the corresponding communication scheme is redesigned based on orthogonal frequency division multiplexing (OFDM) technology. In brief, we conclude our main contributions as the following three-folds:

- The introduction of time-varying parameters based on the original CMT modulation method increases the uncertainty of the non-cooperative party and improves the waveform randomness. The corresponding time-varying chaotic multitone modulation scheme is designed.
- To improve the bandwidth utilization, the corresponding communication scheme is redesigned based on OFDM technology. After coding the modulated information, the implementation scheme based on inverse fast Fourier transform (IFFT)/ fast Fourier transform (FFT) is given.
- The detection and demodulation method of the cooperative receiver based on diversity and combination energy detection is given. Thus, the upper bound of bit error rate (BER) that this scheme can achieve is analyzed theoretically. To illustrate the performance of this scheme in reducing the detection probability for eavesdroppers, considering the worst security situation, the eavesdroppers' detection ability of the multitone signal generated by this method under the energy detection scheme based on filter banks is theoretically analyzed.

The rest of this paper is organized as follows. Section II describes the system model composed of the time-varying CMT (T-CMT) modulation method, transmitter communication scheme, and the T-CMT signal detection and demodulation based on OFDM. Section III is the theoretical analysis of the performance of the proposed method. Section V provides the simulation experiment analysis. Finally, Section VI concludes the paper and presents future work directions.

II. SYSTEM MODEL

For the equidistant available frequency points set (AFS) $\Omega = \{f_1, f_2, \cdots, f_N\}$, select m single tones as a MTG F_z from it by random combination and represent all of them as a multitone frequency group set (MTGS) $\Omega_F = \{F_1, F_2, \cdots, F_{N_m}\}$ [12]. Where $N_m = C_N^m = \frac{N!}{m!(N-m)!}$ represents the number of MTG in MTGS. It is noteworthy that the frequency interval between adjacent single tone is Δf. When the modulation order of baseband symbol data is M, different from [11], based on the principle of chaotic cryptography in [12], a secure mapping relationship with demodulation resistance and a method of generating the corresponding discrete chaotic index sequence were proposed. For simplicity, the mathematical mapping function between baseband data and MTG can be defined as:

$$\Phi(F_z) = a, F_z \in A_a, \quad z \in [1, N_m], \; a \in [0, M-1] \tag{1}$$

That is when the ith baseband data is $d_i = a$, a class of MTGs that can be used to represent it is $A_a = \left\{F_{a,1}, F_{a,2}, \cdots, F_{a,N_a}\right\}$ and it is a one-to-many mapping relationship between baseband data and MTG. Assume the corresponding chaotic index sequence of A_a is ς_a, $\varsigma_a \in [1, N_a]$, where N_a is the number of MTGs in A_a. For the baseband data $d_i = a$, the final MTG is:

$$F_{a,\varsigma_a(i)} = \{f_1, f_2, \cdots, f_m\} \tag{2}$$

where the discrete chaotic sequence ς_a, $\varsigma_a \in [1, N_a]$ is used as the address index sequence to ensure that the variation of MTG conforms to the chaotic law [11], [12]. The design of the corresponding chaotic index sequence and mapping function has been given a specific illustration in [12] and there is no much discussion here.

When the modulation parameter m changes in $[m_1, m_2]$, the number of optional MTG combinations changes from C_N^m to $\sum_{m=m_1}^{m_2} C_N^m$. When the original modulation scheme can ensure that MTG is randomly used, this method can further enhance the randomness of the modulation waveform.

A. TIME-VARYING CMT MODULATION METHOD

This method employs the variable satellite timing information V to represent the variable m and the mapping relationship can be expressed as $f(V) = m$, where $m_1 < m < m_2$, $m_1 \geq 0, m_2 \leq n$ and $m \in R^+$. When the distance between the transmitter and the receiver is d_{ab}, to avoid the error caused by the transmission time delay of electromagnetic wave [13], the minimum interval between different V is limited as $\Delta V \gg d_{ab}/c$ ignoring the internal signal processing time. Where c is the propagation rate of the electromagnetic

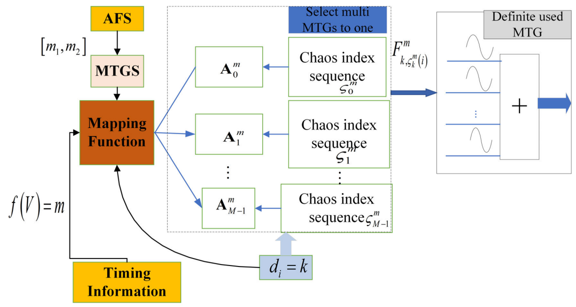

FIGURE 1. T-CMT modulation scheme.

wave in the air, which is generally defaulted as $3 \times 10^8 m/s$. The T-CMT modulation scheme is shown in FIGURE.1.

As shown in FIGURE.1, for the same AFS, let $\Omega_F^m = \{F_1^m, F_2^m, \cdots, F_{N_m}^m\}$ denotes the corresponding MTGS under different m. To illustrate the influence of the time-varying parameter on the system performance, the original mapping method is still used in this paper. To distinguish the same type of MTGS under different m, let A_a^m represents optional MTGS for category a and the MTG in which is composed of m single tones. Similarly, according to the different numbers of MTG in A_a^m, the corresponding address index sequences ς_a^m are established respectively. Taking $d_i = a$ as an example, when the timing information at the sending time is V, the final MTG is determined as $F^m_{a,\varsigma_a^m(i)} = \{f_1, f_2, \cdots, f_m\}$.

