Physical Layer Key Generation Method Based on SVD Pre-processing

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Received 27 October 2022; Accepted 24 November 2022;
Publication 31 January 2023

Abstract

Environmental factors such as channel noise and hardware fingerprints affect the encryption effect of physical layer key generation techniques, resulting in low consistency of generated keys. Feature pre-processing is a common means of improving consistency of keys. However, most of the existing feature pre-processing algorithms improve key consistency by sacrificing key generation rate, which is not very usable. Therefore, it is proposed a physical layer key generation method based on SVD pre-processing. This method uses the SVD feature processing algorithm to pre-process the channel features extracted from both sides of the communication before quantization, in order to simultaneously improve key consistency and key generation rate. The simulation results show that when the channel SNR is greater than 10 dB, the BER of the SVD scheme is significantly lower compared to the scheme without pre-processing and the DCT and PCA pre-processing schemes; when the SNR is greater than 20 dB, the SVD scheme KGR can reach a level of

Journal of Cyber Security and Mobility, Vol. 11_6, 777–794.
doi: 10.13052/jcsm2245-1439.1163

10bit/s, which is significantly higher than the other three schemes. The results show that this scheme can significantly increase the key generation rate while effectively improving key consistency.

Keywords: Wireless channels, physical layer keys, feature pre-processing, key consistency.

1 Introduction

In recent years, wireless communication technology has been used extensively in both the military and civilian sectors [1], however, due to the open and broadcast characteristics of wireless channel, the inherent security problem of information leakage in wireless communication is caused [2], the stability of the wireless network signal transmission is relatively low. At the same time, with the increasing development of attack methods, various security problems in wireless communication will become more and more prominent [3], wireless security is confronted with the complexity of the secret key distribution process [4], putting forward new and higher requirements for the security of current wireless communication.

Currently, wireless communication channels are receiving more attention from scholars because of their inherent properties: random time-varying, channel reciprocity, space-time uniqueness and unpredictability. Legitimate communication users can use the real-time changing wireless channel information as a pool of public random resources [5] and perform session key extraction from it. This technique, known as wireless channel key extraction, also known as physical layer key extraction, eliminates the need for the key distribution and management process found in traditional key algorithms, largely enhancing existing security protocol mechanisms and improving the security and reliability of session keys [6]. At the same time, compared with traditional key algorithms, the generation of physical layer keys does not require a large amount of storage space and has lower computational complexity. It can be better applied to wireless communication technologies with small memory space and weak computational power. Thus is heavily used in the encryption of wireless communication [7].

In the literature [8], based on the analysis of key BER, provides a reliable key synthesis algorithm for messaging based on the channel transmission characteristics. Liu Jingmei et al. [9] provides a method for implementing key synthesis using k-mean clustering for the case of incomplete utilization of the channel. It allows the use of several aspects of data, namely frequency and phase, to enhance the accuracy of the synthesized key. However, the above method does not consider the key generation rate, in order to further improve the efficiency of key generation. The authors of [10] proposed an improved channel quantization alternation(CQA) algorithm, meet the high Key Generation Rate (KGR) and low Key Disagreement Rate (KDR) requirements of the key extraction process. And in order to simultaneously take into account the randomness of the key, it is proposed an innovative key distribution and encryption control scheme based on physical layer channel feature extraction and C. Chen [11] improves the security and randomness of the key by analyzing the non replicability of the channel and the randomness of the channel noise.

However, there are still many shortcomings in the current physical layer key extraction techniques, such as poor key consistency due to half-duplex wireless channels and channel noise and hardware fingerprints, and low key generation rate due to incomplete utilization of channel features [11]. Pre-processing of the feature data extracted by channel probing is one of the common methods to resolve key inconsistencies. The goal of channel feature pre-processing is to eliminate as much as possible the effects of system half-duplexity, hardware fingerprints, and channel noise on channel measurements, and to ensure the consistency and randomness of the generated keys. Therefore, the selection of a suitable pre-processing method is particularly important in physical layer key extraction.

