A 24 GHz Band FM-CW Radar System for Detecting Closed Multiple Targets with Small Displacement

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***Abstract*—In this paper, detection method for 24 GHz band FM-CW radar system under closed multiple targets with small displacements environment is proposed, and its performances are analyzed. The proposed detection method was used a tunable FIR filter for signal processing, and the distance and small displacement can be separated for each target correctly from the received signal including all of signals from the targets at the FM-CW radar. Computer simulations were carried out for evaluating the proposed detection method for FM-CW radar and analyzing the performance according to the parameters under closed multiple targets environment. The results show that the proposed detection method can detect both the distance and small displacement correctly under closed multiple targets environment.**

I. INTRODUCTION

Radar systems with 24 GHz band is based on ARIB standard T73 [1] as sensors for detecting or measuring mobile objects for specified low power radio station. And the 24 GHz band radar system can be applied in various field such as security, medical imaging and so on under indoor and outdoor environments. Various radar systems were reported [2], [3], [4], [5]. Pulsed radar systems can measure the period between the transmitted and received signals. The pulsed radar can detect the distance in far field; however, the target in near field can not be detected correctly. Doppler radar systems can measure the frequency difference between the reflected and transmitted signals. The Doppler radar can detect the moving velocity of the target; however, the distance of the target can not be detected. FM-CW (Frequency-Modulated Continuous-Wave) radar systems [6], [7] is the most widely used for detecting the distance of the target object in near field and the small displacement of the target.

As previous study, we reported the design, performance analysis, and applications with 24 GHz band radar system for detecting both the distance from the radar and the small displacement for human breathing [8]. The radar system could detect both the distance to the human from the radar and the small displacement of the human breathing correctly; however, it was difficult for detecting the distances and displacements for multiple humans at the same time.

In this paper, in order to detect the distances and displacements under closed multiple targets environment, we propose a detection method for signal processing with a tunable FIR filter in the FM-CW radar system. Furthermore, performance analysis for FM-CW radar system was shown in computer simulations.

This paper consists of the following sections. In Section II, we describe the principle of a FM-CW radar system under single target environment. In Section III, we describe the proposed detection method under multiple targets environment. In Section IV, we show the computer simulations and analysis with the proposed FM-CW radar system. Finally, in Section V, we conclude this paper.

II. FM-CW RADAR SYSTEM

A. Principle of FM-CW radar

FM-CW (Frequency-Modulated Continuous-Wave) radar is a radar which is transmitting a continuous carrier modulated by a periodic function such as a sawtooth wave to provide range data shown in Fig. 1. Fig. 2 shows the block diagram of a FM-CW radar system [9].

In the FM-CW radar system, frequency modulated signal at the VCO is transmitted from the transmitter Tx; then, signals reflected from the targets are received at the receiver Rx. Transmitted and received signals are multiplied by a mixer, and beat signals are generated as multiplying the two signals. The beat signal pass through a low pass filter; then, an output signal is obtained. In this process, the frequency of the input signal is varied with time at the VCO. The modulation waveform with a linear sawtooth pattern [10] as shown in Fig. 1. This figure illustrates frequency-time relation in the FM-CW radar, and the red line denotes the transmitted signal and the blue line denotes the received signal. Here, f_0 denotes the center frequency, f_w denotes the frequency bandwidth for sweep, and t_w denotes the period for sweep.

We define that the transmitting signal $V_\mathrm{T}(f,x)$ is represented as

$$V_\mathrm{T}(f,x) = A\mathrm{e}^{j\frac{2\pi f}{c}x} \quad , \tag{1}$$

where f denotes a frequency at a time, x denotes a distance between a target and the transmitter, A denotes an amplitude value, and c denotes the speed of light.

