Moving target detection based on OFDM radar

Houyuan Zhang1,2*, Yun Zhang1, Xin Qi1, Chengge Zong1

1Harbin Institute of Technology, Institute of Electronic Engineering Technology, Harbin, People’s Republic of China
2E-mail: zhangyunhilt@hit.edu.cn

Abstract: The study combines the general hardware platform of the radar system and wireless communication system, as well as applies it in a real detecting scenario. To detect target, the periodogram-based estimation algorithms based on the signal of orthogonal frequency-division multiplexing (OFDM) is introduced. According to range-Doppler (R-D) spectrum, as an enhanced detection algorithm of constant false alarm rate (CFAR), a radar-target detection method, also referred to as binary successive target cancellation, is presented. This research has important theoretical significance for the communication radar-integrated detection technology, and the research results have essential application value for the technology of radar target detection as well as the fusion and development of wireless communication technology.

1 Introduction

The technology of orthogonal frequency division multiplexing (OFDM) has been widely applied in the communicational field. It is the core technology of fourth-generation (4G) mobile communication and further develops a new generation of 5G technology based on OFDM. The OFDM technology has good performance in the implementation of spectrum resource control and high-speed transmission in a wireless environment. Therefore, it is first applied to the communication field. In 1998, Jankiraman et al. [1] introduced the OFDM technology into the radar system. They designed a radar called ‘PANDORA’, whose signals are composed of several narrow LFM channels, and the output signals of a channel are synthesised in the receiver to obtain high resolution.

In recent years, OFDM technology has developed continuously and has been used in the design of radar system. The high bandwidth characteristic of this signal has improved the anti-jamming performance of radar system, and it has high target resolution, which has become the mainstream direction of modern radar research and development. It can be seen that the OFDM signal used for communication can be applied to the present radar system and becomes an essential aspect of the integrated research of communication-radar.

In this paper, the work is mainly divided into two aspects. On the one hand, the radar test system based on the single channel and general equipment is built for detecting. On the other hand, the OFDM signal is applied to this system for the real object detection. Furthermore, an improved CFAR detection algorithm is used in this system for target detection.

2 Methodology

2.1 Periodogram-based estimation algorithms

Periodogram-based estimation algorithms are advanced for OFDM signal to get R-D Spectrum of the targets. If the sinusoids can be addressed well, as a well-comprehended tool, periodogram is actually an optimal solution for the single case to identify sinusoids in a discrete-time signal. The periodogram can be defined as below based on the length N samples’ discrete-time signal s(k):

$$\text{Per}_{ab}(f) = \frac{1}{N} \left| \sum_{k=0}^{N-1} s(k) e^{-j2\pi fk} \right|^2$$  (1)

To utilise the Fast Fourier Transformation (FFT) and to quantise the frequency in usual intervals is the common means to calculate this in the digital system.

$$\text{Per}_{ab}(f) = \frac{1}{N^2} \left| \sum_{k=0}^{N-1} \sum_{l=0}^{M_{RF}} \sum_{m=0}^{N_{t}} (F_{k,l}) e^{-j2\pi (\frac{m}{N_{t}} + fk + \frac{l}{M_{RF}})} \right|^2$$  (2)

The periodogram with a number of modifications can be utilised here, as proposed by Sturm et al. in [2] and [3] and has been fully described in [4] as the radar algorithms of OFDM are sinusoidal identification.

The matrix F is the periodogram’s input data. The periodogram needs to be extended to two dimensions as this is two dimensional and the solution put forward is below:

$$\text{Per}_{x}(n,m) = \frac{1}{N^2} \left| \sum_{l=0}^{M_{RF}} \sum_{m=0}^{N_{t}} (F_{k,l}) e^{-j2\pi (\frac{m}{N_{t}} + \frac{l}{M_{RF}})} \right|^2$$  (3)

where $\text{Per}_{x}(n,m)$ is OFDM symbol duration, $F_{k}$ is transmitted OFDM signal, $F_{k,l}$ is received OFDM signal. Sinusoids in $F$ will lead to a peak in $\text{Per}_{x}(n,m)$. Thus, the peaks must be first detected by the algorithms based on the periodogram. Thus, $F$ has a row-wise oscillation of frequency $\hat{f} = 2\pi n_{f}/N_{t}$ and a column-wise oscillation of frequency $\hat{f} = 2\pi m_{f}/M_{RF}$ if $\text{Per}_{x}(n,m)$ corresponds to a peak value. This corresponds to a target estimate of relative velocity and distance by