A. K. B and M. M. Kodabagi [12] propose a variable automatic coding pre-processing algorithm, which solves the problem of information loss caused by the undersampling method by optimizing the lower bound of the likelihood function, but the amount of data is too large when dealing with the actual problem, and it cannot solve the influence of hardware fingerprints and channel noise on the channel measurements. A. K. B and M. M. Kodabagi [13] propose an efficient data preprocessing method for unbalanced datasets in email classification domains. It is able to reduce the size of the dataset and improve the accuracy and performance of preprocessing, but the performance is poor when applied to the physical layer for key extraction. A. Stavridis [14] proposes the Preprocessing Assisted Space Modulation (PSM) method, which simplifies the complexity of preprocessing. M. Maleki and K. Mohamed-pour [15] propose a two-stage precoding based on Zero-forcing (ZF) that can reduce the Channel State Information (CSI) feedback overhead in the frequency division duplex mode. The literature [16] proposes a ZF-based Propensity Score Matching (PSM) procedure to reduce the hardware complexity design by reducing the number of Radio Frequency (RF) chains for millimetre wave and associated channels. However, these preprocessing methods are costly and complex, so literature [17] and literature [18] proposed the preprocessing methods of Discrete Cosine Transform (DCT) and Discrete Fourier Transform (DFT), which are easy to implement on the computer, but cannot guarantee the randomness of the generated keys.

In order to solve the problems that existing pre-processing methods are too costly and complex or have low accuracy and performance, and it is difficult to take into account the key consistency and key generation rate at the same time, this paper proposes a physical layer key generation algorithm based on Singular Value Decomposition (SVD) pre-processing scheme [19]. SVD is a generalization of Eigen Value Decomposition (EVD) to arbitrary matrices of any size, and has shown good performance in key extraction applications. The pre-processing scheme based on SVD [20] algorithm compensates the existing pre-processing schemes [21] such as Discrete Cosine Transform (DCT), which is difficult to combine key consistency and key generation rate at the same time, and can improve key consistency while significantly increasing key generation rate.

2 System Model

The wireless channel communication model is shown in Figure 1. Legitimate communication parties communicate over legitimate channels, and eavesdroppers use eavesdropping channels to steal communication data from legitimate users. The feasibility of physical layer key generation techniques

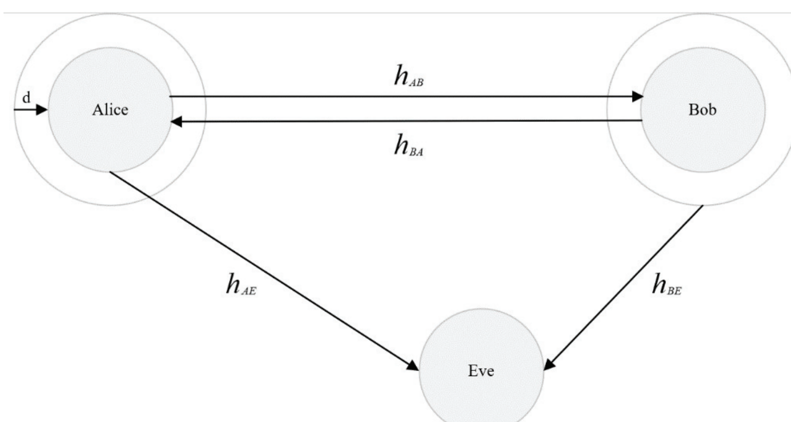

Figure 1 Wireless channel communication model diagram.

stems from three characteristics of the wireless channel, namely channel reciprocity, random time variability and spatial uniqueness. The reciprocity of the wireless channel ensures that channel probing between the communicating parties during channel coherence time results in highly similar channel characteristics. It guarantees the consistency of the generated keys; Random time-variability indicates that the channel characteristics of a wireless channel are randomly varying and not regular. It guarantees randomness of channel characteristics as a key source; And because the wireless channel is spatially unique, when the distance between the eavesdropping third party and the legitimate communicating parties is more than half the electromagnetic wavelength, it is impossible to obtain channel characteristics similar to those of the legitimate communicator through the eavesdropping channel. It ensures that the generation of session keys is safe and secure.

