Uncorrelated Phase Noise Cancellation for Low-IF Radar With Separate Reference Sources of Dual PLLs

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***Abstract*—This paper presents a low-IF dual-PLL radar architecture with two separate reference sources of two PLLs. Compared with the existing low-IF architectures, an additional mixer is used to generate an IF reference signal whose phase noise correlates to the received down-converted IF signal. These two IF signals can be combined destructively by tuning the phase and attenuation of the IF reference signal. Consequently, IF cancellation can be implemented. The phase noise can be significantly eliminated in the IF cancellation and improved SNR of the radar receiver can be obtained. Signal-noise model and experiment measurement are provided to illustrate the proposed concept.**

***Index Terms*—Correlated phase noise, IF cancellation, low-IF, uncorrelated phase noise, vital sign**

I. Introduction

Doppler radars have been studied in the past decade as a feasible way for vital sign monitoring and tiny vibration measurements [1]–[3]. In these applications, the target signal strength is extremely weak, the frequency is usually low, and it is easily buried in the noise interference. Thus, it is of great importance to explore radar sensors with high sensitivity. Accordingly, noise suppression to improve system SNR becomes challenging.

The noise in a Doppler radar can be classified into phase noise and amplitude noise. The phase noise can be further divided into correlated and uncorrelated parts. The correlated noise can be effectively suppressed according to the range-correlation effect [4], [5] by coupling a portion of the transmit signal to serve as the LO signal of the receiver mixer. The uncorrelated part specifically exists in the dual-PLL system due to the flicker noise from different phase detectors (PD) of PLLs, and its intensity is proportional to $1/f$ in the close-in region [6]. Besides, TX-RX leakage and static clutter reflection in Doppler radar result in SNR degradation of the target signal [7].

In this paper, an IF cancellation architecture in a low-IF dual-PLL radar has been proposed for uncorrelated phase noise cancellation. As shown in Fig.1, an additional mixer is used to mix signals from two PLLs, providing a reference IF signal $IF_{\text{cancel}}(t)$ whose phase noise is correlated with the down-converted RX signal. After tuning the amplitude and phase of $IF_{\text{cancel}}(t)$, IF cancellation can be implemented by combining $IF_{\text{cancel}}(t)$ and $IF(t)$ to significantly suppress the uncorrelated phase noise.

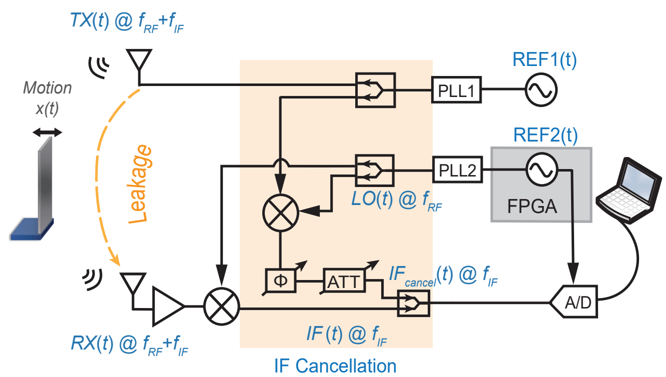


Fig. 1: Block diagram of the proposed dual-PLL low-IF radar with IF cancellation for uncorrelated phase noise suppression.

II. Theory analysis

A. IF Noise Cancellation Architecture

Fig.1 shows the block diagram of the proposed low-IF dual-PLL radar. Two separate references $REF1(t)$ and $REF2(t)$ are used for PLL1 and PLL2. One of the output of PLL1 radiates to the free space through the transmit antenna and its phase is modulated by the target displacement. One of the output of PLL2 is connected to the receiver mixer as LO signal. As a result, the phase noise of the dual PLLs and references contribute to the residual uncorrelated phase noise of the uncorrelated phase noise of received IF signal $IF(t)$. A mixer is used to mix the other output of PLL1 and PLL2 to generate a reference IF signal $IF_{\text{cancel}}(t)$, whose phase noise is correlated with that of $IF(t)$. After a tunable phase shifter and a tunable attenuator, $IF_{\text{cancel}}(t)$ and $IF(t)$ are combined, amplified, and sampled to make the motion frequency visible in frequency spectrum by performing fast Fourier transform (FFT). A 20-MHz crystal oscillator provides the reference source $REF1(t)$ for PLL1. An FPGA board provides a 500-KHz sampling clock for the ADC module and a 50-MHz reference source $REF2(t)$ for PLL2.

