Trade-off on Detection Range and Channel Usage for Moving Target Tracking using FSK Radar

Jing Wang[1], Daniel Nolte[1], Karp Tanja[1], José-María Muñoz-Ferreras[2], Roberto Gómez-García[2], and Changzhi Li[1]

[1]Department of Electrical and Computer Engineering, Texas Tech University, Lubbock, TX, 79409, USA
[2]Department of Signal Theory & Communications, University of Alcalá, Alcalá de Henares, 28871, Spain

***Abstract* — Spectrum-efficient frequency shift keying (FSK) radar has been investigated previously for range tracking and localization of both moving and stationary human targets. Traditionally, both in-phase (*I*) and quadrature (*Q*) channels are used for range tracking of moving targets using FSK radar. In this paper, a single channel moving target tracking method is proposed, which brings the benefit of reduced circuit complexity at the trade-off of half of the maximum unambiguous range. Range tracking theory including quadrature channel demodulation, single channel demodulation, and phase difference correction are discussed. Simulation is provided to validate the proposed tracking method. Experiments demonstrate that the target trajectory can be successfully measured with the proposed single channel tracking method if it is within half maximum unambiguous range of an *I/Q* channel system, while the range estimation will be inaccurate if the target movement is beyond the limit of half maximum unambiguous range.**

***Index Terms* — Frequency-shift keying (FSK) radar, moving target, range tracking, single channel, wireless sensor.**

I. Introduction

Range tracking and localization of both moving and stationary human targets are indispensable tasks in both military and civilian applications, for instance, security surveillance, autonomous driving, and healthcare. Compared with other range tracking technologies, wireless radars are attractive for their benefits of privacy protection, immunity to ambient light and temperature changes, and robustness against weather conditions [1]. In the coming Internet of Things (IoT) era, a considerable number of devices will be connected to the internet in an already crowded spectrum. Spectrum-efficient technologies and radio spectrum sharing are inevitable to cope with the conflict between massive IoT connections and limited spectrum resource [2]. Therefore, a spectrum-efficient frequency shift keying (FSK) radar technology has been investigated previously in [3]-[5] for range tracking and localization of both moving and stationary human targets.

Traditionally, both in-phase (*I*) and quadrature (*Q*) channels are required by FSK radar to track a moving target in order to differentiate between positive and negative Doppler components. In this paper, a single channel range tracking method is proposed for FSK radar so that the trajectory of a two-way moving target can be successfully measured using a single channel, i.e. either *I* or *Q* channel, at the trade-off of half of the maximum unambiguous range of a traditional *I/Q* channel system. To the best of authors' knowledge, this is the first appearance of such single channel range tracking method in literature. The quadrature channel demodulation and single channel demodulation with phase difference correction are explained in Section II. System implementation and experiments are discussed in Section III. Finally, conclusions are drawn in Section IV.

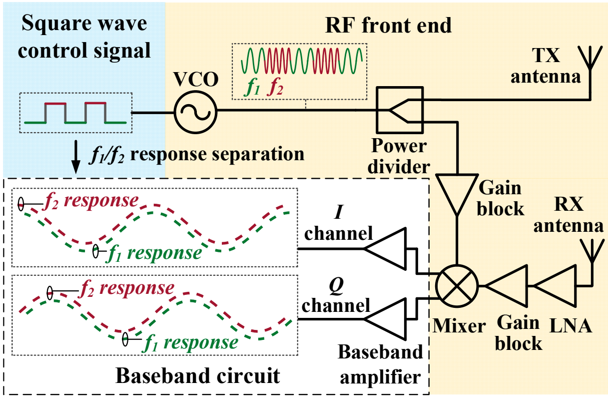

Fig. 1. Block diagram of the implemented 5.8-GHz FSK radar.

II. Range Tracking Theory

As shown in Fig. 1, in an FSK radar system, two discrete frequencies f_1 and f_2 are transmitted in a shared RF chain with a switching modulation. The frequency shift between the two carriers is usually very small compared with the carrier frequencies, which is denoted as $\Delta f = f_2 - f_1$, assuming $f_2 > f_1$. For range tracking of a moving target, Doppler frequencies will be generated and obtained by down-converting the received signals with a copy of the transmitted signals.

A. Quadrature Channel Demodulation

Assuming a target is moving towards the radar, when both *I/Q* channels are available, the obtained baseband output can be represented as:

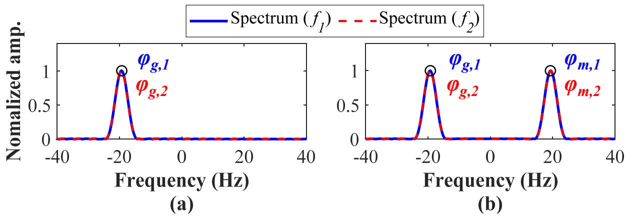

Fig. 2. Simulated spectra for range tracking of a target moving towards radar. (a) Quadrature channel spectra. (b) Single (I) channel spectra.