Existing physical layer key generation schemes typically consist of five main components: channel probing, feature extraction, feature quantization, conformance negotiation and confidentiality enhancement. In order to minimise the impact of the half-duplex nature of the wireless channel, as well as channel noise, hardware fingerprints and other unavoidable factors on the consistency of the generated keys, the channel characteristics are pre-processed in the text before being quantified. Figure 2 shows the key generation process in this paper.

2.1 Channel Probing and Feature Extraction

The two legitimate communicating parties, Alice and Bob, agree in advance to obtain a common guide signal x_p. Due to the half-duplex nature of the wireless channel, the communicating parties send x_p to each other for channel probing at moments t_1 and t_2 successively. The signals received by Alice and Bob are denoted by y_a and y_b respectively.

$$y_a = h_{BA}(t_1)x_p + n_A \tag{1}$$

$$y_b = h_{AB}(t_2)x_p + n_B \tag{2}$$

where h_{BA} and h_{AB} denote the channel gain at moments t_1 and t_2, and n_A and n_B denote Gaussian white noise.

Commonly used channel feature extraction algorithms include Least Square (LS), Minimum Mean Square Error (MMSE) and Linear Minimum Mean Square Error (LMMSE) [22]. The LS-based algorithm has the advantages of low computational effort, low complexity and high algorithmic efficiency. This method is used in this paper for channel feature extraction.

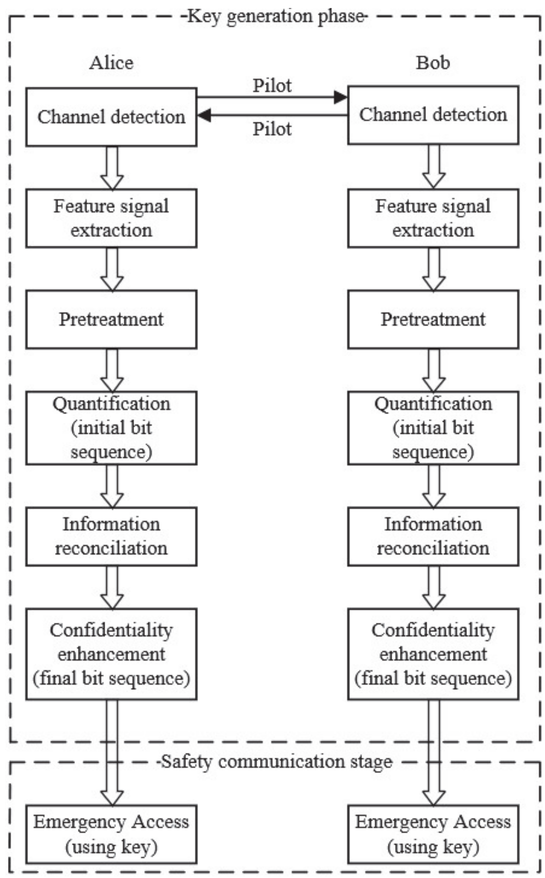

Figure 2 Key generation flow chart.

Equations (3) and (4) shows the LS algorithm procedure. It use $\tilde{h}_{BA}$ and $\tilde{h}_{AB}$ to denote the feature measurements obtained by Alice and Bob after channel feature extraction, respectively.

$$\tilde{h}_{BA} = \frac{y_a}{x_p} = h_{BA}(t_1) + \frac{n_A}{x_p} \tag{3}$$

$$\tilde{h}_{AB} = \frac{y_b}{x_p} = h_{AB}(t_2) + \frac{n_B}{x_p} \tag{4}$$

In order to obtain a key of sufficient length, Alice and Bob send each other guide signals several times to extract sufficient channel feature measurements.

