

24-GHz Band Radar for Driving Safety Support Systems

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We are developing driving safety support systems to reduce traffic accidents. One function of this system is to provide information on the presence of pedestrians on a crosswalk to a vehicle turning right at an intersection and call attention to the driver. We have developed a 24-GHz band radar to detect pedestrians as a roadside sensor, and started shipping it in March 2018. The radar features robustness against changes in weather and sunshine conditions, high performance in pedestrian detection, and a wide detection area. This paper introduces the radar and shows the result of a field test.

Keywords: vehicle-to-infrastructure cooperative system, driving safety support system, pedestrian sensor, 24-GHz band radar

1. Introduction

In Japan, the number of traffic fatalities (3,694 in 2017) has been decreasing year by year.⁽¹⁾ However, various measures are required to attain the goal of reducing the number of traffic fatalities to below 2,500 by 2020 as set by the Japanese government. It should be noted that almost half of traffic accidents occur at intersections.⁽²⁾ In particular, blind intersections require not only an autonomous driving safety support system designed to avoid hazards using in-vehicle sensors but also a vehicle-to-infrastructure cooperative system designed to exchange information between vehicles and infrastructure. We have been developing vehicle-to-infrastructure cooperative systems for driving safety support in order to help prevent traffic accidents.⁽³⁾

One of such systems has been operated by the prefectural police in Japan. The system provides vehicles that enter an intersection to make a right turn with information about the presence of pedestrians on a crosswalk and on-coming vehicles detected by a roadside sensor. The information is transmitted by a wireless roadside unit (see Fig. 1). An in-vehicle device designed for the system alerts the driver with indications on the display and alarms. The drivers of vehicles equipped with this device can use the service.

Previously, we have put wireless roadside units and vehicle sensors on the market. In addition to them, we commercialized a 24-GHz band radar to be used as the infrastructure pedestrian sensor for the first time in the

world, and started shipment in March 2018.

The 24-GHz band radar is resistant to weather and sunlight change, and is equipped with our proprietary pedestrian detection algorithm. It can accurately detect pedestrians (including bicycle riders) on an entire crosswalk and in the pedestrian waiting area*¹ around the crosswalk. The radar can also be installed on a pedestrian signal pole near a crosswalk. It achieves a broad detection area that covers the pedestrian waiting area in close proximity and an entire crosswalk of more than 40 m long.

This paper introduces the 24-GHz band radar and reports the results of a performance verification experiment at an actual intersection.

2. 24-GHz band radar as pedestrian sensor

Table 1 summarizes the specifications of the sensor, and Fig. 2 shows the appearance of the sensor unit.

2-1 Principle of the FMCW radar

We used a frequency modulated continuous wave (FMCW) radar. The radar measures the distance to an object by detecting the frequency difference between the frequency-modulated transmission waves and the waves reflected by target objects (beat frequency). The detection method can be applied even if the velocity of the target is zero. Thus, target pedestrians can be detected while walking or standing still. However, the radar also receives intense waves reflected from stationary objects such as utility poles near the crosswalk. It was necessary to cope

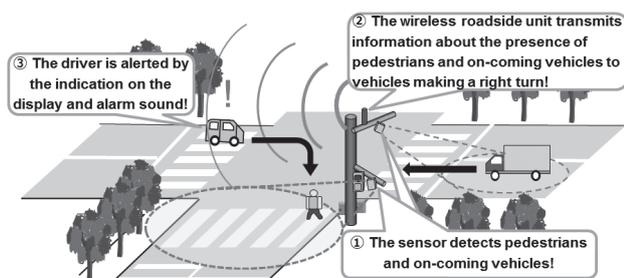


Fig. 1. Image of the vehicle-to-infrastructure cooperating driving safety support system

Table 1. Specifications of the pedestrian sensor

Modulation method	FMCW
Power supply voltage	90 to 110 V (AC)
Power consumption	20 W (Typ.)
Frequency band	24.05 to 24.25 GHz
Transmitter power	20 mW
Temperature range	-20 to 50°C
Dimensions	265 × 265 × 147 mm
Weight	7 kg or less (excluding the mounting brackets)

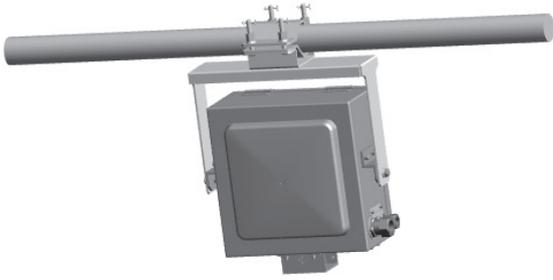


Fig. 2. Appearance of the sensor

with this problem in developing the detection algorithm, as discussed below.