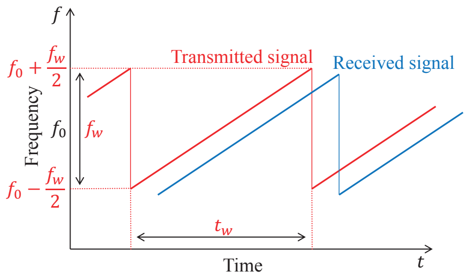


Fig. 1. Sawtooth frequency modulation

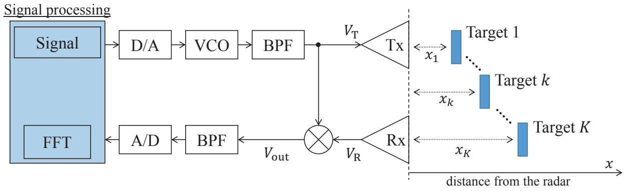


Fig. 2. Block diagram of a FM-CW radar system

The reflected signal $V_{\mathrm{R}}(f,x)$ is represented as

$$V_{\mathrm{R}}(f,x)=\sum_{k=1}^{K}A\alpha_k\gamma_k\mathrm{e}^{j\varphi_k}\mathrm{e}^{j\frac{2\pi f}{c}(2d_k-x)} \quad , \tag{2}$$

where γ_k and φ_k are the reflectivity coefficients for amplitude and phase on kth target, respectively. α_k denotes an amplitude coefficient for transmission loss from the kth target, and d_k is the distance between the transmitter and the kth target.

Here, at the receiver whose position is $x=0$, Eq. (2) is rewritten as

$$V_{\mathrm{R}}(f,0)=\sum_{k=1}^{K}A\alpha_k\gamma_k\mathrm{e}^{j\varphi_k}\mathrm{e}^{j\frac{2\pi f}{c}(2d_k)} \quad . \tag{3}$$

The beat signal is generated as multiplying the transmitted signal in Eq. (1) and the received signal in Eq. (3) at the position $x=0$. After through LPF, the output signal $V_{\mathrm{out}}(f,0)$ is generated by

$$V_{\mathrm{out}}(f,0)=\sum_{k=1}^{K}A^2\alpha_k\gamma_k\mathrm{e}^{j\varphi_k}\mathrm{e}^{j\frac{4\pi f d_k}{c}} \quad . \tag{4}$$

By using signal processing, a distance and a displacement for the target are given from the generated output signal in Eq. (4). By using the Fourier transform, the distance spectrum of the output signal $P(x)$ is calculated as follow.

$$\begin{aligned}P(x)&=\int_{f_0-\frac{f_w}{2}}^{f_0+\frac{f_w}{2}}V_{\mathrm{out}}\mathrm{e}^{-j\frac{4\pi f}{c}}df\\&=\int_{f_0-\frac{f_w}{2}}^{f_0+\frac{f_w}{2}}\sum_{k=1}^{K}A^2\alpha_k\gamma_k\mathrm{e}^{j\varphi_k}\mathrm{e}^{j\frac{4\pi f d_k}{c}}\mathrm{e}^{-j\frac{4\pi f x}{c}}df\\&=A^2\sum_{k=1}^{K}\alpha_k\gamma_k\mathrm{e}^{j\varphi_k}\int_{f_0-\frac{f_w}{2}}^{f_0+\frac{f_w}{2}}\mathrm{e}^{j\frac{4\pi f(d_k-x)}{c}}df\\&=A^2\sum_{k=1}^{K}\alpha_k\gamma_k\mathrm{e}^{j\varphi_k}\mathrm{e}^{j\frac{4\pi f_0(d_k-x)}{c}}f_w\frac{\sin\left\{\frac{2\pi f_w(d_k-x)}{c}\right\}}{\frac{2\pi f_w(d_k-x)}{c}} \quad .\end{aligned} \tag{5}$$

The amplitude value of the distance spectrum $|P(x)|$ in Eq. (5) is given as

$$\begin{aligned}|P(x)|&=A^2\left|\sum_{k=1}^{K}\alpha_k\gamma_k\mathrm{e}^{j\varphi_k}\mathrm{e}^{j\frac{4\pi f_0(d_k-x)}{c}}f_w\frac{\sin\left\{\frac{2\pi f_w(d_k-x)}{c}\right\}}{\frac{2\pi f_w(d_k-x)}{c}}\right|\\&\le A^2 f_w\sum_{k=1}^{K}\alpha_k\gamma_k\left|\frac{\sin\left\{\frac{2\pi f_w(d_k-x)}{c}\right\}}{\frac{2\pi f_w(d_k-x)}{c}}\right| \quad ,\end{aligned} \tag{6}$$

and we have equality if and only if the phase components $\phi_k+\frac{4\pi f_0(d_k-x)}{c}$ about all of k are equal.