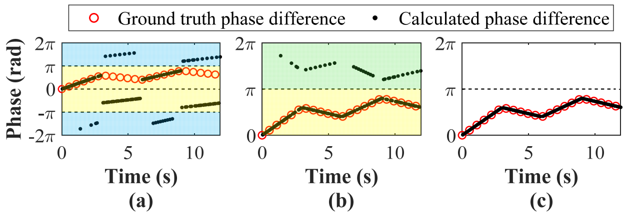

Fig. 3. Simulated phase differences of a two-way moving target. (a) Raw phase difference results. (b) Absolute phase differences. (c) Results after applying the phase difference correction.

$$x_k(t) = \exp\left[j\left(-2\pi f_{d,k}t + \frac{4\pi R_0}{\lambda_k} + \varphi_k\right)\right], \quad (1)$$

where $k = \{1, 2\}$, $f_{d,k}$ stands for the generated Doppler frequency associated with each carrier frequency, λ_k is the carrier wavelength, R_0 represents target range at a particular time $t = t_0$, and φ_k denotes the total residual phase accumulated in the circuit. According to the range correlation theory [6], φ_k is very small compared to the other phase term in (1) and hence will be neglected. Without loss of generality, the amplitudes of all signals are normalized to unity. Since the range detection theory of continuous carrier frequencies and discrete carrier frequencies are essentially the same, for the convenience of demonstration, continuous carrier frequencies without switching are considered in the following analysis. The corresponding Fourier transform of the complex baseband signal can be expressed as:

$$\mathrm{X_k}(f) = e^{j\frac{4\pi R_0}{\lambda_k}}\delta(f - f_{d,k}). \quad (2)$$

As shown in Fig. 2(a), Doppler frequencies show up on the negative side of the spectra. Since Δf is very small in comparison to f_k, the two Doppler frequencies are nearly identical, i.e., $f_{d,1} \approx f_{d,2}$. The phase difference between them can be found according to (2) as $\Delta\varphi = 4\pi R_0/\lambda_2 - 4\pi R_0/\lambda_1$. The target range can be derived accordingly as:

$$R_0 = \frac{c\Delta\varphi}{4\pi\Delta f}. \quad (3)$$

Since $\Delta\varphi$ can only reach a maximum of 2π, range will become aliased beyond this limit. Hence, FSK radar has a maximum unambiguous range limitation of $R_{max} = c/(2\Delta f)$.

B. Single Channel Demodulation

For the same target tracking scenario, when only one channel (assuming the I channel) is available, the corresponding Fourier transform becomes symmetric with respect to zero frequency:

$$\mathrm{X_k}(f) = e^{j\frac{4\pi R_0}{\lambda_k}}\delta(f - f_{d,k}) + e^{-j\frac{4\pi R_0}{\lambda_k}}\delta(f + f_{d,k}). \quad (4)$$

As can be seen in Fig. 2(b), beside the desired Doppler peaks for the negative frequencies, symmetrical Doppler peaks with opposite phase occur at positive frequencies as well. Similarly, if the target is moving away from the radar, beside the desired Doppler peaks at positive frequencies, mirrored Doppler peaks will appear at negative frequencies as well. Therefore, additional direction information will be needed in order to select the desired Doppler peaks and make correct range estimation for a two-way moving target.

An irregular two-way motion between 0 m and 6 m was simulated in MATLAB with $f_1 = 5.8$ GHz, $f_2 = 5.81$ GHz, and sampling frequency of 10 kHz. The maximum unambiguous range is calculated as 15 m. Note that continuous carrier frequencies were simulated for simplicity. The calculated phase differences were plotted in Fig. 3. It is assumed that no extra directional information is available and only the positive frequencies of the spectra are being used.

Theoretically, correct range estimation can be made for a target moving away as desired Doppler peaks occur for positive frequencies. For target moving towards the radar scenario, according to (2), the measured phase difference will be $\Delta\varphi_m = -(4\pi R_0/\lambda_2 - 4\pi R_0/\lambda_1) = -\Delta\varphi_g$, where $\Delta\varphi_g$ represents the ground truth phase difference. In this case, taking the absolute value of $\Delta\varphi_m$ should lead to the correct phase difference measurement, as highlighted with yellow background in Fig. 3(a) and (b). However, due to the phase ambiguity, leading and lagging of 2π happen at some locations, which are highlighted with blue background in Fig. 3(a). After taking the absolute value, all the phase-ambiguity induced phase differences become $2\pi-\Delta\varphi_g$, which are illustrated with green background in Fig. 3(b). Since the simulated target motion is within $R_{max}/2$, which means $\Delta\varphi_g$ is less than π and $2\pi-\Delta\varphi_g$ is more than π, the phase-ambiguity induced phase differences can be separated and a subtraction by 2π can be performed to adjust them back to the desired phase difference measurement, as displayed in Fig. 3(c).

If parts of the target motion exceed $R_{max}/2$, i.e., $\Delta\varphi_g$ exceeds π, then after the absolute-value operation, the phase-ambiguity induced phase differences will be less than π, causing them to be inseparable. Therefore, this single channel range tracking method brings the benefit of reduced circuit complexity, however, at the trade-off of half of the maximum unambiguous range of a traditional I/Q channel system. Similarly, the proposed phase correction method also applies to the scenario where the negative frequencies of the spectra are used. It is also worth pointing out that beside the range sacrifice, there may also be degradation in tracking performance because the single channel demodulation has lower signal-to-noise ratio than the quadrature channel demodulation.