$$d = \frac{1}{2} c_{0} \hat{f} \tau_{o} = \frac{\hat{f} c_{0}}{2\Delta f}$$  (4)

$$v = \frac{\hat{f} c_{0}}{2f_{c}} = \frac{\hat{f} c_{0}}{2f_{c} N_{t}} = \frac{\hat{f} c_{0}}{2f_{c} M_{RF}}$$  (5)

where $c_{0}$ is the speed of light, $\Delta f$ is sub-carrier spacing, $f_{c}$ is carrier frequency, $\tau_{o}$ is OFDM symbol duration, $N_{t}$ is the number of rows per two-dimensional periodogram, $M_{RF}$ is the number of columns per two-dimensional periodogram.
2.2 Target detection

A majority of radar systems are configured for a constant false alarm rate (CFAR), which is chosen for the OFDM radar system (refer to [5, 6]). The CFAR’s accurate definition is different in the literature (e.g. the comparison between [7, 8]), which is the reason why the below definitions are put forward:

A false alarm refers to the event in which target detector determines that there exists a target at a related speed and at a range, which cannot make contribution to the received matrix $F_{Rx}$. A false alarm $P_{FA}$’s probability refers to the one that, no less than one false alarms take place during the single frame processing while there was only noise ($F_{Rx} = Z$, $Z$ refers to the matrix of AWGN). Last but not least, the FAR refers to the expected amount of detection per processing of one frame, when there was only noise.

This definition is different from the false alarm probability’s other definitions (and FAR) in many aspects:

Clutter is explicitly which is not discussed in the context. As detecting an object which backscatters the energy yet is not of interest for the usage, this does not count as the false alarm.

Other systems, like the algorithms of target tracking [9], may further process the output of the target detector. Thus, FAR may be reduced.

The time base for the ratio of false alarm refers to one frame’s duration (when compared, [7] the amount of false alarms per second for the FAR), which makes the result as discussed becomes independent of the update ratio.

To discriminate noise from signal power, the periodogram is subjected to a hypothesis test and a threshold $\eta$ is introduced.

$$\text{Per}_f(n, m) > \eta \Rightarrow H_1$$
$$\text{Per}_f(n, m) < \eta \Rightarrow H_0$$

(6)

In which $H_1$ refers to the hypothesis that a target makes contribution to the given bin’s amplitude; $H_0$ means the null hypothesis without any target. When there was only noise, let $Z$ refer to the (random) amplitude of any bin of $\text{Per}_f(n, m)$ to calculate the probability of false alarm.

The probability that the periodogram’s any single bin exceeds the threshold is

$$p_{FA, \text{bin}} = P[Z > \eta] = \int_{\eta}^{\infty} f_Z(z)dz$$

(7)

where $f_Z(z)$ and $F_Z(\eta | H_0)$ are the PDF and CDF, respectively. The result of $Z$ as the magnitude-squared of AWGN with power $\sigma_z^2$ is the exponential term (7).

It should solve (16) for $\eta$ to reach a certain per-bin ratio of false alarm:

$$\eta = - \frac{\mu}{\sigma_z^2} \ln p_{FA, \text{bin}}$$

(8)

Skolnik [10, Chap. 15] introduces the optimality of the detecting approach. The probability of false alarm is as below to realise a particular probability false alarm for a non-zero-padded periodogram,

$$p_{FA} = 1 - (1 - p_{FA, \text{bin}})^{NM}$$

(9)

Addressing this for $p_{FA, \text{bin}}$ and then inserting into (8) yields

$$\eta = - \frac{\mu}{\sigma_z^2} \ln (1 - (1 - p_{FA, \text{bin}})^{NM})$$

(10)

Usually, $\sigma_z^2$, as the noise power, remains unknown at the receiver. The noise power might be estimated from the periodogram through averaging over the bins without containing a target in order to specify a threshold. It remains unclear which bins correspond to the targets as this takes place before the detection of the target. The solution is to rely on the correct parametrisation of the OFDM radar system, and there exists a maximal index ($N_{\text{max}}$) after which there are no more peaks. A maximal likelihood for $\sigma_z^2$ can be identified by the below by averaging over more than one row beyond $N_{\text{max}}$,

$$\hat{\sigma}_z^2 = \frac{1}{M_{\text{Per}}}K \sum_{k=1}^{K} \sum_{m=0}^{M_{\text{Per}}} \text{Per}_f(N_{\text{Per}}, m)$$

(11)

in which $K$ refers to the number of rows above the average. The value of 1 or 2 for $K$ remains sufficient unless $M_{\text{Per}}$ is very small.

