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RESEARCH ARTICLE

Fountain Code-Based LT-SLT Anti-Eavesdropping Coding Design

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ABSTRACT In wireless communication wiretap channel, for the eavesdropper to obtain the legitimate receiver decoding rules situation, this paper proposes a LT-SLT fountain code anti-eavesdropping channel coding design. This method targets the Luby Transform (LT) code transmission for some of the original symbols of the Shifted LT (SLT) code and utilizes the fountain code to receive the correct symbols in different noise channels with differential characteristics so that the decoding process of the eavesdropper changes and cannot be decoded in synchronization with the legitimate receivers, and then the partial symbols of the recovered source are different from those of the legitimate receivers. When these symbols continue to participate in SLT decoding, increasing the untranslated rate of the eavesdropper. Experimental results show that although the method proposed in this paper increases the number of decoded symbols by a small amount, the eavesdropper untranslated rate of this scheme gets improved by about 15% when the main channel or the wiretap channel is varied individually, compared with LT code and SLT code. When both the main channel and the wiretap channel are varied simultaneously, the untranslated rate of the eavesdropper in this scheme gets approximately 30% higher compared to LT code and SLT code, and the untranslated rate of the eavesdropper in this scheme gets approximately 14% higher compared to SLT-LT fountain code. When the main channel is worse or slightly better than the wiretap channel, the untranslated rate of eavesdroppers of this scheme is better than that of SLT-LT fountain code, which effectively ensures secure transmission of information.

INDEX TERMS Anti-eavesdropping, erase channel, physical layer security, fountain codes, coding complexity.

I. INTRODUCTION

With the rapid development of modern communication, a large amount of data is collected and transmitted, and in the process of data transmission, there is a risk of data privacy leakage, and most privacy protection efforts fail to achieve the desired data utility. For the network information security transmission problem, literature [1] proposes to use the Markov Chain Monte Carlo to infer the optimal dendrogram and generate sanitized data graphs to ensure data utility and protect data privacy, however, the large amount of data generated by this method burdens the wireless network. On heterogeneous edge IoT networks, literature [2], [3] alleviates the stress caused by data transmission through multi-access edge computing resource optimization and optimal caching probability algorithms. There is a desire to find a transmission scheme that reduces data transmission redundancy while ensuring secure transmission of information.

The Shannon's information-theoretic security model [4] and the wiretap channel model proposed by Wyner [5] provide a strong foundation for the development of secure transmission of information at the physical layer.

Currently, there exist various solutions to ensure the security of the communication. For example, literature [6] proposes to utilize transmit power algorithms to communicate

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with the cooperation of multiple Cooperating Relays. As well as the literature [7] exploit node cooperation to achieve physical layer based security by retransmitting a weighted version of the source signal or weighted noise that reduces the transmit power and secrecy power to a one variable. Utilizing the inherent properties of wireless channels, literature [8] proposes a secure multi-antenna transmission method based on artificial-noise-aided beamforming, and literature [9] proposes a cooperative diversity method to achieve secure communication. In addition, literature [10] enhanced system confidentiality by combining secrecy beamforming with cooperative jamming, and literature [11] utilized stochastic geometry to investigate the physical layer security of non-orthogonal multiple access in large-scale networks. In wireless communications in the presence of eavesdropping attacks, the literature [12] presents opportunistic relay selection and quantifies the improvements that can be made to the security-reliability tradeoffs when increasing the number of relays.

Physical layer security coding also ensures the security and reliability of information transmission. Based on information-theoretic principles, literature [13] has theoretically demonstrated a secrecy method based on channel coding design, whereby by encoding and transmitting a precoding scheme as well as utilizing channel state information, it is possible to achieve secret communication over a wireless medium. When the channel is noisy, literature [14] constructs secure encoders relying on pruning a mother convolutional code secretly are constructed. This results in a secret subspace that legitimate users are using to perform decoding, in contrast to an eavesdropper that employs the mother code which improves semantic security.

In order to realize secure communication, the combination of fountain code and existing anti-eavesdropping technology is widely used in physical layer secure transmission with certain anti-eavesdropping function. Literature [15] proposes a fountain-coding aided PLS scheme that combines cooperative jamming and constellation rotation approach to reduce the negative effect of the jamming on the legitimate receiver while deteriorating the quality of the wiretap channel. Literature [16] develops a fountain coding mechanism that dynamically adjusts the construction of fountain codes through feedback, utilizes transmit power control to enhance the packet reception rate at the legitimate receiver, and reduces the decoding delay. Literature [17] proposes a dynamic fountain-coding aided secure transmission method for fading wiretap channels, where the source adjusts the number of transmitted FC packets based on the channel quality of the legitimate link, thereby reducing the decoding delay at the legitimate receiver. Literature [18] proposes a fountain code video coding strategy based on an indefinite length window, which introduces interfering noise to guarantee lower intercept probability while degrading the quality of the eavesdropper's signal. Literature [19] proposes Online Fountain Codes without Build-up phase and Systematic Online Fountain Codes to achieve a trade-off between the intermediate performance and the full recovery overhead. Literature [20] utilizes the implicit transmission mechanism of codebook information and the independent fading of wireless channels to propose a secure transmission scheme via cross-locking between the fountain-coded data and the codebook information, and protects the codebook information between data by encrypting the key associated with the generating matrix in combination with the upper layer encryption protocol. Literature [21] proposes relative-entropy-based fountain codes, where the distance between the degree distribution of coded symbols adjusted at the transmitter and the robust soliton distribution is measured by relative entropy. It outperforms previous fountain codes with feedback in terms of intermediate performance with low overhead. Literature [22] proposes a weighted online fountain code with low feedback, which can reduce buffer occupancy and feedback transmission with good intermediate performance by adjusting the weights. A secure multi-path transmission algorithm based on fountain codes—FMPST is proposed in the literature [23], which evaluates the channel packet loss rate through an improved random forest model and utilizes the FMPST algorithm to reduce data leakage and link congestion. For the communication confidentiality protocol is easy to be deciphered and stolen, literature [24], [25] pointed out that LT code, SLT code, and other fountain codes can be used as anti-eavesdropping codes, and combining them can greatly increase the untranslated rate of eavesdroppers. As a result, literature [24] proposes DEMR-LT codes and also points out that the part of the encoding matrix is reordered according to the degree value of each column from large to small, to delay the appearance of the degree 1 symbol at the receiving node during the BP decoding process to reduce the interception efficiency of the eavesdropper. Literature [25] proposes SLT-LT joint code anti-eavesdropping codes and states that the ratio of recovered symbols n at the receiving end to the original symbols k at the source in the SRSD degree distribution in the SLT code is 0.2, which allows for the eavesdropper to reach a high the false symbol rate.