Here, we assumed that the number of target is 1. The distance spectrum in Eq. (5) is rewritten as

$$P(x)=A^2\alpha_1\gamma_1\mathrm{e}^{j\varphi_1}\mathrm{e}^{j\frac{4\pi f_0(d_1-x)}{c}}f_w\frac{\sin\left\{\frac{2\pi f_w(d_1-x)}{c}\right\}}{\frac{2\pi f_w(d_1-x)}{c}} \quad , \tag{7}$$

and the amplitude value of distance spectrum is given as

$$|P(x)|=A^2\alpha_1\gamma_1 f_w\left|\frac{\sin\left\{\frac{2\pi f_w(d_1-x)}{c}\right\}}{\frac{2\pi f_w(d_1-x)}{c}}\right| \quad . \tag{8}$$

This equation indicates that the distance for the target is generated by the amplitude value of distance spectrum.

The phase value of distance spectrum $\angle P(x)$ is represented as

$$\angle P(x)=\varphi_1+\frac{4\pi f_0(d_1-x)}{c}=\theta_1(x) \quad . \tag{9}$$

Here, $\theta_1(x)$ satisfy $-\pi\le\theta_1(x)\le\pi$, then the displacement for the target is

$$-\frac{c(-\pi-\varphi_1)}{4\pi f_0}\le d_1\le\frac{c(\pi-\varphi_1)}{4\pi f_0} \quad . \tag{10}$$

If the phase value satisfies $\phi_1=0$, Eq. (10) is rewritten as -3.11 [mm] $\le d_1\le +3.11$ [mm] with $f_0=24.15$ [GHz]. That is, the small displacement of the target within ±3.11 [mm] is generated by the phase value of distance spectrum.

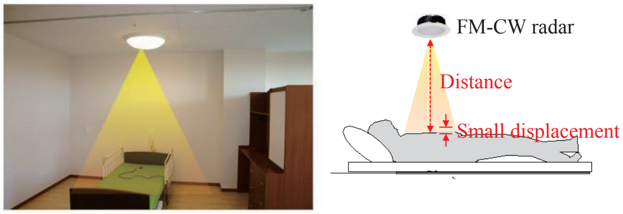


Fig. 3. An example of FM-CW Radar for detecting human breathing

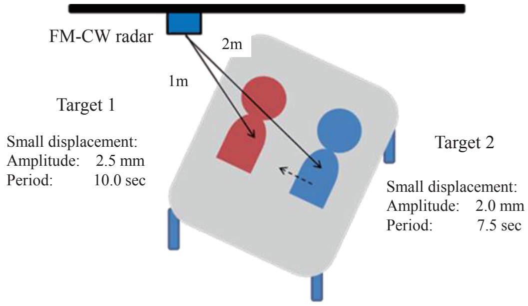


Fig. 4. Setup conditions with 2 targets

On the other hands, the maximum distance for measuring $d_{\max}$ is

$$\Delta f = \frac{f_w}{t_w/t_s}[\mathrm{Hz}] \quad ,$$

$$d_{\max} = \frac{c}{4\Delta f}[\mathrm{m}] \quad , \qquad (11)$$

where t_w denotes the sweep time, t_s denotes the interval time for sampling. For example, in the case with t_w = 1024 μs and t_s = 1 μs, the maximum distance is $d_{\max}$ = 384 [m].

B. Detection for single target

In this section, an example of detection using the FM-CW radar system is demonstrated by using the computer simulation. The setup condition in the computer simulation is shown in Fig. 3, and the condition was corresponding to the experiment in [8]. We assumed that the FM-CW radar was located on the ceiling, and the target was the human who lie in bed. If there was only single target within the range of the FM-CW radar, the individual distance and small displacement was detected correctly shown in Fig. 5.

III. PROPOSED DETECTION METHOD

As mentioned in the above section, the FM-CW radar system could detect both the distance and displacement correctly under single target environments; however, the FM-CW radar could not detect both the distance and displacement correctly under closed multiple targets environments. In order to realize detections for closed multiple targets, we propose the detection method by using the signal processing with a tunable FIR filter.

The procedures of the proposed detection method is as follow. We assumed that the FM-CW radar is located a short distance from a bed as shown in Fig. 4. The radio waves are radiated from the FM-CW radar, and 2 targets lie on the bed.