2.2 Eigenvalue Pre-processing

Most of the existing feature pre-processing methods aim to improve key consistency at the expense of key generation rate. It is difficult to ensure a balance between the performance of session keys. In the paper, the SVD algorithm is used in the process of feature pre-processing. It proposed pre-processing scheme based on the SVD algorithm.

2.2.1 Introduction to the SVD algorithm

SVD is a generalisation of EVD to arbitrary matrices and is widely used in the field of machine learning. Compared to the EVD algorithm, which can only be used for square matrix decomposition, SVD can decompose arbitrary matrices and can therefore be better applied to the processing of channel identity matrices.

The details of the SVD algorithm are as follows:

Assume that there is an $m \times n$ matrix M. Define the SVD decomposition of M as:

$$M = U\Sigma V^T$$

where U is a square matrix of order $m \times m$, $u_1, u_2, \ldots, u_m$ denote column vectors and it calls left singular vectors, Σ is a semi-positive definite diagonal matrix of order $m \times n$ whose elements on the main diagonal are called singular values of the matrix M, and V is a square matrix of order $n \times n$, $v_1, v_2, \ldots, v_n$ denote column vectors and are called right singular vectors. where both U and V are You matrices, i.e. they satisfy $U^TU = I$, $V^TV = I$.

Thus, Equation (5) express the singular value decomposition of M as:

$$M = \begin{bmatrix} u_1 & \ldots & u_k & u_{k+1} & \ldots & u_m \end{bmatrix} \begin{bmatrix} \delta_1 & & & \\ & \ddots & & 0 \\ & & \delta_k & \\ & 0 & & 0 \end{bmatrix} \begin{bmatrix} v_1^H \\ \vdots \\ v_k^H \\ \vdots \\ v_n^H \end{bmatrix} \tag{5}$$

Performing matrix blocking operations on Equation (5), expanding and simplifying gives Equation (6):

$$M = \begin{bmatrix} u_1 & \ldots & u_k \end{bmatrix} \begin{bmatrix} \delta_1 & & \\ & \ddots & \\ & & \delta_k \end{bmatrix} \begin{bmatrix} v_1^H \\ \vdots \\ v_k^H \end{bmatrix} \tag{6}$$

U' denote $[u_1 \quad \dots \quad u_k]$, Σ' denote $\begin{bmatrix} \delta_1 & & \\ & \ddots & \\ & & \delta_k \end{bmatrix}$, V' denote $[v_1 \quad \dots \quad v_k]$, Then Equation (7) express the singular value decomposition of M:

$$M = U'\Sigma'V' \tag{7}$$

2.2.2 Pretreatment program

SVD can decompose arbitrary matrices, and the singular values are ordered from largest to smallest, and its computational complexity is significantly lower than that of EVD algorithm. The details of the eigenvalue preprocessing method based on the SVD algorithm are as follows:

Alice and Bob use the SVD algorithm to decompose the eigenvalue matrix obtained by feature extraction (Alice is used as an example here), as shown in Equation (8).

$$\tilde{h}_{BA} = U_{BA}\Sigma_{BA}V_{BA}^{H} \tag{8}$$

From the above SVD algorithm introduction, it can be seen that $\tilde{h}_{BA}$ can also be expressed by Equation (9).

$$\tilde{h}_{BA} = U'_{BA}\Sigma'_{BA}V'^{H}_{BA} \tag{9}$$

Where the diagonal elements of Σ'_{BA} are the singular values of $\tilde{h}_{BA}$ and they are arranged in decreasing numerical order. In general, the decreasing speed is slow when the singular value is large, and the decreasing speed will gradually level off when the singular value gradually decreases. To perform the feature reconstruction, the singular values with larger values in the front ranking are selected. In this paper, the top 90% (r) singular values are taken as the heterogeneous singular values to calculate the reconstructed feature matrix. It can be expressed by Equation (10).