Aiming at the situation that the eavesdropper obtains the decoding rules of the legitimate receiver, this paper proposes a physical layer LT-SLT fountain code anti-eavesdropping scheme. Based on the SLT code structure, some of the original symbols of the source are first LT coding, and then the SRSD degree distribution is adjusted to send the SLT code. The receiver jointly decodes the decoded portion of the original symbols of the source with the SLT code to recover all the original symbols of the source. In this paper, the LT-SLT fountain code scheme is theoretically analyzed from the number of decoded symbols and coding complexity, and from the experimental results, it is noted that the eavesdropper untranslated rate of the scheme is improved to a certain extent, to ensure secure transmission of information.

The remainder of this paper is organized as follows: Section II introduces the basic coding and decoding models and their associated definitions. Section III proposes a LT-SLT fountain code encoding method to improve the security of data transmission. Section IV presents the related analysis. Section V gives the conclusions of this article.

II. FOUNTAIN CODE WIRETAP CHANNEL MODEL

Fountain code is a code-rate-free code suitable for the erase channel, which randomly selects source symbols for XOR computation based on the degree distribution function, obtains encoded symbols, and sends them to the receiver in a continuous stream. The receiver keeps receiving encoded symbols until it receives a degree 1 encoded symbol to start decoding. Each translated data symbol carries out an XOR operation with all the encoded symbols connected to it, and the result of the calculation replaces the original value of the corresponding encoded symbols, and deletes the connection relationship with them after the completion of the operation. The above process is repeated until all source symbols are recovered. This decoding method is called Belief Propagation (BP) decoding [26].

Due to the randomness of the fountain code encoding, and the existence of channel condition differences between the main channel and the wiretap channel, leading to the eavesdropper is more difficult to steal useful information, with a certain degree of anti-eavesdropping function. Based on the traditional anti-eavesdropping model [5], the physical layer selects the fountain code anti-eavesdropping encoding, which can increase the untranslated rate of eavesdroppers to a certain extent, and its structure is shown in Fig. 1.

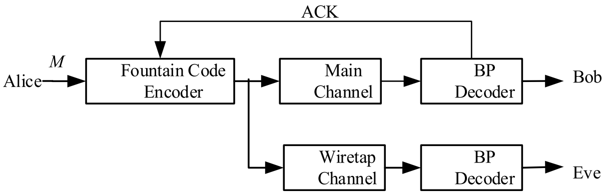

FIGURE 1. Fountain code wiretap channel model.

In Fig. 1, it can be seen that in wireless communication systems, the wiretap channel model of fountain codes mainly consists of the source (Alice), the legitimate receiver (Bob), the eavesdropper (Eve), the main channel and the wiretap channel and the ACK feedback. Alice sends fountain code coded symbols through the main channel, Bob performs BP decoding on the received coded symbols, and when the source information is recovered, then an ACK is sent to inform Alice to stop sending coded symbols. At the same time, Eve can also receive the fountain code coded symbols sent by Alice through the wiretap channel. Due to the difficulty of having the same noise in the main channel and the wiretap channel, there are differences in the coded symbols received by Eve and Bob, and the process of BP decoding performed by Eve is different from that of Bob. If Alice stops sending coded symbols, Eve has an unfinished decoding situation, resulting in an untranslated rate. The greater the Eve untranslated rate, the more secure the communication system is. The magnitude of the untranslated rate of Eve is related to the design scheme of the fountain code, and the design of the encoding matrix.

A. DEGREE DISTRIBUTION FUNCTION FOR THE FOUNTAIN CODE

Literature [27] proposes a RSD degree distribution of the fountain code, as shown in (1)

$$\mu\left(d\right)=\frac{\rho\left(d\right)+\tau\left(d\right)}{z}\quad d=1,2,\cdots,k \tag{1}$$

where K represents the number of original symbols in the source, d represents the degree of the RSD encoded symbol. $z=\sum_d\left(\rho\left(d\right)+\tau\left(d\right)\right)$, $p\left(d\right)$ represents the ideal soliton distribution, $\tau\left(d\right)$ represents the enhancement factor.

The fountain code obtained from the RSD degree distribution is called the LT code.

When part of the information n has been recovered at the receiving end, shifting the RSD degree distribution function yields the SRSD degree distribution function [28].

$$\gamma(j)=u_{(k-n)}(d)\text{ for }j=\text{round}\left(\frac{d}{1-n/k}\right) \tag{2}$$

where n denotes the number of correct original symbols known at the receiving end, $u_{(k-n)}(d)$ denotes the RSD degree distribution function of the transfer n, and j represents the degree of the RSD encoded symbols.

If the receiving end has recovered n symbols, the source obtains the SRSD degree distribution according to n, and the resulting fountain code is called the SLT code.

B. WIRETAP CHANNEL FOUNTAIN CODE ENCODING MATRIX

Literature [24] proposes to rearrange the fountain code encoding matrix based on the size of the RSD degree value to obtain an LT code encoding matrix suitable for use in the wiretap channel. Let there be the main channel deletion probability P_{AB} and k source symbols. The first ${}^{k}\!/_{1-P_{AB}}$ columns of the encoding matrix are selected and rearranged according to the degree value d in each column from largest to smallest to get the encoding matrix G_1. In order to ensure that all source symbols can be completely recovered in the final decoding, the encoding matrices of columns ${}^{k}\!/_{1-P_{AB}}+1$ through w are obtained from the degree distribution G_2, thus obtaining the fountain code encoding matrix G.