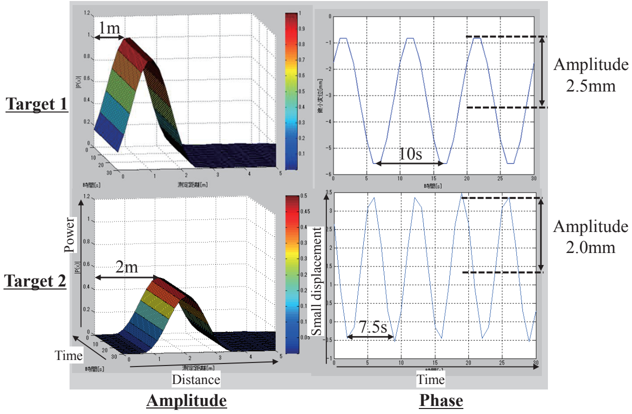


Fig. 5. Results of individual detections for single moving target

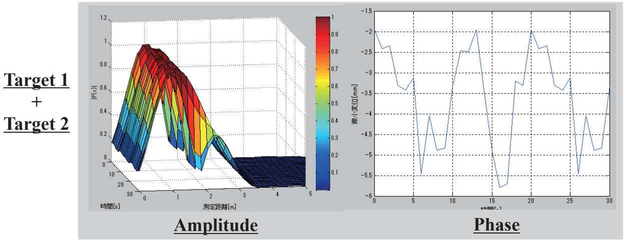


Fig. 6. Results of detection for multiple moving targets

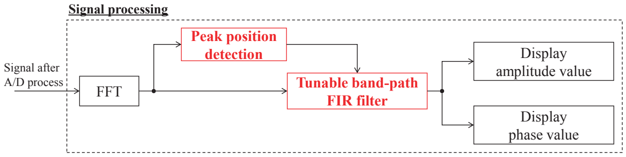


Fig. 7. Block diagram of the proposed detection method in signal processing

The distances from the radar to each target are different, so that the peaks of distance spectrum are detected at different frequency. In this case, the detected result shown in Fig. 6 is sum of these 2 targets, and it is difficult for detecting both the distance and phase values for each user correctly.

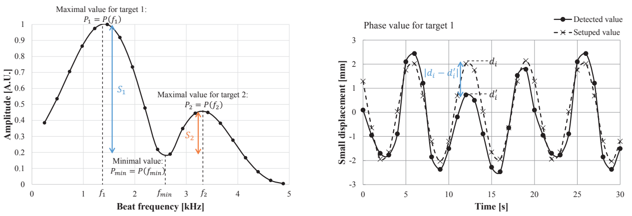
In order to solve this problem, signal processing with the tunable FIR filter is used in the proposed detection method. Figure 7 shows the block diagram of the proposed detection method. At first, the A/D converted signal is carried out the FFT operation, and the distance spectrum is obtained. After processing the FFT operation, the peaks of amplitude value of the distance spectrum are calculated. In the peak position detection processing, the two frequency value according to the targets is obtained; then, FIR filters are designed according to the peak positions. The tunable FIR filter has the center frequency corresponding to the calculated frequency in the peak position detections, and the linear property for the phase value. By using the designed FIR filter, band-path filtering operation is carried out for the distance spectrum. After through band-path filter, the amplitude and phase value for each target are detected correctly.

TABLE I. PARAMETERS IN COMPUTER SIMULATIONS

Parameters	Value
Center frequency f_0	24.15 GHz
Bandwidth of sweep frequency f_w	100, 200, 400, 800 MHz
Sweep time t_w	256, 512, 1024, 2048 μs
Bandwidth for FIR filter	200, 400, 800, 1600, 3200 Hz
Number of FFT points	4096
Window function	hamming

TABLE II. SETUP CONDITIONS FOR TARGETS

Parameters	Target 1	Target 2
Distance	1.0 m	2.0 m
Amplitude of Displacement	2.5 mm	2.0 mm
Period of displacement	10.0 s	7.5 s



(a) Amplitude value (b) Phase value

Fig. 8. Definitions of evaluation values for computer simulation

IV. COMPUTER SIMULATION

A. Setup condition

In order to evaluate the performance for FM-CW radar system with the proposed method under multiple targets environment, we carried out computer simulations. Parameters for computer simulations are listed in Table I, and the parameters are based on ARIB standard T73 [1]. Center frequency was 24.15 GHz, and frequency bandwidths were 100, 200, 400, and 800 MHz. Note that the 400 and 800 MHz bandwidth were only used for the computer simulation because of standards in the Radio Law in Japan. Sweep times were 256, 512, 1024, and 2048 μs, sampling time of sweep was 0.1 μs, number of FFT points was 4096, and the hamming windows was adapted as the window function in signal processing. The bandwidths for FIR filter were 200, 400, 800, 1600, and 3200 Hz.