B. TRANSMITTER COMMUNICATION SCHEME BASED ON OFDM

After T-CMT modulation, the corresponding MTG is $F^m_{a,\varsigma_a^m(i)} = \{f_1, f_2, \cdots, f_m\}$ for the ith baseband code $d_i = a$. The communication scheme in [11], [12] is implemented by the filter bank based on the FDM to obtain the time domain signals of multitone superposition. Since the filter is greatly restricted by hardware conditions, the implementation complexity is high when the number of frequency points in the AFS is large [16], [17].

With the orthogonality between subcarriers, OFDM technology can save nearly 50% of the spectrum resources [20]. When the number of subcarriers is N, an OFDM symbol contains the composite signal of a modulated subcarrier. According to the T-CMT modulation method, the logical mapping of the MTG to describe the baseband data is established. For simplicity, the MTG in Ω_F^m can be represented by F_z^m and one of the logic coding methods is expressed as:

$$x_z(\alpha) = \begin{cases} 1, & f_\alpha \in F_z^m \\ 0, & f_\alpha \notin F_z^m \end{cases} \tag{3}$$

After encoding, each MTG can get a binary sequence $X_z = \{x_z(0), x_z(1), \cdots, x_z(\alpha), \cdots, x_z(N-1)\}$, among which $x_z(\alpha)$ indicates whether the $(\alpha+1)th$ single tone of Ω is used in F_z^m. If yes, $x_z(\alpha) = 1$, otherwise, $x_z(\alpha) = 0$. After coding, based on the OFDM method, the single symbol time is constrained as $T_s = 1/\Delta f$. The T-CMT symbol corresponding to the ith baseband symbol can be expressed as:

$$s_i(t) = rect(t - iT_s) \sum_{\alpha=0}^{N-1} x_z(\alpha) \times \left(\sqrt{P_b/m}\right) \exp\left(j2\pi\left(f_1 + \frac{\alpha}{T_s}\right)(t - iT_s)\right) \tag{4}$$

where P_b represents the power required to transmit the unit baseband symbol.

According to the OFDM method, the equivalent baseband signal in the complex domain is expressed as:

$$s_i(t) = rect(t - iT_s) \sum_{\alpha=0}^{N-1} b(\alpha) \exp(j2\pi \frac{\alpha}{T_s}(t - iT_s)) \tag{5}$$

where $b_\alpha = x_z(\alpha)\sqrt{P_b/m}$ is the energy normalization factor. Each multitone symbol period contains the integral multiple periods of one single tone and the difference between adjacent single tones is one period which ensures the orthogonality [21].

When the number of single tones N is relatively large, IFFT can be used to reduce implementation complexity [18], [20]. Based on these analysis, a transmitter communication implementation scheme based on OFDM of proposed T-CMT modulation method is shown in FIGURE.2.

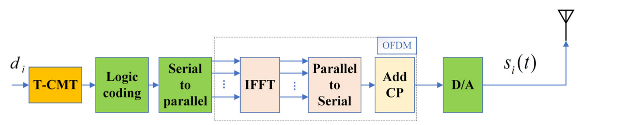

FIGURE 2. Transmitter communication scheme. Implementation scheme based on IFFT after T-CMT modulation and coded in frequency-domain.

As shown in FIGURE.2, the superposition of multitone signals in the time-domain can be completed by using IFFT. Similar to the conventional OFDM signals, the purpose of adding a cyclic prefix (CP) is to avoid inter-symbol interference (ISI) and inter-tone crosstalk [21].

However, it is worth noted that the conventional OFDM-based modulation methods such as QAM modulation can use each subcarrier to transmit different symbol information in parallel [20]. In contrast, the T-CMT modulation method is serially transmitted within the same symbol time.

C. T-CMT SIGNAL DETECTION AND DEMODULATION BASED ON OFDM

For the scheme of the transmitter, the corresponding receiver structure is shown in FIGURE.3:

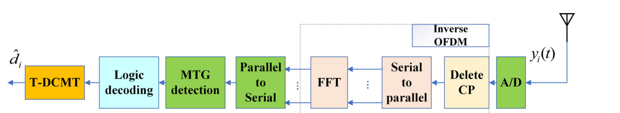

FIGURE 3. Receiver scheme.

Considering the addition of CP and IFFT operation at the transmitter, the receiver should implement the inverse OFDM operation composed of CP deletion, serial to parallel conversion, and FFT operation to obtain the frequency domain information after completing the signal reception.

Then the detected MTG is demodulated to obtain the baseband data. The specific detection and demodulation scheme applies diversity combined with the energy values $\{e_1, e_2, \ldots, e_\alpha, \cdots, e_N\}$ of N single tones to obtain the corresponding MTG based on the timing information V, as shown in FIGURE.4.