$$G=\left(G_1,G_2\right)_{k\times w} \tag{3}$$

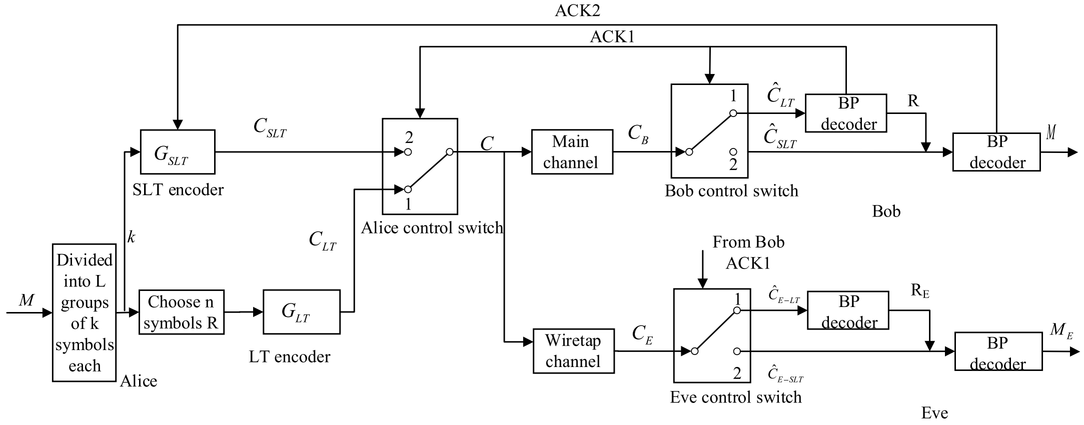

FIGURE 2. LT-SLT fountain code anti-eavesdropping model.

where G_1 is the $k \times {}^{k}/_{1} - P_{AB}$ matrix and G_2 is the $k \times \left(w - {}^{k}/_{1} - P_{AB}\right)$ matrix. To ensure a sufficient number of decoded symbols $w \gg {}^{k}/_{1} - P_{AB}$.

III. LT-SLT FOUNTAIN CODE ANTI-EAVESDROPPING CODE

Aiming at the situation that the eavesdropper obtains the decoding rules of the legitimate receiver, this paper designs the LT-SLT fountain code anti-eavesdropping model at the physical layer. Let the source k original symbols, on the basis of SLT code as the anti-eavesdropping code, this paper on the randomly selected n encoded symbols first LT encoding, and then SLT encoding, to construct LT-SLT fountain code anti-eavesdropping code. And both encoding processes rearrange the partial encoding matrix according to the degree value of each column from the largest to the smallest, so as to delay the start time of decoding at the receiving node and improve the untranslated rate of the eavesdropper, thus realizing the purpose of anti-eavesdropping. The LT-SLT fountain code anti-eavesdropping model for the physical layer is shown in Fig. 2.

In Fig. 2, the LT-SLT fountain code anti-eavesdropping model consists of a source (Alice), a legitimate receiver (Bob) and an eavesdropper (Eve). Let the main channel and the wiretap channel are erase channels with deletion probabilities P_{AB} and P_{AE}, respectively. Before encoding, the source Alice agrees with the legitimate receiver Bob to randomly select n symbols in the position of the source's original symbols and the encoding matrix information. The fountain code encoding matrix used is obtained from equation (3): the LT encoding matrix is $G_{LT} = (G_{LT-1}, G_{LT-2})_{n \times w_1}$, where G_{LT-1} is the RSD degree distribution rearranged $n \times \frac{n}{1-P_{AB}}$ order matrix and G_{LT-2} is the $n \times \left(w_1 - \frac{n}{1-P_{AB}}\right)$ order matrix obtained from the RSD degree distribution with $w_1 \gg \frac{n}{1-P_{AB}}$; the SLT encoding matrix is $G_{SLT} = (G_{SLT-1}, G_{SLT-2})_{k \times w_2}$, where G_{SLT-1} is an $k \times \frac{k-n}{1-P_{AB}}$ order matrix rearranged based on the SRSD degree distribution, G_{SLT-2} is an $k \times \left(w_2 - \frac{k-n}{1-P_{AB}}\right)$ order matrix based on the SRSD degree distribution, and $w_2 \gg \frac{k-n}{1-P_{AB}}$.

The design method for LT-SLT fountain code anti-eavesdropping at the physical layer is described in the following steps:

(1) Alice splits the message M to be sent into L groups of source symbols, each group containing k source original symbols. Select the k source symbols in group 1.

(2) The Alice control switch of the source points to "1". Among the k source original symbols, $n = 0.2k$ [22] source original symbols, i.e., the set R, are selected according to the agreement with Bob, and the G_{LT} encoding matrix performs LT encoding on the selected n symbols, and the resulting LT code G_{LT} is sent to the legitimate receiver in a continuous sequence.

(3) At the receiving end, Bob control switch points to "1", receives the LT code $\hat{C}_{LT}$ through the main channel, selects the correct $\hat{C}_{LT}$ symbols, performs BP decoding, and decodes the set R. At the end of LT decoding, sends ACK1 to the source, and at the same time, Bob control switch points to "2".

(4) Alice receives ACK1, points the Alice control switch to "2", and stops sending LT code. At the same time, SLT encoding is performed on the k source original symbols, and the encoding matrix uses G_{SLT} to obtain C_{SLT} symbols, which are sent to Bob in a continuous stream.

(5) Bob receives the $\hat{C}_{SLT}$ symbols sequentially, selects the correct $\hat{C}_{SLT}$ symbols, performs BP decoding together with the n source original symbols in the recovery set R in step (3), and obtains k source symbols after recovering the remaining $k - n$ source original symbols. Send to ACK2 to Alice;

(6) Alice receives ACK2 and stops sending SLT codes. Select the next set of encoded symbols and repeat steps (2) (3) (4) (5) (6) until Bob recovers the L set of source symbols M;

(7) End.

In the wiretap channel, if Eve knows Bob's decoding rules, it also needs to receive the $\hat{C}_{E-LT}$ for BP decoding to recover the source L groups encoded packet. Due to the randomness of the erase channel error symbols, there is a difference between the encoded symbols $\hat{C}_{E-SLT}$ received by Eve and $\hat{C}_{SLT}$ received by Bob, resulting in a situation where the number of symbols in the recovered R set is equal to or less than n. If the number of recovered symbols is less than n, Eve needs to receive more $\hat{C}_{E-SLT}$ symbols to complete the decoding to get M. After Bob ends the decoding, when Alice no longer sends encoded symbols, Eve is unable to continue decoding, resulting in more untranslated original symbols, i.e., the number of M_E is less than that of M, and Eve exists a higher untranslated rate. If the number of recovered symbols is equal to n, the randomness of the erase channel error symbols, the existence of Eve completing the decoding with Bob at the same time, or only partially completing the decoding, there will also be a certain number of untranslated original symbols, and there exists the case where the number of M_E is less than M. It can be seen that this method makes it difficult to recover all source symbols of L groups even if Eve has known legal reception rules.

