Possibility in Analyzing Real-time LFM Signals under Complex Jamming Conditions

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***Abstract*— In this paper, a method for detecting and estimating the chirp rate and the pulse width of radar signals with linear frequency modulation based on the cross-correlation function under jamming conditions by continuous-wave signals and white noise is investigated. The proposed method includes two stages; the first is used to detect or estimate the chirp rate of the linear frequency modulation signal, and the second one is used to estimate the pulse width of this signal. In the first part of the paper, the accuracy of the method is studied by simulation a linear frequency modulation signal in the MATLAB environment to determine the lowest value of SNR, at which this technique is still able to detect and estimate the parameters of this signal. Based on the simulation results, a real-time signal is used to verify its functionality in the second part of this paper. The experimental results confirm that the proposed method can detect and estimate the parameters of linear frequency modulation signal under jamming conditions by continuous-wave signals and white Gaussian noise at the value of *SNR* > -7 dB.**

Keywords—chirp-rate, cross-correlation function, linear frequency modulation, pulse width, radar signals

I. INTRODUCTION

Linear frequency modulation (LFM) signals are found in many military systems due to their suitability for covert message transmission and resistance jamming [1,2]. The detection and estimation of the parameters of these signals are essential for electronic warfare systems. However, the LFM signals are transmitted under noise or low spectral density conditions. The first existing method for detecting and estimating the LFM signal parameters in electronic warfare systems is based on the Wigner-Ville distribution. The problem with this method is that the signal parameters with $\text{SNR} < 0$ dB could not be detected and extracted [3,4]. The second one is called short-time Fourier transform (STFT). This method is only able to detect and extract those parameters in white Gaussian noise at the value of $\text{SNR} \geq -3$ dB [5-7].

With the development of artificial intelligence in recent years, a new method for recognizing the LFM signals was presented [8-10]. It provides the best result for LFM signals in white Gaussian noise with the value of $\text{SNR} \geq -6$ dB. In [11], another approach based on the time-frequency rate distribution (SCPF) was presented. The lowest value of SNR at which the parameters of LFM signals in white Gaussian noise can still be extracted is $\text{SNR} \geq -8$ dB.

All mentioned methods work well with white Gaussian noise, but they have problems with LFM signals in the mixture of white Gaussian noise and CW signals or under complex jamming conditions in which three CW signals and white Gaussian noise are used as jamming signals. The paper will present a new way to address this problem using the cross-correlation function (CCF) between unknown and reference LFM signals.

The theoretical description of the proposed method is presented in Section 2. Section 3 gives details about the accuracy of this method by simulation of the LFM signal in the MATLAB environment. Based on the simulation results in Section 3, the functionality of this method is verified by the real-time LFM signal in Section 4. The main discussion is summarized in Section 5.

II. THE PROPOSED METHOD

The method for detecting and estimating the parameters of the single component LFM signal in white Gaussian noise, but not CW signals, based on the cross-correlation function is presented in [12,13]. In this paper, its accuracy for detecting and estimating the parameters of the single component LFM signal under jamming conditions by CW signals and white Gaussian noise is investigated. The parameters of signal needed to estimate are chirp rate μ and pulse width τ.

TALB. I. SIMULATION PARAMETERS

Signals	Parameters	Values
Unknown LFM signal	$\mu\ (\text{GHz.s}^{-1})$	200
	$\tau\ (\mu\text{s})$	15
	f_c (MHz)	1.6
	SNR (dB)	0
First set of reference LFM signals	$\boldsymbol{\mu}_{\mathbf{ref}}\ (\text{GHz.s}^{-1})$	$10 \div 350$
	$\tau\ (\mu\text{s})$	20
	f_c (MHz)	1.6
	n (-)	100
Second set of reference LFM signals	$\mu\ (\text{GHz.s}^{-1})$	200
	$\boldsymbol{\tau}_{\mathbf{ref}}\ (\mu\text{s})$	$1 \div 25$
	f_c (MHz)	1.6
	n (-)	100
First CW signal	f_c (MHz)	0.1
	A (V)	1
Second CW signal	f_c (MHz)	1.6
	A (V)	1
Third CW signal	f_c (MHz)	3.1
	A (V)	1