2-2 Features

The features of the pedestrian sensor are as follows.

(1) Excellent environmental performance

The radar is a sensor that utilizes radio waves, and therefore there is no performance difference attributed to the differences in sunlight conditions (during the daytime and at night) or temperature differences. The influence of weather on radio wave propagation characteristics is also limited. Thus, the radar is resistant to changes in weather conditions (e.g., fine weather, rain, snow, fog) and is therefore effective in an environment where driver visibility is low.

(2) High pedestrian detection accuracy

The developed pedestrian detection algorithm offers a function to track pedestrians and estimate their movement based on the characteristic information of the reflected waves. Pedestrians can be detected with high accuracy even at an actual intersection where there are many objects other than pedestrians.

(3) Broad detection area

It was difficult for the radar to cover the area in its close proximity and to extend the detection distance simultaneously. We developed antennas of multiple channels, a 24-GHz transmitter-receiver circuit, and the signal processing technology for utilizing the antennas and circuit.

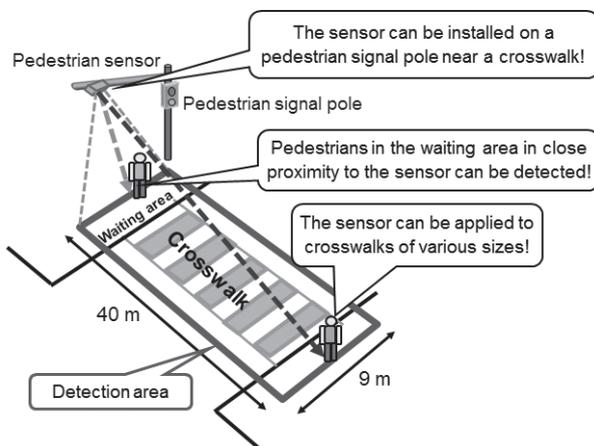


Fig. 3. Installation image of the pedestrian sensor

The radar can be installed on a pedestrian signal pole near a crosswalk, as shown in Fig. 3. The broad detection area covers the pedestrian waiting area almost directly below the sensor as well as the crosswalk of more than 40 m long. These characteristics ensure application to crosswalks of various sizes and result in high installation flexibility.

3. Configuration

Figure 4 shows the block diagram of the radar.

This chapter explains the three components: (1) antenna that achieves a broad detection area, (2) 24-GHz transmitter-receiver circuit, and (3) pedestrian detection algorithm that operates on the processing circuit unit and achieves high detection performance.

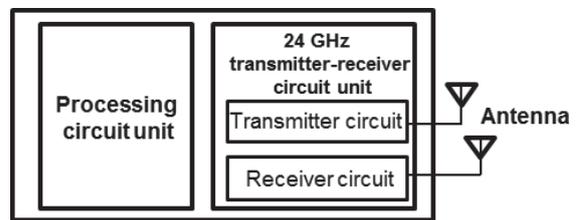


Fig. 4. Block diagram of our radar

3-1 Antenna

The antenna element pattern is formed on a non-fluorine-based substrate characterized by low dielectric constant and low loss. Two transmitter channels and four receiver channels are configured on the same substrate.

The antenna has high gain and wide-angle directivity in the horizontal and vertical directions. Therefore, the detection area is 9 m wide and more than 40 m long. Notably, the high gain characteristics in deep angles (downward from the sensor) allow installation with a short setback distance from the edge of the detection area. Thus, the antenna can be used for crosswalks of various sizes (see Fig. 3).

The waves reflected from objects are received by four channels of receiver antennas. The phase difference between the channels is detected to estimate the direction of the objects. In combination with the distance detection results, the position coordinates of the objects can be identified on the crosswalk plane.

The gap between the receiver antenna channels affects the generation of grating lobes*2 in the direction estimation. With the physical constraints of the antenna element layout taken into account, the gap between the four antennas is optimized at unequal intervals to reduce the detection error attributed to the grating lobes.

Any unwanted couplings between transmitter and receiver antennas increase the receiving noise and decrease the object detection accuracy. Thus, it is important to reduce the couplings. The couplings between antennas can

be reduced by increasing the gap, but this increases the sensor dimensions. We ensured the gap by optimizing the internal layout, employed a substrate structure for minimizing the couplings, and improved the pattern shape. Accordingly, we minimized the gap between the antennas and reduced the overall sensor size.