IV. LT-SLT FOUNTAIN CODE PERFORMANCE ANALYSIS

A. LT-SLT FOUNTAIN CODE DECODING PROCESS

According to Fig. 2, the LT-SLT fountain code encoding method of this paper is used to observe the BP decoding process of receiving symbols by the legitimate receiver Bob. Let the number of the source original symbols for each group $k = 200$, and $n = 0.2k$ in the set R. A total of $L = 5000$ sets of encoded symbols are sent and averaged over them, where the RSD degree distribution and SRSD degree distribution are set to $c = 0.03$, $\delta = 0.05$, and the main channel deletion probability $P_{AB} = 0.3$. The experimental results are shown in Fig. 3.

Fig. 3 shows that the LT-SLT fountain code decoding process under erase channel conditions consists of three parts. First paragraph, 0$\sim$61.25. The encoded symbols received by Bob are LT codes under the erase channel, and since the encoding matrix is arranged according to the value of the degree from the largest to the smallest, almost all of the 52.5 encoded symbols received first have a degree greater than "1", and the number of decoded code symbols is close to 0. In the first segment, when the number of received encoded symbols is greater than 52.5, it starts to receive degree "1" symbols for BP decoding, and Bob quickly decodes and receives the number of encoded symbols until 61.25, and the number of decoded code symbols reaches 39.18, which almost recovers the set R symbols.

Second paragraph, 61.25$\sim$201.3. Bob starts receiving SLT encoded symbols under the erase channel and jointly BP decodes them with the set R. The encoding matrix of the SLT code is arranged according to the degree from the largest to the smallest, and the encoded symbols with the larger encoding degree are received first, even though the 40 original symbols of the source with the equivalent degree "1" in the set R are already present in the Bob, they cannot be decoded because they have not been received with the contained low-degree encoded symbols yet. The average number of decoded symbols increases by only 0.82 when 122.5 encoded symbols are received. When continuing to increase the number of SLT encoded symbols to 201.3, the average number of decoded symbols increases by only 16.

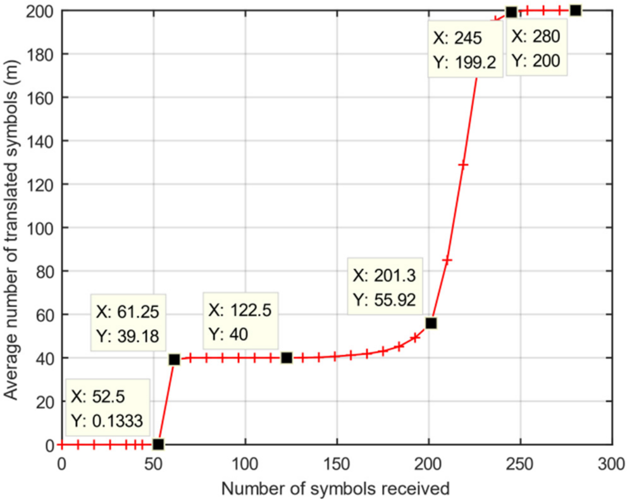

FIGURE 3. Decoding process of LT-SLT fountain code under erase channel.

Third paragraph, 201.3$\sim$245. Bob continues to start receiving SLT encoded symbols under the erase channel, accumulating enough SLT encoded symbols of low degree that the number of decoded symbols increases rapidly from 55.92 to 199.2 until all source original symbols are recovered.

In LT-SLT fountain code for wiretap channels, LT-SLT encoding is performed on one of the sets of source symbols, and when n original symbols are recovered at the end of the first stage of Bob's LT code decoding, the number of Eve decoded symbols, m, exists less than or equal to n. In the second stage, Eve waits for the arrival of low-degree encoded symbols to start decoding as Bob does, but if m is smaller than n, even if low-degree encoded symbols are received, the BP decoding time may start later than Bob due to the insufficient number of degree "1" symbols. When Bob enters phase 3 and decodes quickly, Eve has trouble keeping up with Bob's decoding speed. When Bob has finished decoding and Alice is no longer sending encoded symbols, Eve has a certain number of untranslated symbols. If the number of symbols m decoded by Eve is equal to n, since SLT codes are also fountain codes, there exists a situation where Bob and Eve end the decoding at the same time, and there also exists a situation where Bob ends the decoding earlier than Eve, so that a certain number of untranslated symbols also exist in Eve. Since Alice needs to send L sets of source symbols, a large value of L will, upon accumulation, cause the number of Eve untranslated symbols to reach a high value.

Therefore, using the LT-SLT fountain code as an anti-eavesdropping code, it is difficult for Eve to fully recover the original symbols of Alice's source when Eve acquires the same decoding rules as Bob.

B. THE NUMBER OF DECODING SYMBOLS

1) NUMBER OF SYMBOLS FOR LT-SLT FOUNTAIN CODE DECODING

From the LT-SLT fountain code encoding method, Alice randomly selects n source symbols from a set of k source symbols for LT encoding, and when Bob finishes LT decoding, Alice then performs SLT encoding. Then the number of symbols $m_{LT-SLT}(k)$ required for LT-SLT decoding is equal to the sum of the number of LT codes $m_{LT}(n)$ and the number of SLT codes $m_{SLT}(k-n)$, i.e.

$$m_{LT-SLT}(k) = m_{LT}(n) + m_{SLT}(k-n) \tag{4}$$

Number of encoded symbols $m_{LT}(n)$ required to decode n input symbols by LT fountain codes [27].

$$m_{LT}(n) = n + o(\sqrt{n} \cdot \ln^2(n/\delta)) \tag{5}$$

A decoder that knows n of k input symbols needs the number of encoded symbols $m_{SLT}(k-n)$ by SLT fountain codes [28].

$$m_{SLT}(k-n) = k - n + o(\sqrt{k-n} \cdot \ln^2((k-n)/\delta)) \tag{6}$$

Substituting (5) and (6) into (4) gives:

$$\begin{aligned} &m_{LT-SLT}(k) \\ &= k + o(\sqrt{n} \cdot \ln^2(n/\delta)) + o(\sqrt{k-n} \cdot \ln^2((k-n)/\delta)) \end{aligned} \tag{7}$$