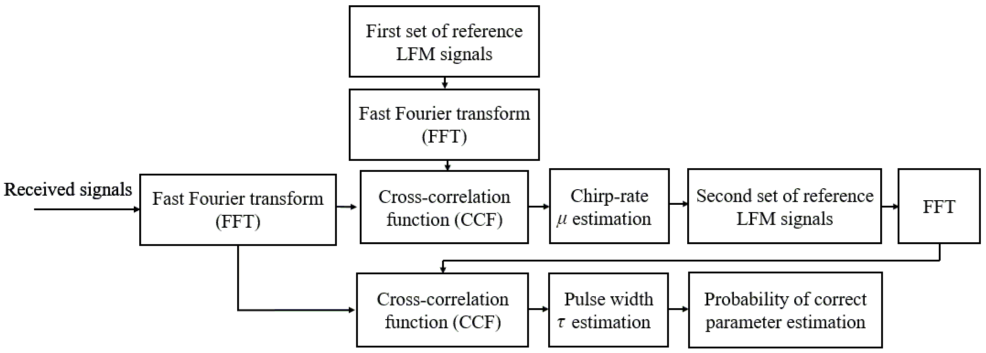
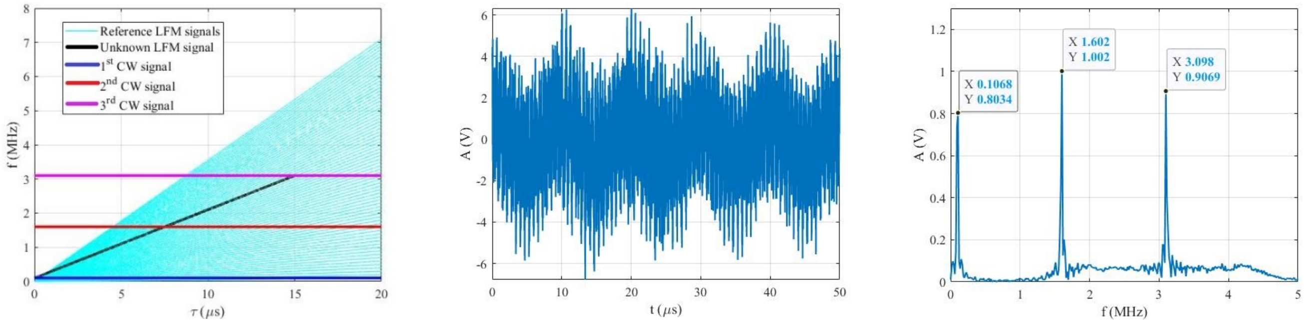
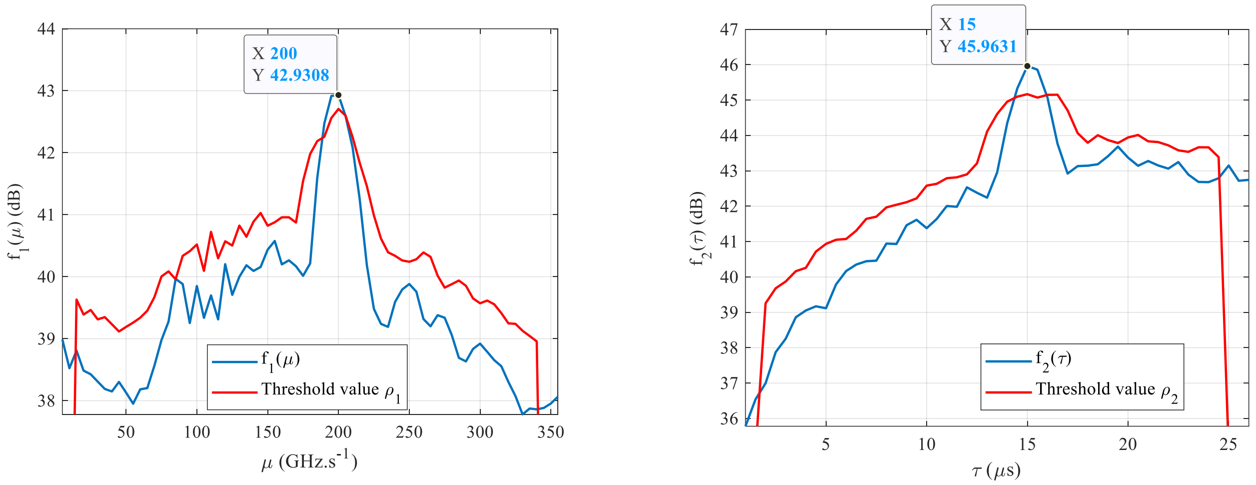