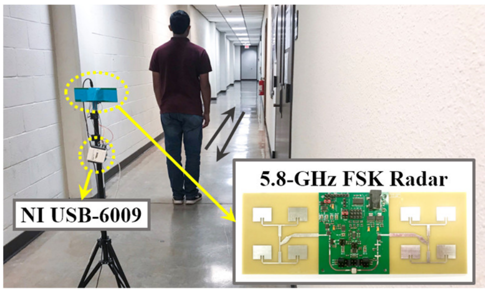

Fig. 4. Photograph of range tracking of a human subject walking back and forth in an interior corridor using the 5.8-GHz FSK radar.

III. System Implementation and Experiments

As shown in Fig. 1, the 5.8-GHz FSK radar used in this work is mainly composed of three components: the square wave control signal, the radio frequency (RF) front-end, and the baseband amplification circuit. A 700 Hz square wave signal was generated, which was used as the control signal of the free-running voltage-controlled oscillator (VCO). The transmit frequency was switched between f_1 = 5.8219 GHz and f_2 = 5.8334 GHz with a frequency shift of 11.5 MHz. The maximum unambiguous range is calculated as 13 m with $R_{max}/2$ being 6.5 m.

For the first experiment, a human subject completed two round trips within the limit of $R_{max}/2$ from 2 m to 6.5 m in an interior corridor, as shown in Fig. 4. Both the square wave and the *I/Q* channel baseband signals were recorded using NI USB-6009 with 10 kHz sampling frequency. The f_1 and f_2 responses were separated based on the synchronization of the square wave control signal. Fast Fourier Transform (FFT) was applied on the separated responses with 0.09 s FFT window size along with Hamming window and zero-padding. The target trajectory obtained using both quadrature channels is plotted in Fig. 5(a). When only *I* channel baseband output and the positive frequencies in the spectrum were used, range tracking result based on the absolute phase differences had some shifted estimations due to phase ambiguity, as highlighted with green background in Fig. 5(b). After phase difference correction was applied, the target trajectory was successfully measured without shifted estimations, as can be seen in Fig. 5(c).

The second experiment was performed with the same experiment setup and processing settings except that the subject walked back and forth between 2 m and 11 m. As shown in Fig. 6(a), the moving trajectory could still be successfully detected by the quadrature channel baseband. However, since some segments of the movement were beyond $R_{max}/2$, when only *I* channel baseband output and the positive frequencies in the spectrum were used, some of the phase-ambiguity induced range estimations after absolute-value operation were below $R_{max}/2$, as highlighted in green in Fig. 6(b). When the phase difference correction was applied,

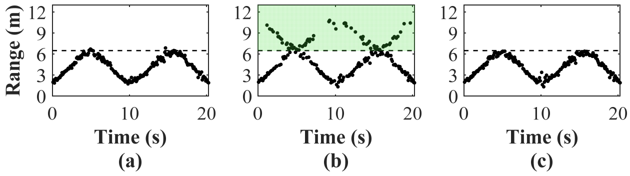

Fig. 5. Range tracking results of a human subject walking back and forth between 2 m and 6.5 m. $R_{max}/2$ is indicated by dashed line. (a) Quadrature channel estimation result. (b) *I* channel estimation result based on the absolute phase differences. (c) *I* channel estimation result with phase difference correction.

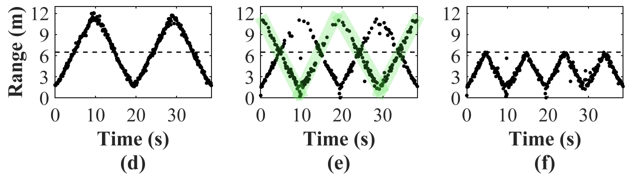

Fig. 6. Range tracking results of a human subject walking back and forth between 2 m and 11 m. $R_{max}/2$ is indicated by dashed line. (a) Quadrature channel estimation result. (b) *I* channel estimation result based on the absolute phase differences. (c) *I* channel estimation result with phase difference correction.

which means the absolute phase differences that were more than π were selected and subtracted by 2π, all the upper trajectories in Fig. 6(b) were mirrored down, leading to incorrect range measurement, as demonstrated in Fig. 6(c).

Note that due to multipath interference, the obtained Doppler peaks associated with the two carriers are not always identical to each other. Therefore, to remove the distorted Doppler peak pairs, only pairs that have the same frequency index were processed.

IV. Conclusion

An FSK radar based single channel range tracking method has been presented in this paper. The trade-off between the detection range and channel usage is discussed. Simulation and experiments have demonstrated that the trajectory of a two-way moving target can be successfully detected by the proposed single channel tracking method with phase difference correction, as long as the movement is within half of the maximum unambiguous range of a conventional *I/Q* channel FSK radar.

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