2) COMPARISON OF THE NUMBER OF DECODED SYMBOLS FOR LT-SLT FOUNTAIN CODE AND OTHER FOUNTAIN CODE METHODS

The number of source symbols is k. The number of symbols decoded by the LT-SLT fountain code is compared with the SLT code, SLT-LT fountain code, and LT code, respectively.

a) Comparison of the number of decoded symbols between LT-SLT fountain code and SLT codes

The number of symbols that the SLT codes correctly decodes $m_{SLT}(k)$:

$$m_{SLT}(k) = k + o\left(\sqrt{k-n} \cdot \ln^2\left((k-n)/\delta\right)\right) \tag{8}$$

Comparing (7) and (8), we can get $m_{LT-SLT}(k) > m_{SLT}(k)$.

b) Comparison of the number of decoded symbols for LT-SLT fountain code and SLT-LT fountain code

According to the SLT-LT method, LT coding of SLT encoded symbols $m_{SLT}(k-n)$ results in the number of decoded symbols m_{SLT-LT}.

$$\begin{aligned} &m_{SLT-LT} \\ &= m_{LT}\left(m_{SLT}(k-n)\right) \\ &= m_{LT}\left((k-n) + o\left(\sqrt{k-n} \cdot \ln^2\left((k-n)/\delta\right)\right)\right) \\ &= k - n + o\left(\sqrt{k-n} \cdot \ln^2\left((k-n)/\delta\right)\right) \\ &\quad + o\left(\begin{array}{l} \sqrt{(k-n) + o\left(\sqrt{k-n} \cdot \ln^2\left((k-n)/\delta\right)\right)} \\ \cdot \ln^2\left((k-n) + o\left(\sqrt{k-n} \cdot \ln^2\left((k-n)/\delta\right)\right)/\delta\right) \end{array}\right) \end{aligned} \tag{9}$$

Comparison of the LT-SLT fountain code with the SLT-LT fountain code, i.e., (7)-(9), leads to:

$$\begin{aligned} &m_{LT-SLT}(k) - m_{SLT-LT}(k) \\ &= \left(k + o\left(\sqrt{n} \cdot \ln^2(n/\delta)\right) + o\left(\sqrt{(k-n)} \cdot \ln^2\left((k-n)/\delta\right)\right)\right) \\ &\quad - (k-n) - o\left(\sqrt{k-n} \cdot \ln^2\left((k-n)/\delta\right)\right) \\ &\quad - o\left(\begin{array}{l} \sqrt{(k-n) + o\left(\sqrt{k-n} \cdot \ln^2\left((k-n)/\delta\right)\right)} \\ \cdot \ln^2\left((k-n) + o\left(\sqrt{k-n} \cdot \ln^2\left((k-n)/\delta\right)\right)/\delta\right) \end{array}\right) \\ &= n - o\left(\sqrt{n} \cdot \ln^2(n/\delta)\right) \\ &\quad - \left(o\left(\begin{array}{l} \sqrt{(k-n) + o\left(\sqrt{k-n} \cdot \ln^2\left((k-n)/\delta\right)\right)} \\ \cdot \ln^2\left((k-n) + o\left(\sqrt{k-n} \cdot \ln^2\left((k-n)/\delta\right)\right)/\delta\right) \end{array}\right)\right) \end{aligned} \tag{10}$$

From Eq. (10), since $o(\bullet)$ is higher order infinitesimal, $n = 0.2k$, and k is the number of source symbols, which is usually a large value, then $m_{LT-SLT}(k) - m_{SLT-LT}(k) > 0$, and therefore, $m_{LT-SLT}(k) > m_{SLT-LT}(k)$.

c) Comparison of the number of decoded symbols for LT-SLT fountain code and LT codes

Theorem: the number of source symbols k, if it is divided into 2 parts of length n and $k-n$, and each part is LT coded separately, the sum of the number of decoded symbols in each segment is greater than the number of decoded symbols of length k. i.e:

$$m_{LT}(n) + m_{LT}(k-n) > m_{LT}(k) \tag{11}$$

Proof:

Decoding overhead for LT codes

$$\begin{aligned} &\varepsilon(k) \\ &= \frac{\text{The number of symbols participating in the decoding}}{\text{The number of original symbols in the source}}, \end{aligned}$$

where $\varepsilon(k) > 1$ and $\varepsilon(k) \to 1$.

The original symbol of the source k is divided into two parts into n and $k-n$. LT coding is performed on n and $k-n$, respectively, and the decoding overheads are $\varepsilon(n)$ and $\varepsilon(k-n)$. Since the number of symbols to be decoded by the LT codes decreases with the increase of k, then we have: $\varepsilon(n) > \varepsilon(k)$ and $\varepsilon(k-n) > \varepsilon(k)$.

Multiplying both sides of the inequality by n, $k-n$, respectively, gives by $n\varepsilon(n) > n\varepsilon(k)$, $(k-n)\varepsilon(k-n) > (k-n)\varepsilon(k)$, and adding the two equations, we get,

$$n\varepsilon(n) + (k-n)\varepsilon(k-n) > k\varepsilon(k) \tag{12}$$

where: $n\varepsilon(n)$ is the number of LT codes decoded symbols of length n, and $(k-n)\varepsilon(k-n)$ is the number of LT codes decoded symbols of length $k-n$.

From (12), we have

$$m_{LT}(n) + m_{LT}(k-n) > m_{LT}(k) \tag{13}$$

End (end of proof).

Here, let $n = 0.8k$ and $k - n = 0.8k$ are brought into (5) and (6), respectively, to obtain

$$m_{LT}(0.8k) = m_{SLT}(0.8k) \tag{14}$$

In the LT-SLT fountain code of this paper, $n = 0.2k$, and from (13) and (14), it is obtained that

$$m_{LT}(0.2k) + m_{SLT}(0.8k) > m_{LT}(k) \tag{15}$$

From (15)

$$m_{LT-SLT}(k) > m_{LT}(k) \tag{16}$$

In summary, from the theoretical analysis of a) b) c) above, it is concluded that the number of decoded symbols of the LT-SLT fountain code proposed in this paper is greater than that of LT codes, SLT codes and SLT-LT fountain code.

The structure of the wiretap channel model is set as shown in Fig. 2, and the experimental parameters are the same as in Fig. 3, comparing the number of symbols sent by the source of LT-SLT fountain code with LT codes, SLT codes and SLT-LT fountain code under the variation of P_{AB} of the main channel, and the experimental results are shown in Fig. 4.