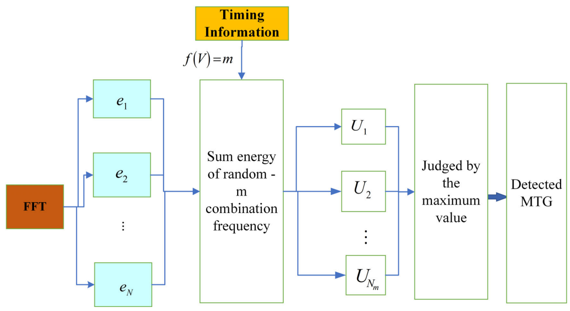

FIGURE 4. Detection and demodulation scheme based on diversity combination.

In FIGURE.4, $U_1, U_2, \cdots, U_{N_m}$ is the decision variable obtained by combining all possible energy combinations of the MTG in Ω_F^m based on the frequency diversity method in the T-CMT. Then, the combination U_p with the largest measurement value in the judgment part is taken as the detected MTG which can be expressed as $\hat{F}_p = \left\{\hat{f}_1^p, \hat{f}_2^p, \cdots, \hat{f}_m^p\right\}$. Finally, $\Phi\left(\hat{F}_p\right) = a$ is calculated according to the mapping relationship between MTG and baseband data, and the corresponding symbol information $\hat{d}_i = a$ is demodulated.

III. PERFORMANCE ANALYSIS

The performance of the proposed communication method depends on the reliability of the cooperative receiver and the detection probability of the eavesdropper [16]. In this section, the reliability is evaluated by analyzing the BER of the method for the cooperative receiver in theory. The detection probability of the eavesdropper, Willie, is evaluated based on the constant false alarm probability detection technology.

A. RELIABILITY ANALYSIS UNDER IDEAL AND FADING CHANNEL

The analysis of the CMT modulation algorithm in [11] shows that the probability used at each frequency point satisfies the uniformity and randomness distribution. After introducing the time-varying parameter m, considering an extreme case, $0 < m < N$, the probability of the αth single tone being used can be approximately expressed as:

$$\begin{aligned} P_r(\alpha \in F_z) &= \sum_{m=1}^{N} P_r(\alpha \in F_z|\ m) P_r(m) \\ &= \frac{1}{N(N+1)} \sum_{m=1}^{N} m \\ &= 1/2 \end{aligned} \tag{6}$$

On this basis, the reliability and concealment of the proposed communication methods in different channel environments are analyzed.

Reliability Analysis under Ideal Channel: Since the m single tones of MTG can be considered as disordered and the mapping relation $\Phi(\bullet)$ between MTG and baseband data is determined by all single tones of the used MTG, when the number of the error single tones in the detected MTG is different, the influence on the final demodulation results is also different with the scheme of diversity combining detection. To value it, represent the influence by the error cost factor $P_m(k)$. For the mapping relation in [12], the experimental simulations show that $P_m(k)$ can be calculated by the proportion of the error single tones in MTG, which can be approximately expressed as:

$$P_m(k) = k/m \tag{7}$$

where k is the number of error single tones between the detected MTG and the correct MTG. Therefore, it is necessary to analyze the probability of the different numbers of single tone detection errors in MTG. The theoretical BER can be deduced according to the BER joint bound [22].

$$P_s \le \sum_{k=1}^{m} P_m(k) P_F(k) \Big/ \log_2(M) \tag{8}$$

where $P_F(k)$ represents the probability that the number of error single tones in the detected MTG is k.

For simplicity, assume the MTG used for sending baseband symbol d_i is $F_p = \{f_1, f_2, \cdots, f_m\}$, the correct detection output should be $U_p = \sum_{j=1}^{m} e_j^p$ as shown in FIGURE.4 and the error decision $U_q = \sum_{j=1}^{m} e_q^j$ corresponds to the MTG F_q.

In the ideal AWGN channel, when the noise power spectral density is N_o. The probability density function (PDF) of each single tone energy e_j^p in the correct MTG obeys the non-central chi-square distribution with two-degrees-of-freedom which can be expressed as:

$$f_p\left(e_j^p\right) = \frac{1}{2\sigma_o^2} \exp\left(-\left(e_j^p + E_c\right)/2\sigma_o^2\right) I_0\left(\sqrt{e_j^p E_c}/\sigma_o^2\right) \tag{9}$$

where $\sigma_o^2 = E_c N_o$ is the variance of a complex Gaussian random variable in which $E_c = E_b/m$. The PDF of error frequency energy e_j^q obeys the central chi-square distribution with two-degrees-of-freedom [18], [19], which can be expressed as:

$$f_q\left(e_j^q\right) = \frac{1}{2\sigma_o^2} \exp\left(-e_j^q/2\sigma_o^2\right) \tag{10}$$