Fig. 1. The block diagram of the proposed technique.



a) b) c)

Fig. 2. The received signal: a) Time-frequency characteristics, b) Time domain, c) Frequency domain.



a) b)

Fig. 3. The simulation results: a) Detection process or chirp-rate estimation b) Pulse width estimation.

The block diagram of the proposed method is shown in Fig. 1. In this figure, two sets of reference LFM signals are used. The first set is generated at the same pulse width but different chirp rates, while the second one is generated at the same chirp rate estimated in the first process of this method and with varying pulse widths. The carrier frequencies of the jamming CW signals are set at the initial, center, and final frequencies of the LFM signals. The characteristics of all signals (black line for the unknown LFM signal, light blue lines for the reference, blue line for the first CW, red line for the second CW, and purple for the third CW) are presented in Fig. 2. It is seen that the classical method or FFT is not able to detect LFM signals under jamming conditions by CW signals and white Gaussian noise. Their parameters are listed in Tab. 1. The main idea of the proposed technique is described below.

Input parameters: Reference chirp rate $\boldsymbol{\mu}_{\mathbf{ref}}$, pulse width $\boldsymbol{\tau}_{\mathbf{ref}}$, threshold values ρ_1, ρ_2. based on constant false alarm rate (CFAR) [15-17].

Output: Chirp rate μ and pulse width τ of the unknown LFM signal

Step 1: Calculating CCF between unknown and the first set of reference signals $\mathbf{R_1}(\zeta)$ based on FFT using (1) and finding out the maximum value of CCF as a function of the chirp-rate $f_1(\mu)$. where $S(\omega)$ and $\mathbf{S_{ref}}(\boldsymbol{\omega})$ are the spectra of received and reference signals, $S^*(\omega)$ is complex conjugate of $S(\omega)$ and F^{-1} is the inverse of FFT.

$$\mathbf{R}(\zeta) = F^{-1}\left\{S^*(\omega) \times \mathbf{S_{ref}}(\boldsymbol{\omega})\right\} \qquad (1)\ [14]$$

Step 2: Determine μ. If $f_1(\mu) \geq \rho_2$, μ is estimated.

Step 3: Calculating CCF between unknown and the second set of reference signals $\mathbf{R_2}(\zeta)$ using (1) and finding out the maximum value of CCF as a function of the pulse width $f_2(\tau)$.

Step 4: Estimate τ. If $f_2(\tau) \geq \rho_2$, τ is estimated.

Fig. 3(a) plots the maximum value of CCF as a function of the chirp rates of the first set of reference LFM signals $f_1(\mu)$ (blue line) and the adaptive threshold ρ_1 (red line). It shows that the estimated chirp rate is $\mu = 200\ \text{GHz.s}^{-1}$ with the value of CCF $f_1(\mu) = 42.93\text{dB}$. In the same case of calculating the chirp rate, the maximum value of CCF versus the pulse widths of the second set of reference LFM signals $f_2(\tau)$ (blue line) and the adaptive threshold ρ_2 (red line) are given in Fig. 3(b). It shows that the estimated pulse width of the unknown LFM signal is $\tau = 15\ \mu\text{s}$ with $f_2(\tau) = 45.96\text{dB}$. The estimated parameters of unknown LFM signal at the value of $\text{SNR} = 0$ dB by running the system for 200 loops are given in Tab. 2. The simulation results show that the proposed method can detect and estimate the chirp rate and pulse width of LFM signal under jamming conditions by CW signals and white Gaussian noise at the value of $\text{SNR} = 0$ dB.