From Fig. 4, it can be seen that the number of symbols sent by the source increases with the increase of P_{AB} for all four schemes, where the LT-SLT fountain code requires more encoded symbols than the LT codes, SLT codes and SLT-LT fountain code coding methods, which is the same as the theoretically derived results.

C. CODING COMPLEXITY

1) LT-SLT FOUNTAIN CODE CODING COMPLEXITY

The fountain code uses the degree distribution $\mu(d)$ to obtain the encoding matrix, and uses the XOR calculation to obtain the encoded symbols, the number of XOR calculation determines the size of the encoding complexity, the coding complexity $E(m)$ is related to the number of decodes m and the average degree $\bar{d}$, then there are

$$E(m) = m \cdot \bar{d} \tag{17}$$

From the LT-SLT fountain code coding method, it can be seen that by selecting n symbols from the source length k for LT code encoding, the number of decoded symbols $m_{LT}(n)$ and the coding complexity E_{LT}. Subsequently, SLT encoding is performed on the source length k, with the number of decoded symbols $m_{SLT}(k-n)$ and the coding complexity E_{SLT}.

$$E_{LT-SLT} = E_{LT} + E_{SLT} \tag{18}$$

where LT code average degree of an encoding symbol is $\overline{d_{LT}} = O(\ln(\frac{n}{\delta}))$ [27], then the LT code coding complexity E_{LT} is derived from (17),

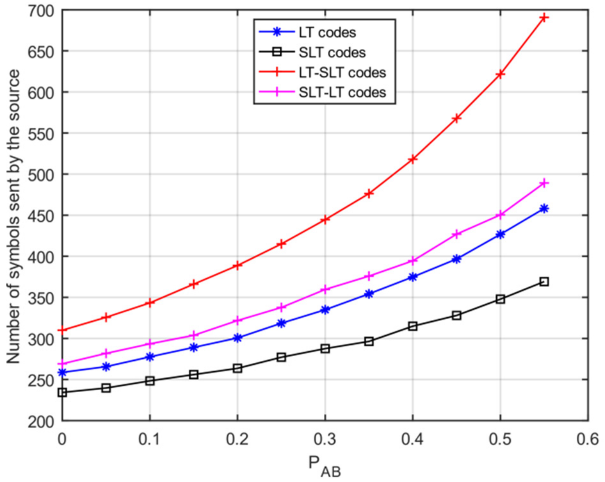

FIGURE 4. Effect of P_{AB} changes on the number of symbols sent by the source.

$$E_{LT} = m_{LT}(n) \cdot \bar{d}_{LT} = m_{LT}(n) \cdot O(\ln(\frac{n}{\delta})) \tag{19}$$

where δ denotes reconstruction failure probability.

The average degree of SLT fountain code [28] $\overline{d_{SLT}} = O(\frac{k}{k-n}\ln(k-n))$, then the SLT code coding complexity E_{SLT} is obtained from (17):

$$\begin{aligned} E_{SLT} &= m_{SLT}(k-n)\left(\overline{d_{SLT}}\right) \\ &= \left(k - n + o(\sqrt{k-n} \cdot \ln^2((k-n)/\delta))\right) \\ &\quad \times O(\frac{k}{k-n}\ln(k-n)) \\ &= O\left(k\ln(k-n)\right) \end{aligned} \tag{20}$$

Bringing (19) and (20) into (18), we get

$$\begin{aligned} E_{LT-SLT} &= m_{LT}(n) \cdot O\left(\ln\left(\frac{n}{\delta}\right)\right) + m_{SLT}(k-n) \\ &\quad \times O\left(\frac{k}{k-n}\ln(k-n)\right) \\ &= \left(n + o\left(\sqrt{n} \cdot \ln^2(n/\delta)\right)\right) \cdot O\left(\ln\left(\frac{n}{\delta}\right)\right) \\ &\quad + \left(k - n + o\left(\sqrt{k-n} \cdot \ln^2((k-n)/\delta)\right)\right) \\ &\quad \times O\left(\frac{k}{k-n}\ln(k-n)\right) \end{aligned} \tag{21}$$

As can be seen from (21), when k is a fixed value, E_{LT-SLT} changes with n. When $n \to 0$, then $E_{LT-SLT}(k) = E_{SLT}(k)$; when $n \to k$, then $E_{LT-SLT} = E_{LT}$.

Continued simplification of (21) yields the following mathematical expression for the coding complexity of the LT-SLT fountain code:

$$E_{LT-SLT} = O\left(n\ln\left(\frac{n}{\delta}\right)\right) + O\left(k\ln(k-n)\right) \tag{22}$$

In this paper $n = 0.2k$ and bringing in (22), we have:

$$E_{LT-SLT} \overset{n=0.2k}{=} O\left(0.2k \cdot \ln\frac{0.2k}{\delta}\right) + O\left(k \cdot \ln 0.8k\right) \tag{23}$$

2) COMPARISON OF CODING COMPLEXITY OF LT-SLT FOUNTAIN CODE WITH OTHER FOUNTAIN CODE METHODS

The number of source symbols is k. The LT-SLT fountain code coding complexity is compared with SLT- LT fountain code, SLT codes, and LT codes, respectively.

a) Comparison of coding complexity between LT-SLT fountain code and SLT-LT fountain code

In the SLT-LT anti-eavesdropping scheme [22], SLT-LT encoding is performed on $(k-n)$ symbols, where the average degree of each encoded symbol in the LT code is $\overline{d_{LT}} = O\left(\ln \frac{k-n}{(1-P_{AB})\delta}\right)$, and the average degree of the SLT code is $\overline{d_{SLT}} = O\left(\frac{k}{k-n}\ln(k-n)\right)$, the coding complexity is E_{SLT-LT}.

$$\begin{aligned} &E_{SLT-LT} \\ &= E_{SLT}\,(k-n)\cdot E_{LT}\,(k-n) \\ &= O\,(k\cdot\ln(k-n))\cdot O\left((k-n)\cdot\ln\frac{k-n}{(1-P_{AB})\,\delta}\right) \end{aligned} \tag{24}$$