The single tone decision error probability P_f can be obtained by integrating the joint PDF:

$$\begin{aligned} P_f &= P\left(e_j^q - e_j^p\right) \\ &= \int_0^{\infty} \int_{e_j^p}^{\infty} f_p\left(e_j^p\right) f_q\left(e_j^q\right) de_j^p de_j^q \\ &= \frac{1}{2} \exp\left(-r_f/2\right) \\ &= \frac{1}{2} \exp\left(-E_s/2mN_o\right) \end{aligned} \tag{11}$$

where r_f is the corresponding signal-to-noise ratio (SNR) on the single tone. In the ideal channel, when the symbol energy of the code element is fixed to $E_s = P_b T_s$, simplifying Gaussian white noise power to $\sigma_b^2 = NN_o$, the SNR on every single tone of the cooperative receiver can be expressed as [12]:

$$r_f = NP_b / m\sigma_b^2 = SNR_b N / m \tag{12}$$

The event that $e_j^q > e_j^p$ occurs equivalent to an event that there is one single tone that was noise but was judged to be a valid single tone. The number of such events can be represented by $\tilde{k}$ and the relationship between $\tilde{k}$ and k can be described as:

$$k = \begin{cases} \tilde{k}, & \tilde{k} \le m \\ m, & m < \tilde{k} \le N \end{cases} \tag{13}$$

According to Bernoulli's law and the above relationship, $P_F\left(\tilde{k}\right)$ can be expressed as:

$$P_F\left(\tilde{k}\right) = \binom{N}{\tilde{k}} \left(P_f\right)^{\tilde{k}} \left(1 - P_f\right)^{N-\tilde{k}} \tag{14}$$

The BER can be expressed as:

$$P_{BER} = P_s / \log_2(M) = \frac{\sum_{\tilde{k}=1}^{N} P_m\left(\tilde{k}\right) \binom{N}{\tilde{k}} \left(P_f\right)^{\tilde{k}} \left(1 - P_f\right)^{N-\tilde{k}}}{\log_2(M)} \tag{15}$$

When $m \in [m_1, m_2]$ is a time-varying parameter, there is $P_{BER}(m_2) < P_{BER}(m) < P_{BER}(m_1)$. This proves that the T-CMT modulation based on OFDM does not destroy the reliability of the original communication scheme in essence. While the BER is affected by m that is similar to the principle of spectrum expansion when the symbol energy of a unite baseband symbol is fixed, the increase of m reduces the distributable energy on single tone and increases the error detection probability.

Reliability Analysis under Fading Channel: For simplicity, taking Rayleigh fading channel as an example, the BER is analyzed when the fading factor is β.

In Rayleigh fading channel, the PDF of each single tone in the correct MTG obeys the central chi-square distribution with degree of freedom 2 [22], [23], which can be expressed as:

$$f_p\left(e_j^p\right) = \frac{1}{2\sigma_\beta^2} \exp\left(-\left(e_j^p\right) / 2\sigma_\beta^2\right) \tag{16}$$

where $\sigma_\beta^2 = E_c N_o\left(1 + \bar{\gamma}_f\right)$ and $\bar{\gamma}_f = SNR_f E\left(\beta^2\right)$ represents the average SNR at each single tone. The PDF of error frequency energy e_j^q can be expressed as:

$$f_q\left(e_j^q\right) = \frac{1}{2\sigma_o^2} \exp\left(-e_j^q / 2\sigma_o^2\right) \tag{17}$$

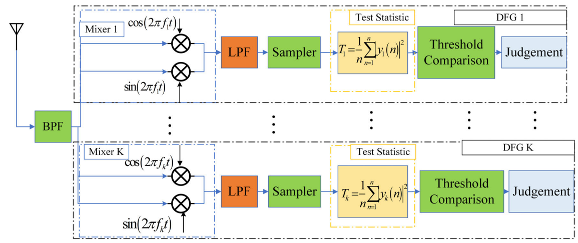

FIGURE 5. Willie's filter bank energy detector.

Similarly, the probability of single tone judgment error can be obtained by integrating the joint probability density function:

$$\tilde{P}_f = 1 / \left(2 + \bar{\gamma}_f\right) \tag{18}$$

Thus, the BER can be expressed as:

$$P_{BER} = \frac{\sum_{\tilde{k}=1}^{N} P_m\left(\tilde{k}\right) \binom{N}{\tilde{k}} \left(\tilde{P}_f\right)^{\tilde{k}} \left(1 - \tilde{P}_f\right)^{N-\tilde{k}}}{\log_2(M)} \tag{19}$$

B. DETECTION ANALYSIS FOR WILLIE

For Willie, the optimal detection scheme for multitone signals is the energy detector based on the filter bank [24], [25]. In this paper, it is assumed that the bandwidth of the detected signal is wide and the specific frequency characteristics of it are unknown for Willie. Considering the worst security situation, as long as Willie could detect the signal in one detected window, the signal is considered to be detected. The detection model based on multi-filter banks is shown in FIGURE.5. Within each detected frequency gap (DFG) the energy is computed and compared to a threshold and the overall detection depends on the judgement outputs of each DFG. Where $T_k = \frac{1}{n} \sum_{n=1}^{n} |y_k(n)|^2$ represents the statistics of the energy detector in the k-th DFG. Assuming Willie's noise spectral density are approximately constant within each DFG which can be denoted as $\sigma_{w,k}^2$.

Noted that $nT_k / \sigma_{w,k}^2$ follows the distribution of Chi-square Probability Density Function $f_{\chi_n^2}$ with n-degree of freedom [18], the hypothesis test model is $\mathcal{H}_1 : T_k > \gamma_k; \mathcal{H}_0 : T_k < \gamma_k$; where $\mathcal{H}_0$ represents there is no signal in the DFG and $\mathcal{H}_1$ represents signal exists. For ease of calculation, the normalized constants are defined as $\alpha_k = n / \sigma_{w,k}^2$ and $\beta_k = n / \left(\sigma_{w,k}^2 + P_{s,k}^w\right)$, thus $\alpha_k T_k |\mathcal{H}_0 \sim f_{\chi_n^2}, \beta_k T_k |\mathcal{H}_1 \sim f_{\chi_n^2}$. Where $P_{s,k}^w = P_b / m$ is a parameter varying with m.