3-2 24-GHz transmitter-receiver circuit

The configuration of the 24-GHz transmitter-receiver circuit is shown in Fig. 5. The circuit of two transmitter channels and four receiver channels is configured on a low-loss substrate, as in the case of the antennas.

In the transmitter circuit, the voltage controlled oscillator (VCO)*³ generates continuous waves of 24 GHz. The phase locked loop (PLL) synthesizer*⁴ performs the frequency modulation of the VCO's control voltage (i.e., a linear frequency increase with passage of time) to output the FMCW chirp signals of 24 GHz.

The variable gain amplifier (VGA)*⁵ in the subsequent stage suppresses the level change in the chirp signals attributed to the temperature change and other factors. The chirp signals are then amplified to the required level by the power amplifier (PA).*⁶ The unwanted waves other than the required band are then removed from the chirp signals by a filter before transmission.

In the receiver circuit, unwanted waves outside the band are removed from the received waves reflected from objects. The signal level is amplified by the low noise amplifier (LNA).*⁷ The received signals whose levels are amplified are mixed with the transmitted signals by the mixer.*⁸ The frequency difference between the transmitted signals and received signals (beat frequency) is output.

The beat signals are converted from analog signals to digital signals by the A/D converter,*⁹ and sent to the signal processing circuit in the subsequent stage. The frequency of beat signals is relatively low, so it is important to avoid sensitivity deterioration caused by the 1/f noise.*¹⁰

In this circuit, a noise reduction filter is inserted, and the beat frequency is separated from the 1/f noise band by reducing the chirp sweep time to eliminate the influence on sensitivity.

The receiver system achieves high dynamic range performance. It also has a low noise performance against faint signals reflected from distant objects and a high

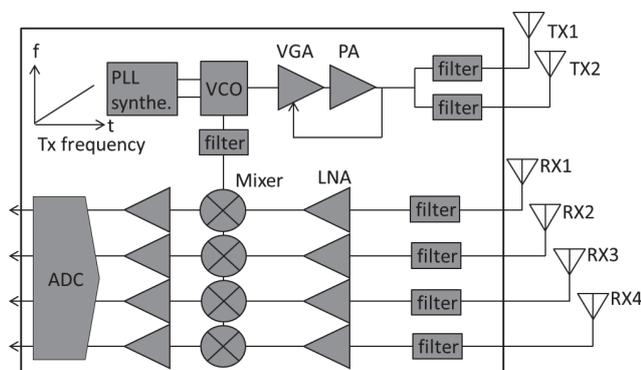


Fig. 5. Block diagram of the 24-GHz transmitter-receiver circuit

linearity against high levels of signals reflected from metals such as vehicles.

In terms of reduction of couplings between transmitter and receiver systems in the circuit, signal separation of 50 dB or more is achieved by separating the parts layout and substrate wiring pattern in the transmitter-receiver circuit area and adding a radio wave shield mechanism.

3-3 Pedestrian detection algorithm

This section explains the pedestrian detection algorithm.

The radio waves reflected from pedestrians are weak (about 1/1,000) compared to those from metals such as vehicles. In an actual intersection where there are many objects other than pedestrians, the waves reflected from pedestrians are likely to be overwhelmed by waves reflected from other objects. A new detection technology was required.

Against this backdrop, we developed (1) a process to remove stationary objects and (2) a process to track pedestrians using the time series filter.*¹¹

(1) Process to remove stationary objects

In the process to remove stationary objects, the features of stationary objects such as signal poles are analyzed for extracting only weak waves reflected from pedestrians. This makes it possible to prevent misdetection of stationary objects and detect pedestrians who stand near the stationary objects whose signals are originally overwhelmed by intense waves from the stationary objects. The experiment results of this process are discussed in Section 4-1.

(2) Process to track pedestrians

Regarding the process to track pedestrians, after the process to remove stationary objects is applied, the position coordinates of objects whose intensity of reflected waves is at the threshold or higher are extracted as “observed values.”

Next, the observed values are used as input information, and the time series filter that operates continuously is applied. The time series filter changes its status based on the status transition diagram (see Fig. 6).

We introduced a status of “Pedestrian candidate status” for terminating the error distribution of the time series filter. In this status, “no pedestrian” is output. “Pedestrian status” represents the status in which a tracking target is recognized as a pedestrian. We determined the condition of transition from pedestrian candidate status to pedestrian status as the time when specific requirements that indicate the characteristics of a pedestrian are met.