$$\tilde{h}'_{BA} = [u_{BA_1} \quad \dots \quad u_{BA_r}] \begin{bmatrix} \delta_{BA_1} & & \\ & \ddots & \\ & & \delta_{BA_r} \end{bmatrix} \begin{bmatrix} v^H_{BA_1} \\ \vdots \\ v^H_{BA_r} \end{bmatrix} \tag{10}$$

Bob also follows the above steps to reconstruct the channel feature matrix to obtain the reconstructed channel feature matrix $\tilde{h}'_{BA}$.

2.3 Feature Quantification

The purpose of feature quantization is to convert the channel feature measurements obtained by CHANNEL probing into a binary bit sequence as an initial key. Among the existing quantization methods, experimentally verified by most scholars, Equal probability quantization algorithm has better performance in all aspects. while multi-bit quantization increases the rate of key generation compared to single-bit quantization. Therefore, the multi-bit equal-probability quantization algorithm [23] is used in the paper to quantify the pre-processed feature measurements.

Alice and Bob select an identical channel parameter and extract the sequence of measurements φ_A and φ_B for that channel parameter from the preprocessed channel feature measurements, $\varphi_A = \{\varphi_{A1}, \varphi_{A2}, \ldots, \varphi_{An}\}$, $\varphi_B = \{\varphi_{B1}, \varphi_{B2}, \ldots, \varphi_{Bn}\}$ where n denotes the length of the sequence to be quantized. Equal-probability quantization is characterized by choosing quantization thresholds based on the characteristics of the elements in the sequence to be quantized, such that the number of samples in each quantization threshold is equal. In the paper, taking Alice as an example, the steps of feature quantification are roughly divided into two processes of classification and encoding, and the specific process is as follows:

1. Alice first arranges the elements within φ_A in ascending order to obtain the new sequence φ'_A to be quantized.
2. The communication parties agree to obtain the number of quantization bits m, and calculate the number of quantization regions R accordingly, $R = 2^m$, and the number of samples in each quantization region $p = n/R$. T denotes quantization threshold, $T = \{t_1, t_2, \ldots, t_{2^{m-1}}\}$, where $t_i = (\varphi'_A(i * p) + \varphi'_A(i * p + 1))/2, i = 1, 2, \ldots, 2^{m-1}$.
3. Alice classifies the sequence to be quantized according to the quantization threshold T obtained in step 2, as shown in Equation (11).

$$\varphi_{Ai} = \begin{cases} 0, & \varphi_{Ai} < t_1 \\ 1, & t_1 \le \varphi_{Ai} < t_2 \\ & \vdots \\ j, & t_j \le \varphi_{Ai} < t_{j+1}, i = 1, 2, \ldots, n, \\ & j = 1, 2, \ldots, R-1 \\ & \vdots \\ R-1, & \varphi_{Ai} \ge t_{2^{m-1}} \end{cases} \tag{11}$$

4. Alice uses Gray's coding method to encode the classified sequences. Suppose the sequence φ'_A to be quantized is divided into 3 classes, denoted by 1, 2 and 3, respectively. Then, according to Gray's coding rules, samples classified as 1 are converted to binary code 00, samples classified as 2 are converted to binary code 01, and samples classified as 3 are converted to binary code 11.
5. Alice gets the quantized binary bit sequence ϕ_A, which is Alice's initial key.

Similarly, Bob also follows the above process to quantize the sequence of channel feature measurements to obtain the quantized binary bit sequence ϕ_B.