For Willie, due to the lack of prior information on m, while the total transmitting power of the signal is constant, changed threshold cannot be used to judge in the DFG each time. When Willie's observation of the kth band gap is long enough, let $P_{s,k}^w = 2P_b / (m_1 + m_2)$. Under the constant false alarm probability detection method, the false alarm probability in each DFG is $P_{FA,k} = P_r\left(T_k > \gamma_k | H_0\right) = 1 - F_{\chi_n^2}\left(\alpha_k \gamma_k\right)$, where $F_{\chi_n^2}$ is the cumulative chi-square probability density function with degree of freedom n.

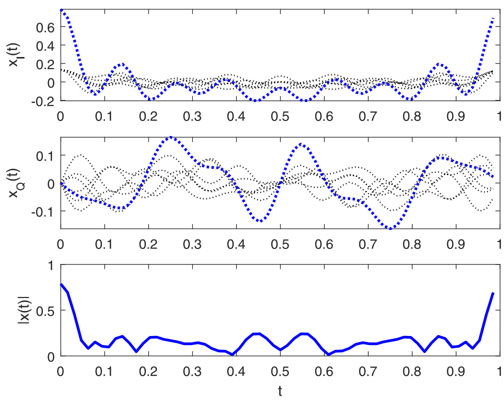

FIGURE 6. Time-domain superimposed signals.

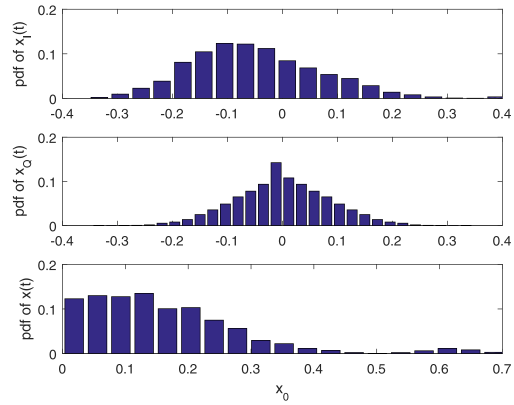

FIGURE 7. Envelope distribution of signals.

The detection threshold is $\gamma_k = F^{-1}_{\chi^2_n}\left(1 - P_{FA,k}\right)\Big/\alpha_k$ and the corresponding detection probability is:

$$\begin{aligned}
&\lim_{n\to\infty} P_{D,k} \\
&\quad = P_r\left(T_k\beta_k > \beta_k\gamma_k \mid H_1\right) \\
&\quad = 1 - F_{\chi^2_n}\left(\beta_k\gamma_k\right) \\
&\quad = 1 - F_{\chi^2_n}\left(n\gamma_k\Big/\left(\sigma^2_{w,k} + P^w_{s,k}\right)\right) \\
&\quad = \frac{1}{m_2 - m_1}\sum_{m=m_1}^{m_2}\left(1 - F_{\chi^2_n}\left(n\gamma_k\Big/\left(\sigma^2_{w,k} + P_b/m\right)\right)\right)
\end{aligned} \tag{20}$$

For conventional CMT communication methods, when m is fixed as $\tilde{m} = (m_1 + m_2)/2$, the detection probability is:

$$\lim_{n\to\infty} \tilde{P}_{D,k} = 1 - F_{\chi^2_n}\left(n\gamma_k\Big/\left(\sigma^2_{w,k} + P_b/\tilde{m}\right)\right) \tag{21}$$

Let $F^{-1}_{\chi^2_n}\left(1 - P_{FA,k}\right) = \tau$, we can obtain that $n\gamma_k\Big/\left(\sigma^2_{w,k} + P_b/\tilde{m}\right) = \tau/\left(1 + SNR_{w,k}\right)$, where $SNR_{w,k} = P_b\Big/\tilde{m}\sigma^2_{w,k}$.

Because $F_{\chi^2_n}(x)$ is a convex function about x, while the extreme point is η, according to Jensen Inequality [26], when $\tau/\left(1 + SNR_{w,k}\right) < \eta$, $\tilde{P}_{D,k} \geq P_{D,k}$, it can be concluded that the existence of time-varying parameters at a range of SNR can theoretically reduce the detection probability of Willie.

IV. EXPERIMENTAL VERIFICATION AND PERFORMANCE EVALUATION

A. SIGNATURE ANALYSIS

In order to analyze the performance of the signal waveform itself, the time domain signals were simulated; the envelope distribution of the signal and the power spectrum density (PSD) under different time-varying parameters were counted.