TABLE. II. ESTIMATED PARAMETERS OF LFM SIGNAL

Parameters	**Simulation value**	**Estimated value**	**Relative error (%)**	**Root mean square error (-)**
$\mu\ (\text{GHz.s}^{-1})$	200	200	0.0	0.0
$\tau\ (\mu\text{s})$	15	15	0.0	0.0

III. SIMULATION RESULTS

The main objective of this section is to determine the lowest value of SNR at which the proposed method is able to detect and estimate the parameters of unknown LFM signal under jamming conditions by CW signals and white Gaussian noise in the MATLAB environment for running the system 200 loops in the range of SNR from -10 to 0 dB.

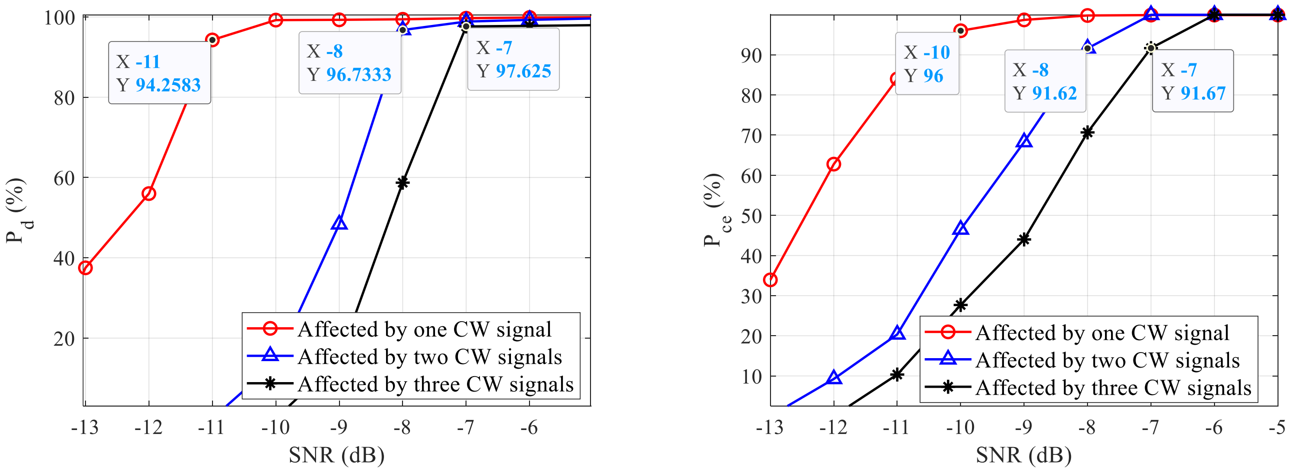
The probability of detection or correct chirp rate estimation as a function of SNR P_d is shown in Fig. 4(a). This figure shows that the lowest SNR value at which the proposed method reaches a perfect probability of correct chirp rate estimation ($P_d \geq 90\%$) is $\text{SNR} \geq -11$ dB ($P_d = 94.26\%$, red line) in affected by CW signal, $\text{SNR} \geq -8$ dB ($P_d = 96.73\%$, blue line) in affected by two CW signals and $\text{SNR} \geq -7$ dB (black line) in the mixture of three CW signals and noise. The same case in estimating the chirp rate of an unknown LFM signal. Fig. 4(b) shows the probability of correct pulse width estimation as an SNR function P_{ce}. It shows that the lowest SNR value for estimating the pulse width of an unknown LFM signal under jamming conditions by three CW signals and noise is $\text{SNR} \geq -7$ dB with $P_{ce} = 91.67\%$ (black line) and $\text{SNR} \geq -8$ dB ($P_{ce} = 91.62\%$, blue line) under interference condition by two CW signals and noise. The required value of SNR for estimating the pulse width of LFM in affected by one CW signal is $\text{SNR} \geq -10$ dB ($P_{ce} = 96\%$, red line).

Overall, the simulation results show that, by using the proposed technique, the parameters of LFM signals are detected and estimated successfully under jamming conditions by CW signals and white Gaussian noise at the value of $\text{SNR} \geq -7$ dB. In the next section, the functionality of the proposed method is investigated by real-time LFM signal generated in the mixture of CW signals and white noise with the value of $\text{SNR} = -7$ dB.