The periodogram refers to a two-dimensional matrix, including Doppler values and the power degrees. An application with the usage of a radar system needs an accurate list of targets, with their Doppler and individual rage.
A multi-target detection algorithm is needed to gain a list from the $\text{Per}_F(n,m)$. The binary successive target cancellation is an algorithm of multi-target detection.

How to segregate noise from individual targets is discussed from the prior part. Extra issues appear with multiple targets:

Even though they are further apart than the radar resolution, weak targets close to strong targets might be overshadowed.

The sidelobes from strong peaks may be incorrectly identified as single targets.

These problems are not independent, and there is a trade-off when trying to minimise them. In short-range radar systems, vehicle radar. In fact, there exists no distinction between valid targets and clutter, as any scattering object may relate to the target.

Thus, in practice, clutter analysis will be left to other sub-systems.

A method of detecting multiple targets is binary successive target cancellation. It requires a binary map $B \in \{0,1\}^{N_w \times M_m}$ with the same dimensions as the periodogram, utilised identify the targets that have been previously positioned. The size of the window's major lobe is required in number of bins for $(M_m)$ and $((N_w))$ as the Doppler and range.

The algorithm operates as below:

(i) To initialise all the binary map's elements to one, $(B)_{n,l} = 1$, and an index value $i = 0$.

(ii) Find the greatest peak

$$\hat{n}, \hat{m} = \arg \max_{n,m} \text{Per}_F(n,m) \quad s.t. \quad (B)_{n,m} = 1$$

(iii) Stop searching if $\text{Per}_F(\hat{n}, \hat{m}) < \eta$.

(iv) To determine the Doppler and range of the $i$th target via an algorithm of interpolation from $(\hat{n}, \hat{m})$, such as quadratic interpolation, and to add them to the target list.

(v) Set

$$(B)_{k,l} = 0 \forall k,l \quad s.t. \quad \frac{1}{(N_w/2)^2} \leq 1$$

(vi) Increment $i$.

(vii) Continue to 2.

3 Experiments

The entire radar integrated system uses the universal calculator as a control unit, controlling the vector signal source to generate and launch OFDM signal, and then modulated by radio frequency source to transmit in a form of electromagnetic wave. The trigger signal and reference clock is connected between transmitter and receiver to achieve synchronisation. After receiving from receiver, the signal is analysed by signal processing, data processing etc.

The whole system consists of a transmitter, a frequency converter, a receiver and a subsystem of receiver, as shown in Fig. 2. Among them, the transmitter frequency range is from 100 kHz to 20 GHz. The highest frequency of the receiver is 26.5 GHz. The physical connection of this system is shown in Fig. 3.

The signal of OFDM is utilised to identify the target according to the test system. OFDM signal parameters are shown in Table 1.

According to parameters in Table 1, the distance resolution is calculated as 1.5 m and the velocity resolution is calculated as 1.24 m/s.

Fig. 4 shows the RD spectrum of the detection performance of periodogram-based estimation algorithms with different SNR.

The physical was placed three stories high to observe the vehicles on the road. Fig. 5 shows the scenario of the detection.

The measurement result by using periodogram-based estimation algorithms is shown as Fig. 6.

In order to eliminate the error detection caused by excessive sidelobes, hamming window is used to deal with the received echo, which is shown as Figs. 7 and 8.

Finally, Fig. 9 shows the position of the target calculated by the algorithms above.

4 Conclusion

A radar test system based on OFDM signal is established for the detection of moving target, and it is applied to the actual situation. By using the binary successive target cancellation algorithms and the estimation algorithms that are based on the periodogram, the moving target was successfully detected. The window of the signal processing decreases the sidelobes effectively, making it easier to distinguish the clutter and sidelobes. Thus, the probability of the correct target detection is improved. Besides, the iteration of binary successive target cancellation algorithms can also improve detection performance when choosing a reasonable time of iteration.

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Fig. 4 Effect of SNR by using Periodogram-based estimation algorithms
(a) SNR = 0 dB, (b) SNR = −10 dB

Fig. 5 Traffic scenario of a street in HIT

Fig. 6 Target detection by using Periodogram-based estimation algorithms

Fig. 7 Target detection with hamming window (Sidelobe attenuation is about 42 dB)
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Fig. 8 Target detection calculated by the Binary Successive Target Cancellation algorithms ($P_{FA} = 1 \times 10^{-6}$)

(a) Binary map $B$ for $i=0$, (b) Binary map $B$ for $i=2$

Fig. 9 Target position after calculating by the algorithms. Except for stationary targets, all two moving vehicles are detected