When the number of available frequency points was $N = 16$ and the range of time-varying parameter m was $m_1 = 4, m_2 = 7$, the initial phase of each single tone is 0 by default. The time-domain superposition signal after IFFT transform was shown in FIGURE.6

As shown in FIGURE.6, only when the initial phase is superimposed, the signal would have a peak-to-average power ratio (PAPR). While the reason for the large PAPR of conventional OFDM symbols is the superposition of multiple subcarrier signals. Because of $m/N < 1$, the existence of vacant carrier and time-varying parameters can reduce the probability of the same phase between subcarriers. In addition, the results in [20] show that the effect of PAPR reduction depends on the allocation of subcarriers for each user. The coding part of the OFDM-based T-CMT modulation method can be equivalent to the subcarrier allocation of discrete fourier transform (DFT) spread spectrum frequency division multiple access (FDMA). Each symbol corresponds to a set of subcarriers to transmit data, and the unused sub-carrier is filled to 0. The difference is due to the randomness of MTG intermediate frequency point distribution in the T-CMT modulation method, its PARP enhancement performance should be between interleaved FDMA (IFDMA) and localized FDMA (LFDMA) in DFT spread spectrum.

In theory, when the protection interval is large enough, the real and imaginary parts of the time domain complex signal should gradually obey Gaussian distribution and the signal envelope should gradually obey Rayleigh distribution. The square distributions of the real part, imaginary part and envelope were counted respectively, as shown in FIGURE.7.

It can be seen from FIGURE.7 that the real part and imaginary part of the complex signal obey Gaussian distribution and envelope obey Rayleigh distribution [26], [27], which is consistent with the hypothesis of test statistics in theoretical analysis.

To verify the PSD of the multitone signal corresponding to a single code element under different m, the power spectrum at different m was analyzed by oversampling and interpolation of the signal, as shown in FIGURE.8.

It can be seen from FIGURE.8 that in the ideal condition without any interference, the frequency characteristics of the signal can be detected by the spectrum characteristics of the observed signal, which provides a basis for the correct demodulation of the cooperative receiver. The specific detection method based on FFT analysis is consistent as described in the third part of the Section II.

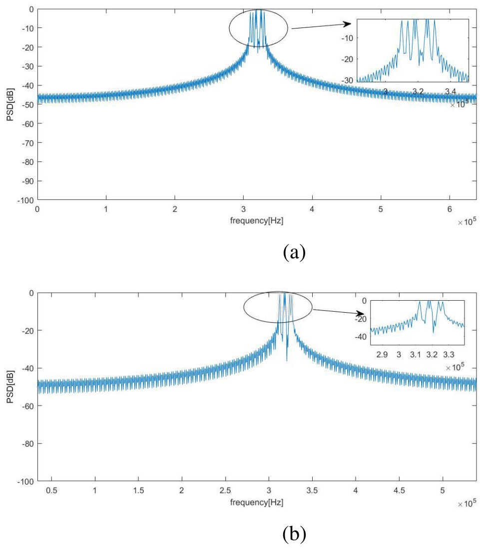

FIGURE 8. PSD of multitone signal under time-varying parameters. (a). PSD of one multitone signal when m=6. (b). PSD of one multitone signal when m=5.

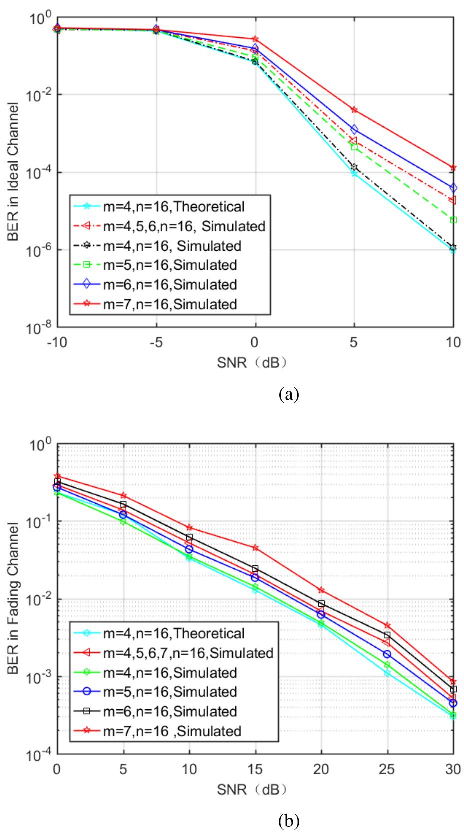

FIGURE 9. BER test and comparison. (a). The simulated and theoretical BER of fixed and variable m under different SNR in ideal channel. (b). The simulated and theoretical BER of fixed and variable m under different SNR in fading channel.

B. RELIABILITY TEST

To verify the reliability of the proposed method, the BER of the conventional CMT method under the different numbers of single tones of MTG and T-CMT method were tested in the ideal channel and Rayleigh fading channel respectively. Notably, to avoid the loss of frequency information, four times oversampling is used in the experiment [21], which is equivalent to a $6dB$ increase in SNRs compared with the theoretical analysis. The BER test and comparison under different channel environments were shown in FIGURE.9.

After removing the SNR compensation caused by oversampling, the theoretical BER curve is basically consistent with the simulated curve. It can be seen from FIGURE.9 that the reliability of the proposed method conforms to the conclusion in theoretical analysis that $P_{BER}(m_2) < P_{BER}(m) < P_{BER}(m_1)$. In short, the introduction of this time-varying parameter would not destroy the original reliability.