In the following sections, we describe the evaluation values for analyzing the results of multiple targets detections, and the performance analysis according to bandwidth for sweep frequency, sweep time, bandwidth for FIR filter, and position of target 2 are described.

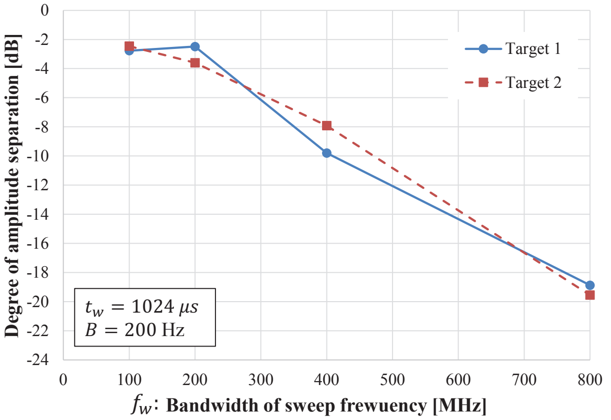
B. Evaluation values for amplitude and phase values

Figure 8 shows the evaluation value for detecting the amplitude and phase values of the distance spectrum of multiple targets. We defined the degree of amplitude separation for amplitude value and NMSE for phase value.

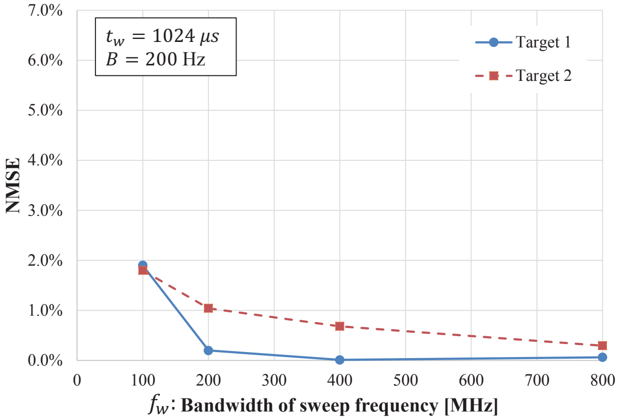
The degree of amplitude separation is represented by

$$S_k = 10\log\frac{|P_{min}|}{|P_k|} = 10\log\frac{|P\left(f_{min}\right)|}{|P\left(f_k\right)|} \qquad [\text{dB}] \quad , \quad (12)$$

where k denotes the number of target, S_k denotes the degree of amplitude separation, P_{min} denotes minimal value of amplitude whose frequency is f_{min}, and P_k denotes the peak value for k-th target with frequency of f_k.



(a): Amplitude



(b): Phase

Fig. 9. Evaluation values versus bandwidth of sweep frequency

The NMSE for phase value is represented by

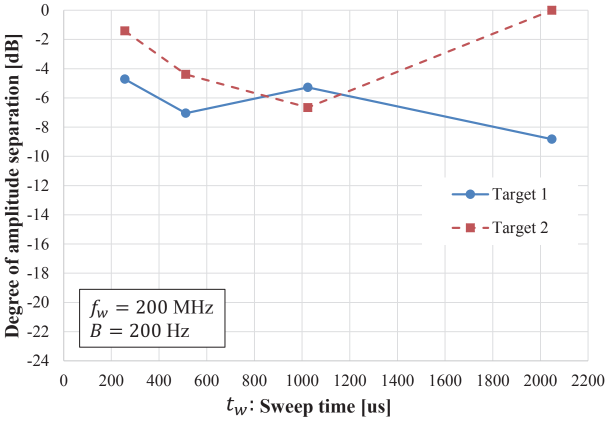
$$\text{NMSE} = \sum_{i=1}^{N}\frac{|d_i' - d_i|^2}{|d_i'|^2} \quad , \qquad (13)$$

where N denotes the number of sampling points, d_i and d_i' denote the sampled signals of detected and setuped values for a target, respectively.