2.4 Generate Key

Due to the half-duplex nature of the wireless channel and the unavoidable impact of channel noise and hardware fingerprints on the session key consistency, it is difficult for ϕ_A and ϕ_B to be completely consistent, and thus the inconsistent bits need to be proposed through consistency negotiation. Consistency negotiation between ϕ_A and ϕ_B by means of parity check is used in the text.

Alice and Bob respectively divide the quantized binary bit stream sequences ϕ_A and ϕ_B into multiple subsequences of equal length, and parity check each subsequence, and send the obtained parity bits to each other through the common channel. After receiving the parity bits from each other, the two communicating parties compare the parity bits of each subsequence respectively, and keep the subsequence with the same parity bits. When a pair of subsequences does not match, the communicating parties divide the subsequence into two equal-length bitstream sequences, then parity check the two bitstreams separately, and send the obtained parity bits to each other through the common channel. Alice and Bob again compare the received parity bits and keep only the sequence of bits with consistent parity bits. After completing the above operation, Alice and Bob re-patch the reserved bit sequences, and both sides can get highly consistent session key sequences α_A, α_B.

Since Alice and Bob exchange a large amount of session key information over the public channel during the key negotiation, there is a risk of key leakage. To further ensure the security of the session key, the communicating parties use a two-way hash function to enhance the secrecy of the negotiated bit sequence, and finally obtain a highly consistent and secure session key sequence β_A, β_B.

3 Simulation Experiment

This paper uses MATLAB for simulation experiments. The common channel model in the experiment uses an OFDM system, The system parameters are: carrier frequency $F_C = 5$ GHz, bandwidth $B = 20$ MHz, simulation time slot $T = 256$, number of subcarriers $N = 64$, cyclic prefix $N_{cp} = 16$, symbol period $T_s = 4us$.

In the simulation experiments, the two communicating parties first send each other guide signals for channel probing, use the LS algorithm for feature extraction, use the SVD preprocessing algorithm for preprocessing operation for the extracted feature measurements, and extract the amplitude information from the preprocessed feature measurements as the sequence to be quantized, use the multi-bit equal probability quantization method to quantize the sequence to be quantized, and finally obtain the final session key after the consistency negotiation and confidentiality enhancement operation.

In the experiment, the amplitude is used as the channel parameter, and the performance of the final session key is tested in terms of key consistency (KAR) and key generation rate (KGR) respectively, The preprocessing scheme (SVD) proposed in this paper is compared with the key generation scheme without preprocessing (Direct), the current common DCT preprocessing scheme and the PCA preprocessing scheme, respectively, and the graphs are plotted according to the simulation experimental results. The variation of bit error rate (BER) and key generation rate (KGR) with channel signal-to-noise ratio (SNR) for the four schemes of key generation are shown in Figures 3 and 4, respectively.

Observing Figure 3, it can be seen that when $SNR \leq 10$ dB, all four schemes have high BER in the range of 30%–70%, among which the scheme with direct quantization without preprocessing has the highest BER and the worst key consistency; When $SNR > 10$ dB, the BER of all four schemes is significantly reduced, and the BER of the keys generated with the SVD scheme is significantly lower than that of the keys generated with the other three schemes, and the BER decreases with the increase of SNR, the BER can be reduced to 0.3% when the SNR reaches 40 dB. This shows that the SVD scheme can effectively reduce the key BER and improve the consistency of session keys when the channel SNR is greater than 10 dB compared to the other three schemes.

Observing Figure 4, it can be seen that the existing DCT scheme and PCA scheme have lower key generation rate compared to the scheme without preprocessing, both of which achieve higher key consistency by sacrificing