C. DETECTION PROBABILITY OF WILLIE

The concealment was evaluated by testing the detection ability of Willie under different SNR with the constant false alarm probability. Based on the Monte Carlo method, the detection probability of each single tone was tested with the conventional CMT communication method $m = 5$ and the proposed method m randomly changes among $\{4, 5, 6\}$. The measured detection probability curves under different SNR were shown in FIGURE.10.

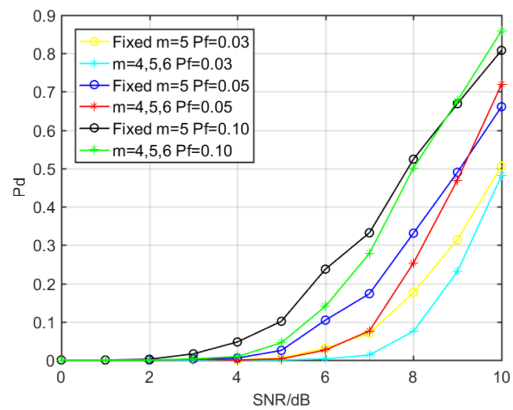

FIGURE 10. Detection probability of Willie under different SNR with the constant false alarm probability method.

In a certain range of SNR, to ensure that the range of detection probability of Willie is $P_d \leq 0.1$, the requirements for SNR of the proposed method can be increased by $1 - 2dB$. In conclusion, when the range of SNR is $0dB - 8dB$, the introduction of time-varying parameters can reduce the detection probability of Willie and improves the concealment of the system.

V. CONCLUSION

This paper introduces time-varying parameters to increase the randomness of the waveform and improves the spectral efficiency based on the original CMT method, and reduce implementation complexity based on the OFDM method. The proposed method gets rid of the drawbacks of conventional LPD communication methods in exchange for LPD enhancement at the cost of their reliability loss or sacrificing more resources. The specific implementation of the corresponding module of this communication method is given and the reliability of it and its contribution to reducing the detection probability of eavesdropper are analyzed theoretically. Theoretical analysis shows that this method can ensure the original reliability performance. Meanwhile it brings detection uncertainty for the eavesdropper parties, thus reducing its detection probability and improving its covertness at low SNR. In the experimental simulation part, first, the time-domain characteristics of the signal show that the proposed method can reduce the PAPR due to the existence of vacant subcarriers, which have engineering practicability. Second, the communication reliability of the proposed method is evaluated by simulating and comparing the influence of time-varying parameters on BER under different channel conditions. Finally, the relationship between the detection performance of eavesdroppers under the constant false alarm probability detection scheme and the energy threshold which is represented by the SNR of the received signal is simulated. The experimental results prove that the scheme can reduce the detection probability of eavesdroppers while ensuring the original reliability. In this paper, the energy loss caused by different single tones in the long-distance transmission is ignored and the next work will consider the engineering implementation of the receiver and transmitter based on this.