IV. EXPERIMENTAL RESULTS

In this section, the functionality of the proposed method for detecting and estimating the parameters of the unknown LFM signal under jamming conditions by CW signals and white Gaussian noise is verified by real-time LFM signal. To do this, the LFM signal is generated at the value of $\text{SNR} = -7$ dB by PSG vector signal generator EC8267C. This vector signal generator operates in the frequency range from 250 kHz to 20 GHz. It generally generates basic signals such as radar pulse, CW, amplitude modulation (AM), or frequency modulation (FM) signals. However, it also can generate particular radar signals such as LFM, non-linear frequency modulation (NLFM), and binary phase-shift keying (BPSK) from an external source MATLAB through LAN or RS-232 communication. The parameters of LFM and CW signals are listed in Tab. 1. All tests are performed under the condition that the chirp rate and pulse width of the generated LFM signal are the same as the range of the parameters of reference signals.

The spectrum of the generated LFM signal at the value of $\text{SNR} = -7$ dB is shown in Fig. 5. In this figure, it is seen that a classical method like FFT or amplitude detector is not able to detect and estimate the generated LFM signal.



a)

b)

Fig. 4. The simulation results: a) Probability of detection or correct chirp-rate estimation, b) Probability of correct pulse width estimation.

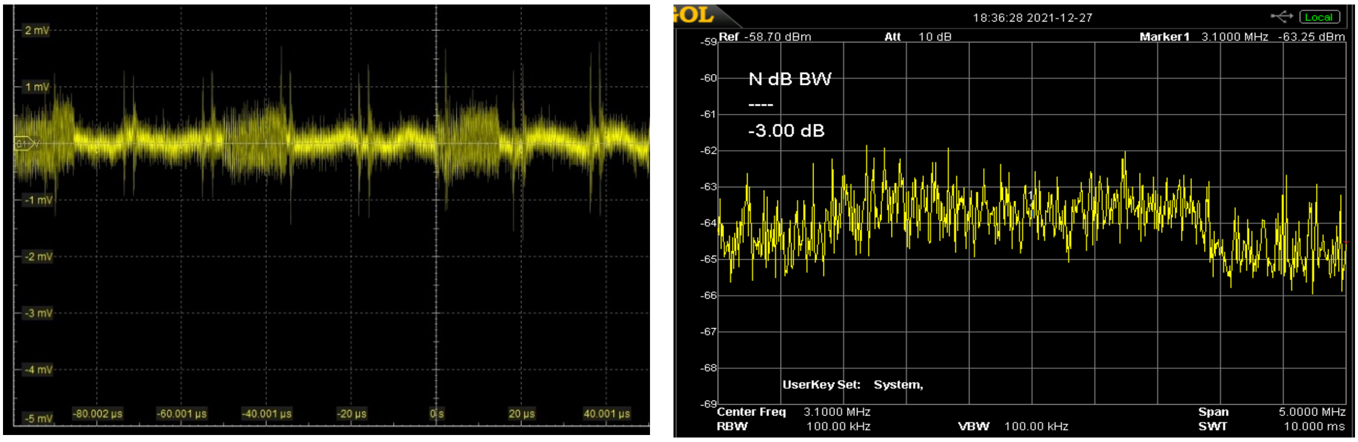


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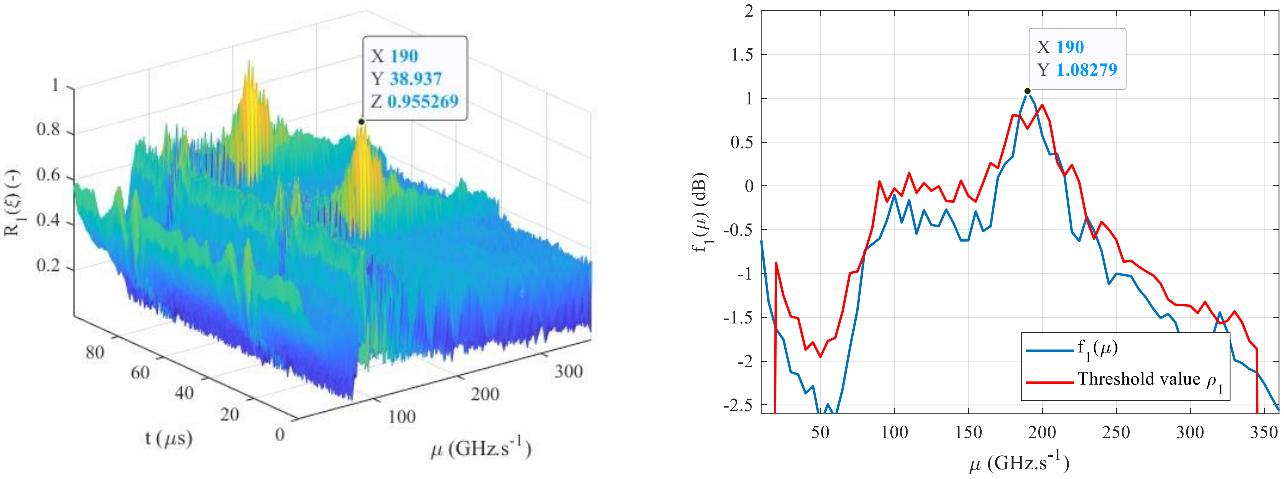
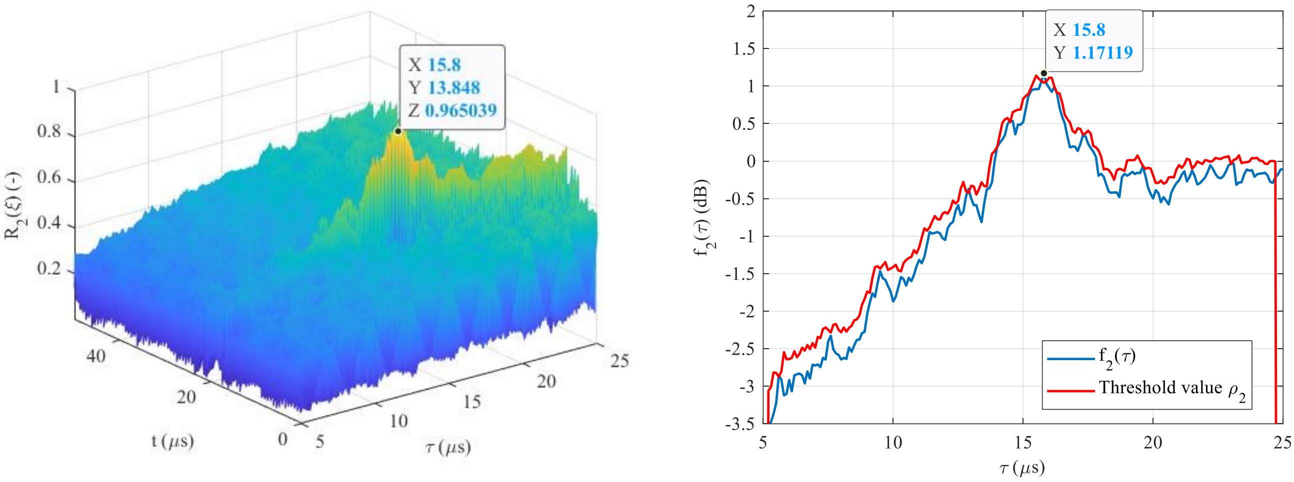
Fig. 5. The generated LFM signal at the value of $SNR = -7$ dB : a) Time domain, b) Frequency domain.



a) b)

Fig. 6. The CCF between generated and the first set of reference LFM signals: a) 3D plot of CCF, b) Chirp-rate estimation.



a) b)

Fig. 7. The CCF between the generated and the second set of reference LFM signals: a) 3D plot of CCF, b) Pulse width estimation.

The CCF between the generated and the first set of reference LFM signals $R_1(\zeta)$ in 3D is shown in Fig. 6(a). The maximum value of CCF as a function of the reference LFM signals chirp rate $f_1(\mu)$ (blue line) and the adaptive threshold ρ_1 (red line) are shown in Fig. 6(b). This figure shows that the estimated chirp rate of the generated LFM signal is $\mu = 190\ \text{GHz.s}^{-1}$ with $f_1(\mu) = 1.083$ dB. It means that the chirp rate of the unknown LFM signal was estimated by the first part of the proposed method.