B. Signal-Noise Model Analysis

The $TX(t)$ and $LO(t)$ signals can be expressed as

$$TX(t) = A_{\text{TX}} \times \exp\left\{j\left[2\pi f_{\text{TX}} t + \phi_{\text{TX}}(t)\right]\right\}, \tag{1a}$$

$$LO(t) = A_{\mathrm{LO}} \times \exp\left\{j[2\pi f_{\mathrm{LO}} t + \phi_{\mathrm{LO}}(t)]\right\}, \tag{1b}$$

where A_{TX} and A_{LO} are the amplitudes, f_{TX} and f_{LO} are the frequency, and $\phi_{\mathrm{TX}}(t)$ and $\phi_{\mathrm{LO}}(t)$ are the phase noise of the transmit and LO signals, respectively. For simplification, a CW low-IF radar system is considered here by setting $f_{\mathrm{TX}}(t)$ to $f_{\mathrm{RF}} + f_{\mathrm{IF}}$ and f_{LO} to f_{RF}. The phase noise $\phi_{\mathrm{TX}}(t)$ and $\phi_{\mathrm{LO}}(t)$ can be modeled as

$$\phi_{\mathrm{TX}}(t) = \frac{f_{\mathrm{TX}}}{f_{\mathrm{REF1}}} \times \phi_{\mathrm{REF1}}(t) + \phi_{\mathrm{PLL1}}(t), \tag{2a}$$

$$\phi_{\mathrm{LO}}(t) = \frac{f_{\mathrm{LO}}}{f_{\mathrm{REF2}}} \times \phi_{\mathrm{REF2}}(t) + \phi_{\mathrm{PLL2}}(t). \tag{2b}$$

As can be seen, both $\phi_{\mathrm{TX}}(t)$ and $\phi_{\mathrm{LO}}(t)$ consist of two parts: one is the frequency-scaled phase noise from the reference source, and the other is the phase noise from corresponding PLL. Since different reference sources and PLLs are used for $TX(t)$ and $LO(t)$, their phase noises are uncorrelated with each other. This differs from previously reported low-IF dual-PLL radar, which uses only one reference source, and both correlated and uncorrelated phase noise exist, while the range-correlation effect in short-range applications can suppress the former and the latter remains leading to an SNR degradation.

Due to the Doppler effect, the moving target will modulate the phase and amplitude of TX signal and the RX signal $RX(t)$ can be modeled as

$$\begin{aligned} RX(t) = & A_{\mathrm{RX}} \times \exp\left\{j 2\pi f_{\mathrm{TX}} t\right\} \times \\ & \exp\left\{ j\left[-4\pi \frac{d_0 + x(t)}{\lambda} + \phi_{\mathrm{TX}}\left(t - \frac{2d_0}{c}\right)\right]\right\}, \end{aligned} \tag{3}$$

here A_{RX} is the amplitude of RX signal which is transmitted as A_{TX} then modulated by the moving target, d_0 is the nominal distance between radar and detected target, $x(t)$ represents the target displacement. When TX-RX leakage is considered in practical radar system, $RX(t)$ can be revised to be

$$\begin{aligned} RX(t) = & A_{\mathrm{RX}} \times \exp\{j 2\pi f_{\mathrm{TX}} t\} \times \\ & \exp\left\{ j\left[-\frac{4\pi(d_0 + x(t))}{\lambda} + \phi_{\mathrm{TX}}(t - \frac{2d_0}{c})\right]\right\} + \\ & A_{\mathrm{leakage}} \times \exp\{j 2\pi f_{\mathrm{TX}} t\} \times \\ & \exp\left\{ j\left[-2\pi f_{\mathrm{TX}} \tau_{\mathrm{leakage}} + \phi_{\mathrm{TX}}\left(t - \tau_{\mathrm{leakage}}\right)\right]\right\}. \end{aligned} \tag{4}$$

A_{leakage} and τ_{leakage} are the amplitude and delay of TX-RX leakage signal, respectively.

Subsequently, $RX(t)$ is amplified by an LNA and mixed by the receiver mixer with the $LO(t)$ from PLL2. The down-converted $IF(t)$ can be modeled as

$$\begin{aligned} IF(t) = & \frac{1}{2} A_{\mathrm{LO}} A_{\mathrm{RX}} \times \exp\left\{ j\left[2\pi f_{\mathrm{IF}} t - 4\pi \frac{d_0 + x(t)}{\lambda}\right]\right\} \\ & \times \exp\left\{ j\left[\phi_{\mathrm{TX}}(t - \frac{2d_0}{c}) - \phi_{\mathrm{LO}}(t)\right]\right\} \\ & + \frac{1}{2} A_{\mathrm{LO}} A_{\mathrm{leakage}} \times \exp\left\{ j\left[2\pi f_{\mathrm{IF}}\left(t - \tau_{\mathrm{leakage}}\right)\right]\right\} \\ & \times \exp\left\{ j\left[\phi_{\mathrm{TX}}(t - \tau_{\mathrm{leakage}}) - \phi_{\mathrm{LO}}(t)\right]\right\}. \end{aligned} \tag{5}$$

It can be observed that the residual phase noise of $IF(t)$ consists of all the phase noise from $TX(t)$, $LO(t)$, and the TX-RX leakage signal, which will lead to a low SNR and reduce accuracy. To mitigate the phase noise degradation, a reference IF signal with correlated phase noise to $IF(t)$ needs to be introduced.