REFERENCES

[1] L. Wang, G. W. Wornell, and L. Zheng, "Fundamental limits of communication with low probability of detection," *IEEE Trans. Inf. Theory*, vol. 62, no. 6, pp. 3493–3503, Jun. 2016.
[2] W. Trappe, "The challenges facing physical layer security," *IEEE Commun. Mag.*, vol. 53, no. 6, pp. 16–20, Jun. 2015.
[3] B. A. Bash, D. Goeckel, and D. Towsley, "LPD communication when the warden does not know when," in *Proc. IEEE Int. Symp. Inf. Theory*, Jun. 2014, pp. 606–610.
[4] K. W. Huang, H. M. Wang, D. Towsley, and H. V. Poor, "LPD communication: A sequential change-point detection perspective," *IEEE Trans. Commun.*, vol. 68, no. 4, pp. 2474–2490, Apr. 2020.
[5] S. Lee, R. J. Baxley, M. A. Weitnauer, and B. Walkenhorst, "Achieving undetectable communication," *IEEE J. Sel. Topics Signal Process.*, vol. 9, no. 7, pp. 1195–1205, Oct. 2015.
[6] Q. E. Zhang, M. Bakshi, and S. Jaggi, "Covert communication over adversarially jammed channels," in *Proc. IEEE Inf. Theory Workshop (ITW)*, Nov. 2018, pp. 1–5.
[7] E. Başar, "OFDM with index modulation using coordinate interleaving," *IEEE Wireless Commun. Lett.*, vol. 4, no. 4, pp. 381–384, Apr. 2015.
[8] K. J. Kim, H. Liu, M. Wen, P. V. Orlik, and H. V. Poor, "Distributed asynchronous cyclic delay diversity-based cooperative systems with a passive eavesdropper," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2019, pp. 1–6.
[9] R. Soltani, B. Bash, D. Goeckel, S. Guha, and D. Towsley, "Covert single-hop communication in a wireless network with distributed artificial noise generation," in *Proc. 52nd Annu. Allerton Conf. Commun., Control, Comput. (Allerton)*, Sep. 2014, pp. 1078–1085.
[10] R. Chen, J. Shi, L.-L. Yang, Z. Li, and L. Guan, "High-security sequence design for differential frequency hopping systems," *IEEE Syst. J.*, early access, Sep. 15, 2020, doi: 10.1109/JSYST.2020.3018115.
[11] Y. Fu, S. Guo, and Z. Yu, "The modulation technology of chaotic multitone and its application in covert communication system," *IEEE Access*, vol. 7, pp. 122289–122301, 2019.
[12] S. Guo, Y. Fu, and L. Yu, "An encrypted multitone modulation method for physical layer security based on chaotic cryptography," *Phys. Commun.*, vol. 47, Aug. 2021, Art. no. 101389.
[13] Y. Zhang, H. Wang, J. Chen, A. Wang, L. Meng, and E. Wang, "Calibration and impact of BeiDou satellite-dependent timing group delay bias," *Remote Sens.*, vol. 12, no. 1, p. 192, Jan. 2020.
[14] W. Zhang, C. Zhang, C. Chen, W. Jin, and K. Qiu, "Joint PAPR reduction and physical layer security enhancement in OFDMA-PON," *IEEE Photon. Technol. Lett.*, vol. 28, no. 9, pp. 998–1001, May 1, 2016.
[15] A. M. Tonello, "A novel multi-carrier scheme: Cyclic block filtered multitone modulation," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Jun. 2013, pp. 5263–5267.
[16] W. Duan, Y. Ji, J. Hou, B. Zhuo, M. Wen, and G. Zhang, "Partial-DF full-duplex D2D-NOMA systems for IoT with/without an eavesdropper," *IEEE Internet Things J.*, vol. 8, no. 8, pp. 6154–6166, Apr. 2021.
[17] S. Adnan, Y. Fu, B. J. Ahmed, M. F. Tahir, and F. Banoori, "Modified ordered successive interference cancellation MIMO detection using low complexity constellation search," *AEU Int. J. Electron. Commun.*, vol. 121, Jul. 2020, Art. no. 153223.
[18] T. G. Dvorkind and A. Cohen, "Maximizing miss detection for covert communication under practical constraints," in *Proc. IEEE Stat. Signal Process. Workshop (SSP)*, Jun. 2018, pp. 712–716.
[19] B. Ning, Z. Li, L. Guan, and F. Zhou, "Probabilistic frequency-hopping sequence with low probability of detection based on spectrum sensing," *IET Commun.*, vol. 11, no. 14, pp. 2147–2153, 2017.
[20] X. Fu, M. Bi, X. Zhou, G. Yang, Q. Li, and Z. Zhou, "A chaotic modified-DFT encryption scheme for physical layer security and PAPR reduction in OFDM-PON," *Opt. Fiber Technol.*, vol. 42, pp. 126–131, May 2018.
[21] E. Zochmann, S. Pratschner, S. Schwarz, and M. Rupp, "Limited feedback in OFDM systems for combating ISI/ICI caused by insufficient cyclic prefix length," in *Proc. 48th Asilomar Conf. Signals, Syst. Comput.*, Nov. 2014, pp. 988–992.
[22] G. Liangcai, D. Yahui, and L. Yuanyuan, "Performance analysis of short-wave wideband channel model," *Chin. J. Electronics.*, vol. 16, no. 1, pp. 132–135, 2007.
[23] Z. Chen, Y. Song, and B. Dong, "Performance of a compressed spectrum differential frequency hopping system over Rayleigh fading channels," in *Proc. MILCOM IEEE Mil. Commun. Conf.*, Nov. 2013, pp. 781–785.
[24] J. Liu, S. Xing, and L. Shen, "Lattice-reduction-aided sphere decoding for MIMO detection achieving ML performance," *IEEE Commun. Lett.*, vol. 20, no. 1, pp. 125–128, Jan. 2016.
[25] P. L. Ramos, F. Louzada, and E. Ramos, "An efficient, closed-form MAP estimator for Nakagami-*m* fading parameter," *IEEE Commun. Lett.*, vol. 20, no. 11, pp. 2328–2331, Nov. 2016.
[26] M. Wu, X. Lin, and P.-Y. Kam, "New exponential lower bounds on the Gaussian Q-function via Jensen's inequality," in *Proc. IEEE 73rd Veh. Technol. Conf. (VTC Spring)*, May 2011, pp. 1–5.
[27] B. A. Bash, D. Goeckel, and D. Towsley, "Limits of reliable communication with low probability of detection on AWGN channels," *IEEE J. Sel. Areas Commun.*, vol. 31, no. 9, pp. 1921–1930, Sep. 2013.

SHENGNAN GUO received the B.S. degree in electronic information engineering from Northeast Forestry University, Harbin, China, in 2014. She is currently pursuing the Ph.D. degree in information and communication engineering with Harbin Engineering University, Harbin. Her current research interests include communication security, covert communication, and weak signal detection.

YONGQING FU received the B.S. degree in automatic control and the M.S. degree in electronic engineering from Harbin Engineering University, in 1982 and 1984, respectively, and the M.S. degree from the National University of Defense Technology, in 1985. He is currently a Professor and the Doctoral Supervisor with Harbin Engineering University. He is also the Leader of the Research Team of Radio Telemetry and Remote Control Technology. He has completed more than ten scientific research projects, published more than 120 articles, edited and published three textbooks and three monographs, and has been granted more than ten national invention patents. His current research interests include weak signal detection, electronic reconnaissance technology, chaotic communication, covert communication technology, virtual time reverse passive direction finding radar technology, and high-speed frequency hopping signal position tracking technology.