In the same case of estimating the chirp rate of the unknown LFM signal, the CCF between the received and the second set of reference LFM signals $R_2(\zeta)$ in 3D is shown in Fig. 7(a). The maximum value of CCF versus the pulse widths of reference LFM signals $f_2(\tau)$ (blue line) and the adaptive threshold ρ_2 (red line) are shown in Fig. 7(b). It shows that the highest CCF value is $f_2(\tau)=1.17$ dB at the pulse width value $\tau=15.8$ μs. It means that the pulse width of unknown LFM signal is estimated by the second part of this method. The estimated parameters of the generated LFM signal under jamming conditions by CW signals and white Gaussian noise are given in Tab. 3.

TABLE III. ESTIMATED PARAMETERS OF THE GENERATED LFM SIGNAL UNDER JAMMING CONDITION

Parameters	**Simulation value**	**Estimated value**	**Relative error (%)**
$\mu\ (\text{GHz.s}^{-1})$	200	190	5.00
τ (μs)	15	15.8	5.33

Overall, the experimental results confirm that the proposed method is effective in detecting and estimating the parameters of the unknown LFM signal under jamming conditions by CW signals and white Gaussian noise at the value of SNR ≥ -7 dB ($P_d \geq 90\%$).

In the last part of this section, the accuracy of the proposed technique is studied in comparison with existing methods for detecting and estimating the chirp rate of LFM signals with $P_d \geq 90\%$. The accuracies of each method are listed in Tab. 4.

TABLE IV. COMPARISION OF THE PROPOSED METHOD WITH OTHER METHOD

Methods	**SNR threshold (dB)**	**Noise type**	**Publication**
STFT	-3	White noise	[5-7]
CNN	-6	White noise	[8]
DCNN	-6	White noise	[9]
CLNN	-6	White noise	[10]
SCPF	-8	White noise	[11]
Proposed method	-7	White noise + CW signals	

In terms of the *SNR* value, the highest accuracy is for the SCPF in [11] ($SNR=-8$ dB), followed by the proposed method ($SNR=-7$ dB), and the lowest accuracy is for STFT ($SNR=-3$ dB) in [5-7]. However, CNN[8], DCNN[9], and CLNN[10] can only be performed by using a database. The performance of these methods depends on the total number of samples—the fewer samples, the lower the performance of techniques. Moreover, the problem of the SCPF [11] is complex to implement in hardware, two-dimensional research (time and frequency domain), and it is only able to detect and estimate LFM signals in white Gaussian noise. Meanwhile, the proposed method detects and estimates LFM signals in white Gaussian noise and the mixture of CW signals and white noise. This method is easy to implement on electronic receiver hardware and does not require a database of LFM signals.

V. CONLUSSION

In this paper, the ability to analyze LFM signals under jamming conditions by CW signals and white Gaussian noise based on the cross-correlation function was investigated. The proposed method was divided into two processes; the first process is used to detect or estimate the chirp rate of an unknown LFM signal, and the second one is used to calculate the pulse width of the LFM signal.

Firstly, the accuracy of this method was tested with a simulated LFM signal in the MATLAB environment to determine the lowest value of SNR, at which this method is still able to detect and estimate the parameters of the signal under jamming conditions by CW signals and white Gaussian noise. The simulation results show that the lowest value of SNR is $\text{SNR}=-7$ dB.

Based on the simulation results, the functionality of this method was verified with generated LFM signal using vector signal generator E8267C. The experimental results confirmed that the proposed method is suitable to detect and estimate the chirp rate and the pulse width of LFM signal under jamming conditions by CW signals and white Gaussian noise with an input value of $\text{SNR} \geq -7$ dB.

In future work, the functionality of the proposed method will be investigated with multi-component LFM signals in white Gaussian noise and the mixture of white Gaussian noise and interference CW signal. In addition, this method can be applied to BPSK signals in the form of the Barker codes 7, 11, and 13, which are commonly used in radar or telecommunication.

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