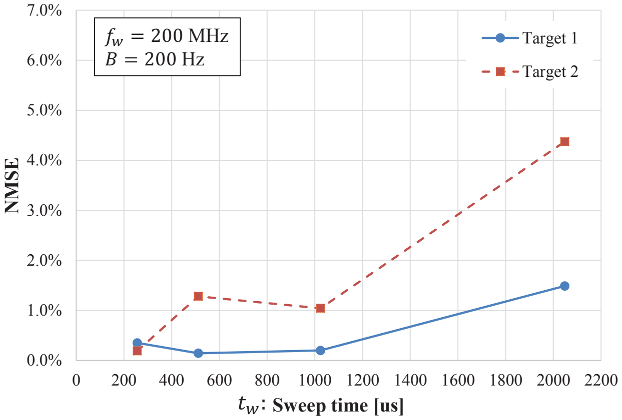
C. Performance for Bandwidth of sweep frequency

Figure 9 shows the evaluation values versus the bandwidth of sweep frequency f_w for amplitude value in (a) and phase value in (b). As shown in (a), the degrees of amplitude separation were about -2.5 dB and -19 dB with $f_w = 100$ MHz and $f_w = 800$ MHz, respectively. Because the resolution of the distance spectrum was increased as an increasing the bandwidth of sweep frequency, the separation of targets for amplitude value become easily.

As shown in (b), NMSE was about 2 % with the bandwidth of sweep frequency $f_w = 100$ MHz, and NMSE was also



(a): Amplitude



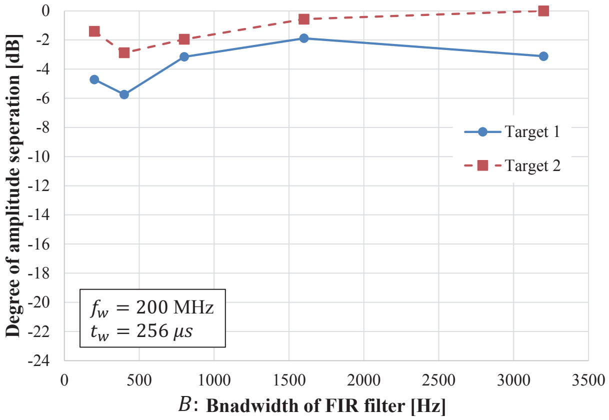
(b): Phase

Fig. 10. Evaluation values versus sweep time

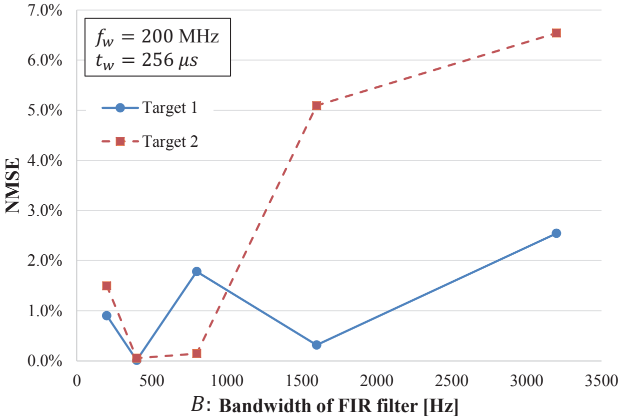
improved as an increasing the bandwidth of sweep frequency. Although there was a few disadvantage for NMSE of target 2, the multiple targets detections could correctly achieved because the degree of amplitude separation with -1 dB and NMSE with 6 % were enough values for detecting multiple targets in practical use.

D. Performance for Sweep time

Figure 10 shows the evaluation values versus the sweep time t_w for amplitude value in (a) and phase value in (b). As shown in (a), the degree of amplitude separation for target 1 kept about -4 dB in accordance not to the sweep time. The degree of separation for target 2 had -1 dB during the sweep time $t_w = 256 \sim 1024\ \mu s$. In the case with $t_w = 2014 \mu s$, the degree of amplitude separation was almost 0 dB. That is, it was difficult to detect the peak value of amplitude for target 2. Moreover, compared to the result in (b), the worst NMSE for target 2 was about 4 % with $t_w = 2048\ \mu s$. Because the resolution for distance spectrum was decreased as an increasing the sweep time, the sweep time should be less than 1024 μs.