If observed values are not obtained continuously for a certain period of time or longer in pedestrian candidate

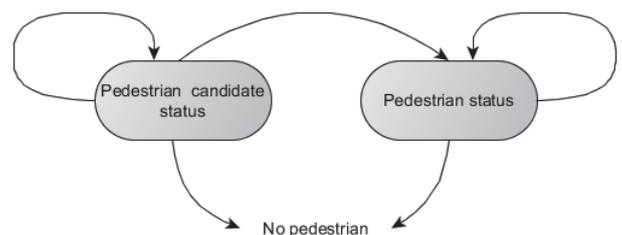


Fig. 6. Status transition of a tracking target

status and pedestrian status, the tracking of the time series filter is terminated.

Application of this logic enables detection of a pedestrian whose waves are overwhelmed by those reflected from moving objects such as passing vehicles as well as detection of a pedestrian who is temporarily hidden by the preceding pedestrian.

4. Performance Verification Experiment at an Actual Intersection

We conducted a performance verification experiment using the pedestrian sensor at the actual intersections in Osaka City.

The left side of Fig. 7 shows the image of the installation environment. The sensor was installed to an arm of a signal pole about 4 m above ground. A reference camera was installed on the arm. The image of the intersection captured by the camera is indicated on the right side of Fig. 7. The box on the right side of Fig. 7 shows the detection area.

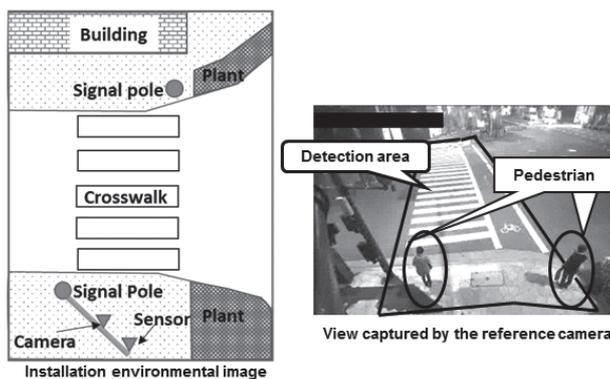


Fig. 7. Image of the installation environment and view of the intersection

4-1 Performance verification of the process to remove stationary objects

To verify the performance of the process to remove stationary objects, the process was applied to the moment shown on the right side of Fig. 7. The results before and after the application of the process are indicated in Fig. 8.

The color shades in the figure represent the intensity of reflection of radio waves from objects on the crosswalk and its surrounding areas. The thicker the color, the more intense the reflection.

Before application of the process to remove stationary objects (on the left of Fig. 8), the intense reflection of radio waves from the objects ① to ④ in boxes is clearly identified.

After application of the process (on the right of Fig. 8), only the radio waves reflected from pedestrians (in circles) are extracted by removing the reflection from objects ① to ④.

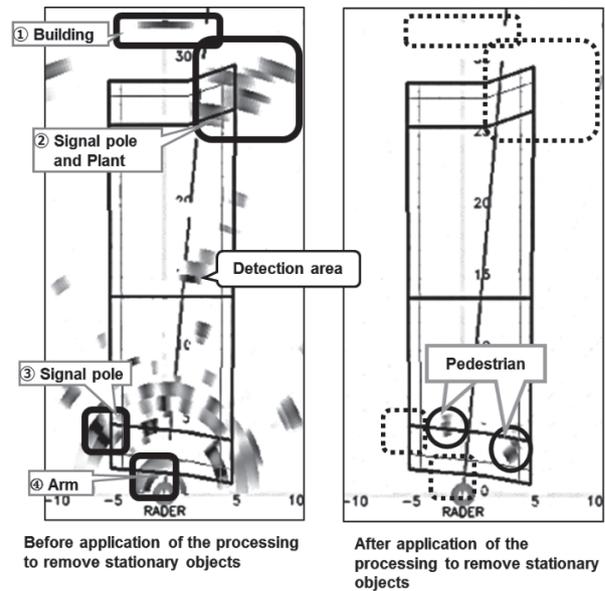


Fig. 8. Application result of the stationary object removal process

4-2 Results of pedestrian detection

Figures 9 and 10 show the results of pedestrian detection at the actual intersection. The left side of Figs. 9 and 10 are the views captured by the reference camera and indicate the presence of pedestrians in the detection area in