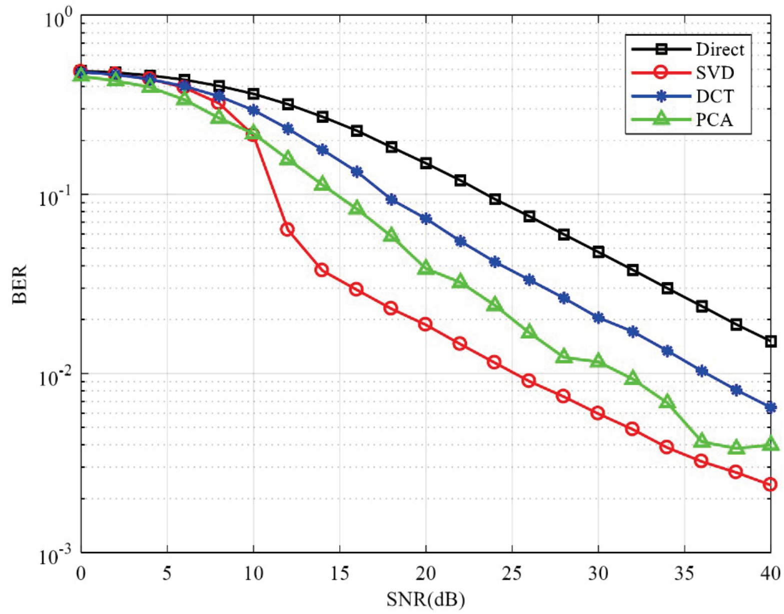

Figure 3 BER variation curve with SNR for four schemes.

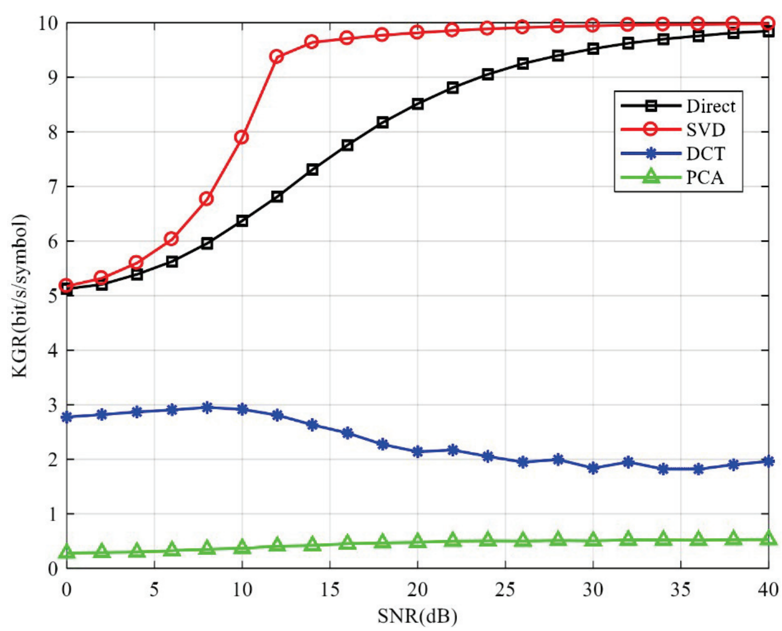

Figure 4 Variation of key generation rate with signal-to-noise ratio for four schemes.

KGR. The SVD preprocessing scheme proposed in the paper, however, can improve the key consistency while significantly increasing the key generation rate, and the KGR can reach 10 bit/s when the $SNR > 20$ dB. This precisely verifies the superiority of the SVD scheme proposed in this paper.

4 Conclusion

This paper addresses the problems of low key consistency and low key generation rate in the current wireless key generation technology. Study of existing characterisation schemes, It proposes a channel feature pre-processing scheme based on the SVD algorithm. The SVD pre-processing scheme solves the problem that the existing pre-processing schemes improve key consistency at the expense of key generation rate. The simulation experiments verify that the SVD pre-processing scheme can significantly improve the key generation rate while improving the key consistency. To a certain extent, it promotes the balanced development of all aspects of the performance of the physical layer key generation technology and provides security for data transmission in wireless channels.

Acknowledgements

The authors acknowledge the State Grid Shanxi Electric Power Company Science and Technology Project Research (No. 52053022000D).

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