By mixing $TX(t)$ and $LO(t)$ directly using an additional mixer, a reference IF signal, namely $IF_{\mathrm{cancel}}(t)$, can be generated as

$$IF_{\mathrm{cancel}}(t) = A_c \times \exp\left\{j 2\pi f_{\mathrm{IF}} t\right\} \times \exp\left\{j \phi_{\mathrm{IF_c}}(t)\right\}, \tag{6}$$

where $\phi_{\mathrm{IF_c}}(t)$ represents the residual phase noise of $IF_{\mathrm{cancel}}(t)$ and

$$\phi_{\mathrm{IF_c}}(t) = \phi_{\mathrm{TX}}(t) - \phi_{\mathrm{LO}}(t). \tag{7}$$

Comparing equation (5) and (7), both the phase noise of $IF(t)$ and $IF_{\mathrm{cancel}}(t)$ originate from that of $TX(t)$ and $LO(t)$, thus they are correlated and can be added destructively in case of equal magnitude and out-of-phase.

In most cases, the leakage signal is 20 dB or even higher than the target reflected signal [7], a proper approximation can be made for simplification by neglecting the target reflection in the combination process of $IF(t)$ and $IF_{\mathrm{cancel}}(t)$. By doing this, the initial attenuation and phase-shift value of $IF_{\mathrm{cancel}}(t)$, A_c and ϕ_c, can be obtained for a complete cancellation with the leakage signal.

$$A_c = \frac{1}{2} A_{\mathrm{LO}} A_{\mathrm{RX}}, \tag{8a}$$

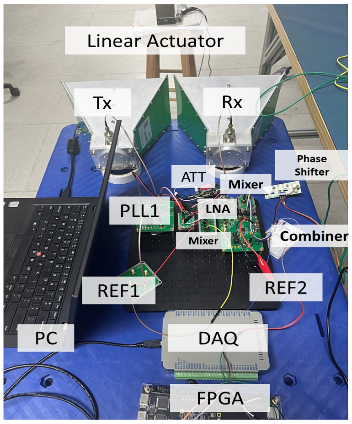
$$\phi_c = \pi + \phi_{\mathrm{leakage}}. \tag{8b}$$

In a practical radar system, however, a fine-tuning of $IF_{\mathrm{cancel}}(t)$ based on the start point of (8) can be carried out to obtain an optimal cancellation effect.

III. Experiments And Results

To validate the proposed idea, a low-IF dual-PLL radar with IF cancellation is constructed and used to measure a linear and periodic motion with an amplitude of 470 um and a back-and-forth frequency of 1.25 Hz. f_{RF} is 5.8 GHz and f_{IF} is 50 KHz. The radar and the measurement setup are shown in Fig. 2 with all the modules listed in the right table.

Fig. 3 is the measured IF frequency spectrum with and without IF cancellation. The noise floor level is calculated by averaging the power across the spectrum region of 1-2 Hz. When there is no IF cancellation, noise floor and motion



Device	Type
PLL	TI LMX259
Mixer	SIM-73L+
FPGA	ALINX AX7103
Attenuator	Pe43702
Phase Shifter*	MCP41010
LNA	PMA3-63GLN+
DAQ module	Smacq USB5211
TX/RX Antenna	Horn antenna

Fig. 2: Picture of the proposed dual-PLL low-IF radar and its measurement setup (The phase shifter is custom-designed using MCP41010 and NE5532).

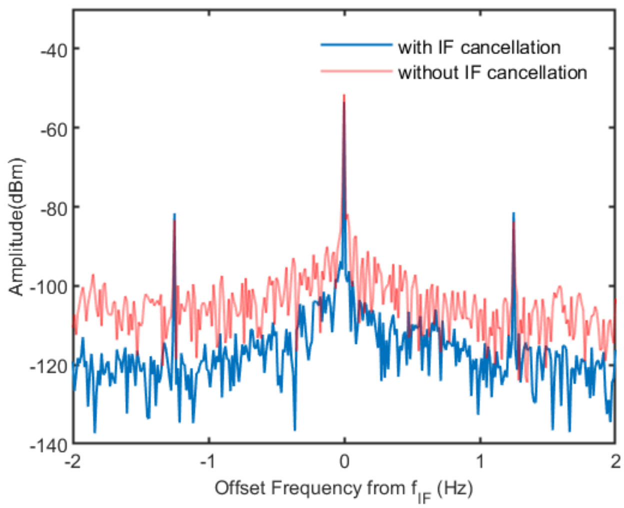


Fig. 3: Comparison of the measured IF spectrum with and without IF cancellation.