(a): Amplitude



(b): Phase

Fig. 11. Evaluation values versus bandwidth of FIR filter

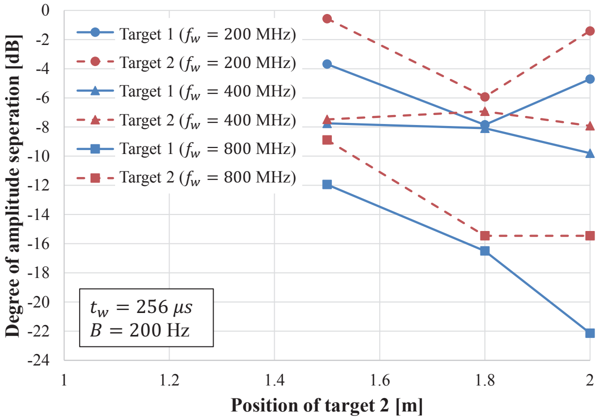
E. Performance for Bandwidth of FIR filter

Figure 11 shows the evaluation values versus the bandwidth of FIR filter B for amplitude value in (a) and phase value in (b). As shown in (a), the degree of amplitude separation for target 1 kept -2 dB in accordance not to the bandwidth of FIR filter B. When B was more than 1600 Hz, the degree was more than -1 dB, therefore, it was difficult to detect the peak value.

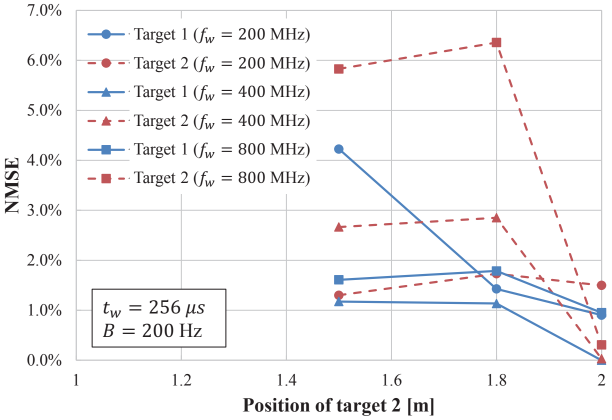
As shown in (b), NMSE for target 1 was less than 3 %, but NMSE for target 2 was more than 5 % with $B = 1600$ and 3200 Hz. Because the widely bandwidth of FIR filter was enough not to cut the signal of the other target completely, the bandwidth of FIR filter should be less than 1600 Hz.

F. Performance for distance between targets

Finally, we show the result for detecting multiple targets when the target 2 comes close to the target 1 from 2 m to 1.5 m. Figure 12 shows the evaluation values versus the position of target 2 from the radar for amplitude value in (a) and phase value in (b). The position of the target 1 was 1 m from the radar.



(a): Amplitude



(b): Phase

Fig. 12. Evaluation values versus position of target 2

Compared to the results, the degree of amplitude separation and NMSE become depleted as the target 2 approaches to the target 1. As shown in (a), when the bandwidth of sweep frequency was more than 400 MHz, the degree of amplitude separation had good property which enough to detect the peaks. However, in the case with $f_w = 200$ MHz, the degree for target 2 was about -0.3 dB, and it was difficult to detect the peaks.

As shown in (b), when f_w was less than 400 MHz, NMSE could be kept about less than 5 %. However, in the case with $f_w = 800$ MHz, NMSE become depleted. It was difficult to detect peaks of amplitude for targets as decreasing distance between targets. Therefore, the center frequency of FIR filter was not enough to cut the other target's signal, and the imperfect FIR filter influenced NMSE values. Although there were a few difficulty for determining the parameters of the proposed detecting method for FM-CW radar, the proposed detecting method could be effective for detecting the distance and the small displacement at the same time under multiple targets environments.

V. CONCLUSION

In this paper, a FM-CW radar system with 24 GHz band with tunable FIR filter for detecting closed multiple moving targets with small displacements was described. The proposed detecting method generates tunable FIR filter whose center frequency is corresponding to the peak positions of distance spectrum of each target. The tunable FIR filtered signal can be detected the distance and displacement for each target correctly. In computer simulations, performances of FM-CW radar system under closed multiple moving targets environment was analyzed in accordance with the bandwidth of sweep frequency, sweep time, bandwidth of FIR filter, and the distance between targets. As the result, the 24 GHz FM-CW radar with the proposed detection method could effectively detect both the distance and the small displacement for each target under the multiple moving targets environments. And it was confirmed that the proposed detection method can detect both the distance and small displacement correctly when the distance between targets was 0.5 m.

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