The coding complexity of the SLT-LT fountain code is E_{SLT-LT} when $n=0.2k$, $P_{AB}=0$, are chosen and brought into (24):

$$E_{SLT-LT} \overset{n=0.2k}{=} O\,(k\ln 0.8k)\cdot O\left(0.8k\cdot\ln\frac{0.8k}{\delta}\right) \tag{25}$$

In fountain code coding, $u(d)$ denotes the degree distribution of the fountain code, hence $\sum_{d=1}^{k} u(d) = 1$, where $k \geq 1$. From $\bar{d} = \sum_{d=1}^{k} du(d)$, $\sum_{d=1}^{k} du(d) \geq \sum_{d=1}^{k} u(d)$, which yields $\sum_{d=1}^{k} du(d) \geq 1$. Bringing this into (17), the number of original symbols of the source is k, which can be derived,

$$E\,(m) = m\cdot\sum_{d=1}^{k} du\,(d) \geq k \tag{26}$$

Usually, the number of decoding of a fountain code $N \gg 1$, yields $E\,(m) > 2$. Then we have that in SLT coding, $E_{SLT} = O\,(k\ln 0.8k) > 2$; in LT coding, when $n=0.8k$, $0.8k \gg 1$, which gives the value $E_{LT} = O\left(0.8k\cdot\ln\frac{0.8k}{\delta}\right) > 2$.

The product of two numbers greater than 2 is greater than the sum of these two numbers, and from (25), it follows that

$$\begin{aligned} &O\left(0.8k\cdot\ln\frac{0.8k}{\delta}\right)\cdot O\,(k\cdot\ln 0.8k) \\ &\qquad > O\left(0.8k\cdot\ln\frac{0.8k}{\delta}\right) + O\,(k\cdot\ln 0.8k) \end{aligned} \tag{27}$$

$O\left(k\cdot\ln\frac{k}{\delta}\right)$ is an increasing function, comparing (27) with (23), we have

$$\begin{aligned} &O\left(0.8k\cdot\ln\frac{0.8k}{\delta}\right) + O\,(k\cdot\ln 0.8k) \\ &\qquad > O\left(0.2k\cdot\ln\frac{0.2k}{\delta}\right) + O\,(k\cdot\ln 0.8k) \end{aligned} \tag{28}$$

where $P_{AB}=0$, by (25) (27) (28), we can obtain: $E_{SLT-LT} > E_{LT-SLT}$.

By (24), $\overline{d_{LT}}$ in E_{SLT-LT} increases as P_{AB} increases. When $P_{AB} \neq 0$, still satisfied: $E_{SLT-LT} > E_{LT-SLT}$.

b) Comparison of coding complexity between LT-SLT fountain code and SLT codes

From (20), the SLT coding complexity for $n=0.2k$

$$\begin{aligned} E_{SLT} &= (k-n)\,O\left(\frac{k}{k-n}\ln(k-n)\right) \\ &\overset{n=0.2k}{=} O\,(k\ln 0.8k) \end{aligned} \tag{29}$$

Compare E_{LT-SLT} and E_{SLT}, (29) and (21), apparently: $E_{SLT} < E_{LT-SLT}$.

c) Comparison of coding complexity between LT-SLT fountain code and LT codes

From (19), when the number of source symbols is k, the coding complexity E_{LT} of the LT code is

$$\begin{aligned} &E_{LT} \\ &= O(k\ln(\frac{k}{\delta})) \\ &= O\left(0.2k\ln\left(\frac{0.2k}{\delta}\right)\right) + O\,(k\ln 0.8k) \\ &\quad + k\,(O\,(\ln 1.25) + O\,(0.2\ln 5) - O\,(0.8\ln\delta) - O\,(0.2\ln k)) \end{aligned} \tag{30}$$

Bringing (23) into (30) gives

$$E_{LT} = E_{LT-SLT} + k\begin{pmatrix} O\,(\ln 1.25) + O\,(0.2\ln 5) \\ -O\,(0.8\ln\delta) - O\,(0.2\ln k) \end{pmatrix} \tag{31}$$

It follows from (31) that when $O\,(\ln 1.25) + O\,(0.2\ln 5) - O\,(0.8\ln\delta) - O\,(0.2\ln k) > 0$, i.e. $O\,(\ln k) < O\,(5\ln 1.25) + O\,(\ln 5) - O\,(0.4\ln\delta)$, then $E_{LT-SLT} < E_{LT}$ and vice versa $E_{LT-SLT} > E_{LT}$.

D. EAVESDROPPER UNTRANSLATED PROBABILITY VERSUS ERASE CHANNELS

The eavesdropper untranslated probability is defined as the ratio of the number of untranslated original symbols by the eavesdropper to the number of original symbols sent by the source when the source sends L sets of LT encoded symbols each set of k original symbols, then there is

$$P_{eve} = \sum_{i=1}^{L} a_i/Lk \tag{32}$$

where a_i represents the number of untranslated symbols for i group eavesdroppers.

Physical layer wiretap channel coding anti-eavesdrop capability measured by eavesdropper's untranslated rate. The simulation conditions are the same as above, comparing the untranslated probability of Eve for LT codes, SLT codes,

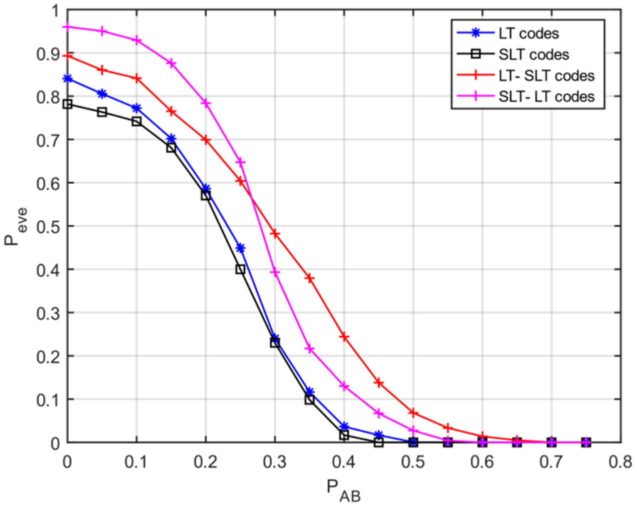

FIGURE 5. Effect of P_{AB} on P_{eve}.