spectrum power are found to be -107.6 dBm and -83.4 dBm, indicating an SNR of 24.2 dB. By applying the IF cancellation, a 3-dB reduction of the IF signal power can be observed. Meanwhile, the noise floor and the motion spectrum power are measured to be -121.6 dBm and -81.6 dBm, indicating an SNR of 40 dB. The IF cancellation lowers the noise floor by 14 dB and improves the SNR by 15.8 dB due to the uncorrelated phase noise cancellation. Fig. 4 shows that manually tuning IF cancellation decreases the IF signal power and lowers the noise floor. As a benefit of the IF cancellation, the corresponding SNR improves from 21.2 dB to 40 dB from the left to the right. Due to the tolerance of the manual tuning and the simple test scenarios, a 1.7-dB variation of the motion spectrum power can be observed during the measurements. Further, adaptive electrically adjustable phase shifter and attenuator can be employed for adaptive fine-tuning and to conduct comprehensive research on the proposed radar architecture.

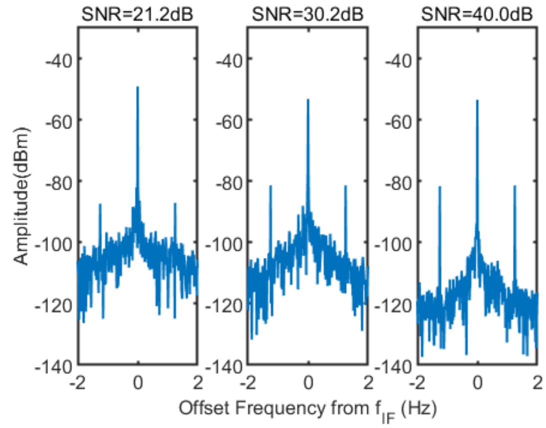


Fig. 4: Measured IF spectrum with respect to different IF cancellation levels.

IV. Conclusion

This paper reports a low-IF dual-PLL radar with separate reference sources. An additional mixer is used to introduce a reference IF signal. As such, noise cancellation in the IF domain is implemented. Proposed concept is validated by the experiment measurements and might find potential applications in future high-sensitivity radar sensors.

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References

[1] T.-Y. Chin, K.-Y. Lin, S.-F. Chang, and C.-C. Chang, "A fast clutter cancellation method in quadrature doppler radar for noncontact vital signal detection," in *2010 IEEE MTT-S Int. Microw. Symp.*, Jul. 2010, pp. 764–767.

[2] C. Gu, C. Li, J. Lin, J. Long, J. Huangfu, and L. Ran, "Instrument-based noncontact Doppler radar vital sign detection system using heterodyne digital quadrature demodulation architecture," *IEEE Trans. Instrum. Meas.*, vol. 59, no. 6, pp. 1580–1588, Oct. 2009.

[3] H. Zhao, H. Hong, L. Sun, Y. Li, C. Li, and X. Zhu, "Noncontact physiological dynamics detection using low-power digital-IF Doppler radar," *IEEE Trans. Instrum. Meas.*, vol. 66, no. 7, pp. 1780–1788, Mar. 2017.

[4] A. D. Droitcour, O. Boric-Lubecke, V. M. Lubecke, J. Lin, and G. T. Kovacs, "Range correlation and I/Q performance benefits in single-chip silicon Doppler radars for noncontact cardiopulmonary monitoring," *IEEE Trans. Microw. Theory Techn.*, vol. 52, no. 3, pp. 838–848, Mar. 2004.

[5] M. Budge and M. Burt, "Range correlation effects on phase and amplitude noise," in *Proceedings of Southeastcon'93*, Apr. 1993, p. 5.

[6] B. Razavi, "Design considerations for direct-conversion receivers," *IEEE Trans. Circuits Syst. II, Analog Digit. Signal Process.*, vol. 44, no. 6, pp. 428–435, Jun. 1997.

[7] X. Jiang, X. Gao, X. Wu, Q. J. Gu, and X. Liu, "Automatic RF leakage cancellation for improved remote vital sign detection using a low-IF dual-PLL radar system," *IEEE Trans. Microw. Theory Techn.*, vol. 71, no. 6, pp. 2664–2679, Jun. 2023.