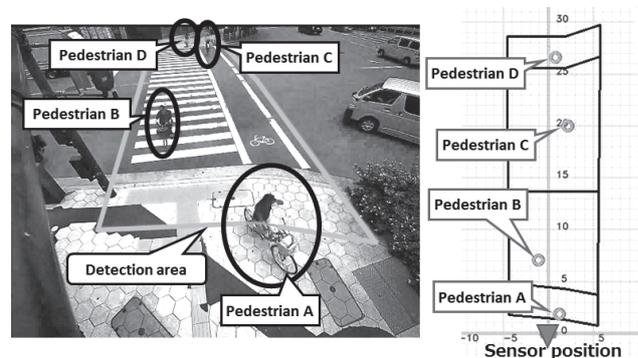


Fig. 9. Example of pedestrian detection result 1

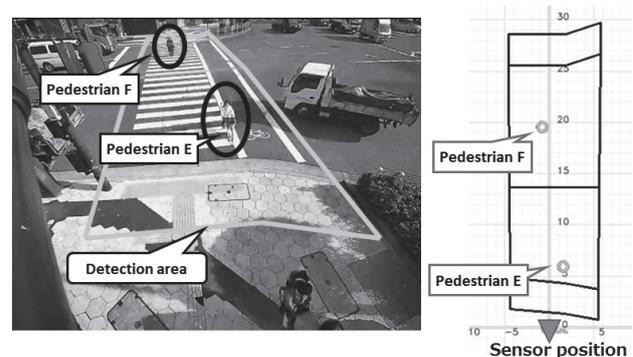


Fig. 10. Example of pedestrian detection result 2

the box.

The right side of Figs. 9 and 10 shows the results of pedestrian detection (indicated as circles) by the sensor at the time indicated on the left side of each figure.

Based on the results of Fig. 9, “pedestrian A” who passed in close proximity to the sensor at a high velocity and “pedestrian D” who entered the pedestrian waiting area across the crosswalk were detected.

The results of Fig. 10 show that “pedestrian E” who was near a vehicle making a left turn that reflected intense waves and “pedestrian F” who was farther than “pedestrian E” were also detected.

4-3 Evaluation of detection accuracy

Next, the results of the detection accuracy evaluation in this experiment environment are discussed.

In the evaluation, the performance was verified using many hours of data that included characteristic situations at actual intersections such as pedestrians passing each other, pedestrians walking in front of/behind passing vehicles, and bicycle riders whose velocity is fast.

As discussed above, the radar is not affected by sunlight change. Thus, this experiment focused on verification of resistance to weather change. The following was used as the evaluation index.

$$\text{Non-detection time rate} = \frac{\text{Non-detection time}}{\text{Total presence time of pedestrians}}$$

$$\text{Misdetction time rate} = \frac{\text{Misdetction time}}{\text{Sensor's detection time}}$$

The experiment results are shown in Table 2.

Table 2. Experiment result

Result	Weather	
	Fine	Rain
Non-detection time rate	0.5%	0.3%
Misdetction time rate	0.4%	0.2%

Based on the results in Table 2, it was verified that high detection performance can be achieved in any weather conditions in the actual environment where objects other than pedestrians are present.

We verified that the difference in the detection results in fine weather and rain was attributed to the difference in the traffic flow, not the sensor performance.

5. Conclusion

We developed a 24-GHz band radar, to be used as a pedestrian sensor, with excellent environmental performance, high pedestrian detection performance, and a broad detection area. We conducted an evaluation at an actual intersection and verified the high detection performance.

We will use the technology established through this development project in new applications such as support systems for merging sections and automated driving technologies on expressways.

6. Acknowledgements

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Technical Terms

- *1 Pedestrian waiting area: An area around a crosswalk used by pedestrians to wait for crossing.
- *2 Grating lobe: A false estimation result that is different from the true incoming direction of an object generated by the periodicity of 2π (phase of the radio wave signal).
- *3 Voltage controlled oscillator (VCO): An oscillator whose oscillating frequency can be changed by the control voltage.
- *4 Phase locked loop (PLL) synthesizer: A circuit for synchronizing the phase of the input signal (i.e., synthesizer reference frequency) with that of the output signal from the VCO.
- *5 Variable gain amplifier (VGA): An amplifier that can control the gain by the control voltage.
- *6 Power amplifier (PA): A high-output amplifier that increases the transmitter signal to the required level.
- *7 Low noise amplifier (LNA): An amplifier that increases the signal level with minimal noise added to the weak signals received.
- *8 Mixer: Signals of two different frequencies are input into a mixer, which outputs the frequency signals of sums and differences of these frequencies.
- *9 Analog to digital (A/D) converter: A circuit to convert analog signals to digital signals.
- *10 1/f noise: The noise in the low frequency band (less than 100 kHz) generated by semiconductor elements in inverse proportion to the frequency.
- *11 Time series filter: A method of estimating or controlling the status of a dynamic system by using observed values with error.

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