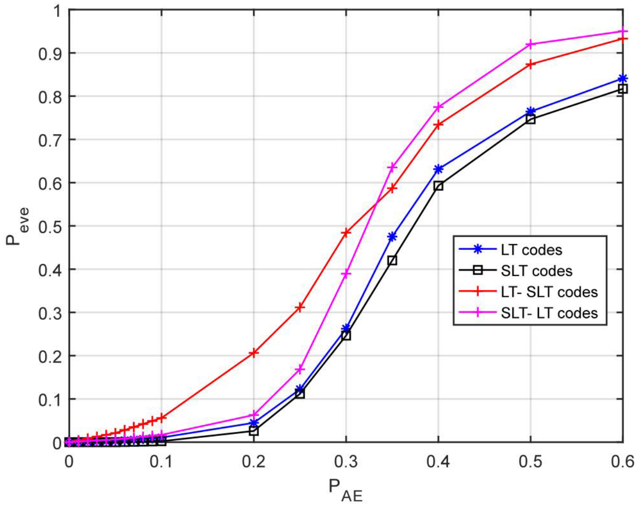

FIGURE 6. Effect of P_{AE} on P_{eve}.

SLT-LT fountain code, and LT-SLT fountain code coding methods under different channel variations.

1) THE RELATIONSHIP BETWEEN THE UNTRANSLATED RATE OF EAVESDROPPERS AND THE MAIN CHANNEL

Assume that Eve acquires all of Bob's decoding rules and can perform BP decoding as well as Bob. Observe the effect of the main channel P_{AB} change on P_{eve}. The experimental conditions are the same as above, where the probability of wiretap channel deletion $P_{AE} = 0.3$. The experimental results are shown in Fig. 5.

From Fig. 5, it can be seen that in the four methods P_{eve} decreases as P_{AB} increases and tends to zero, and the values of P_{eve} for all LT-SLT fountain code coding methods are greater than those for LT codes and SLT codes. Compared with SLT-LT fountain code, when $P_{AB} \leq 0.27$, P_{eve} of LT-SLT fountain code coding method is less than SLT-LT fountain code, when $P_{AB} > 0.27$,then LT-SLT fountain code coding method is better than SLT-LT fountain code.

Experimental results show that LT-SLT fountain code coding gives the eavesdropper a high untranslated rate when the wiretap channel is some fixed value and the main channel deletion probability is low. When the deletion probability of the main channel is large, the LT-SLT fountain code coding method still allows the existence of a certain untranslated rate for the eavesdropper, and its untranslated rate is higher than that of LT codes, SLT codes, and SLT-LT fountain code.

2) THE RELATIONSHIP BETWEEN THE UNTRANSLATED RATE OF EAVESDROPPERS AND THE WIRETAP CHANNEL

Observe the effect of the change in the wiretap channel P_{AE} on P_{eve} where the main channel deletion probability $P_{AB} = 0.3$. The experimental results are shown in Fig. 6.

From Fig. 6, it can be seen that the P_{eve} of the four methods increases as P_{AE} increases, and the P_{eve} values of the LT-SLT fountain code coding methods are all greater than those of the LT and SLT codes. Compared with SLT-LT fountain code, the P_{eve} of LT-SLT fountain code coding method is greater than that of SLT-LT fountain code when $P_{AE} \leq 0.33$, and the P_{eve} of LT-SLT fountain code coding method is greater than 0.58 in all cases when $P_{AE} > 0.33$, but lower than that of SLT-LT fountain code.

The experimental results show that the LT-SLT fountain code coding method outperforms LT codes, SLT codes, and SLT-LT fountain code when the main channel is a particular value and the deletion probability of the wiretap channel is lower or slightly higher than the main channel. When the deletion probability of the wiretap channel is larger than that of the main channel, the anti-eavesdropping effect proposed in this paper is slightly lower than that of the SLT-LT fountain code, but P_{eve} is also greatly improved, much better than LT codes and SLT codes, making it difficult for eavesdroppers to obtain the relevant information.

3) EFFECT OF SIMULTANEOUS CHANGES IN THE MAIN CHANNEL AND THE WIRETAP CHANNEL ON THE UNTRANSLATED RATE

Observe the change of the eavesdropper's untranslated probability when the deletion probability of the main channel and the wiretap channel change at the same time, i.e., $P_{AB} = P_{AE}$.The values of P_{AB} and P_{AE} range from 0 $\sim$ 0.85, and the specific experimental results are shown in Fig. 7

As can be seen from Fig. 7, when the channel deletion probability is small, the untranslated rate of Eve for all four schemes increases with the channel deletion probability, and starts to decrease after increasing to a certain level. Comparing the four schemes, the LT-SLT fountain code gives Eve the largest untranslated rate, especially after the channel deletion

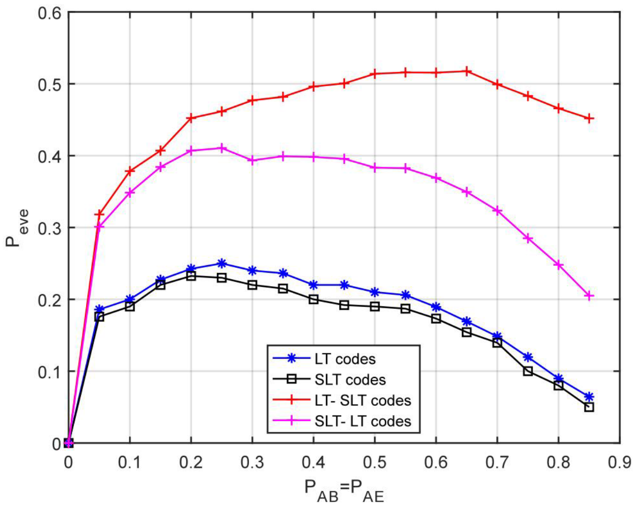

FIGURE 7. Effect of changes in P_{AB} and P_{AE} on P_{eve}.

probability is greater than 0.5, the untranslated rate of Eve is much larger than the other schemes.

Experimental results show that when the main channel is the same as the wiretap channel, the LT-SLT fountain code is more effective when the channel deletion probability is high compared to the other three schemes.

V. CONCLUSION

From the above analysis, it can be seen that, for the situation of wireless communication eavesdroppers obtaining confidential information such as the decoding rules of legitimate receivers, the LT-SLT fountain code coding method proposed in this paper is used as an anti-eavesdropping code in wiretap channels, which increases the number of decoding symbols by a small amount as a price to effectively improve the untranslated rate of eavesdroppers and to ensure the secure transmission of wireless communication information.

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