

Radio Wave Propagation Analysis for In-Cabin Radar

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Abstract

Efforts are underway to reduce the risk of accidents such as heatstroke for infants left behind in vehicles, including the addition of child presence detection (CPD) to the European New Car Assessment Programme (NCAP) assessment criteria¹. A 60 GHz-band millimeter-wave radar is regarded as a promising in-cabin sensor; however, given that its detection performance is affected by transmission, reflection, and other effects caused by in-cabin structures, it is important to determine during the pre-product-development stage whether factors such as the sensor specifications, installation conditions, and in-cabin layout are appropriate. Mitsubishi Electric Corporation's "radio-wave visualization technology"² was applied for this development to an in-cabin radar, and experimental verification was performed by comparing measured data of human-body scattering. A detection feasibility map for the vehicle cabin was also created to show that radio-wave propagation analysis is effective for determining radar detection performance during the pre-product-development stage.

1. Introduction

In recent years, millimeter-wave radars, which have mainly been used outdoors, have started to be used even in enclosed spaces such as indoors and vehicle cabins, and demand is increasing in particular for in-cabin monitoring in automobiles. One factor behind this is that CPD has been added to the Euro NCAP assessment criteria used to evaluate vehicle safety. As shown in Fig. 1, CPD is intended to reduce the risk of accidents such as infant heatstroke by detecting the presence of an infant left behind in a vehicle cabin and notifying the user or a third party.

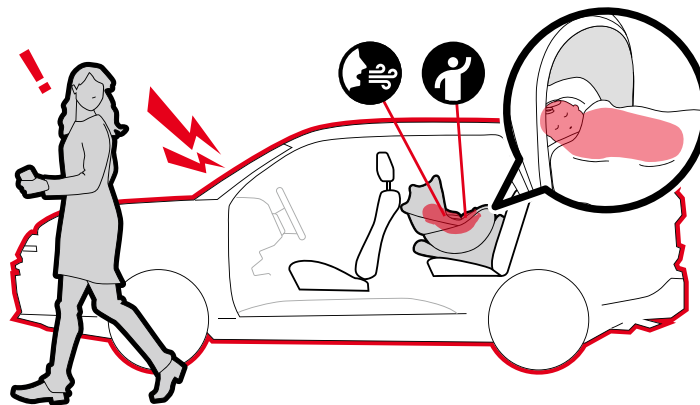


Fig. 1 Child presence detection system

Under Euro NCAP, the presence of an infant needs to be detected even under conditions such as when a blanket covers a sleeping infant in a rear-facing Child Restraint System (CRS) with a sunshade, or when an infant has slipped into the footwell area of the seat. Under such conditions, it is difficult for optical sensors such as cameras to detect an infant, whereas radio-wave sensors such as radar are more suitable; accordingly, Mitsubishi Electric Corporation is advancing the development of a CPD system that uses a 60 GHz-band millimeter-wave radar³. Given that radio-wave sensors are able to penetrate objects to some extent as long as they are not metal, they can detect the presence of an infant even in the scenarios described above.

The detection performance of an in-cabin radar varies not only with the specifications of the radar unit itself, but also with changes in the radio-wave propagation conditions resulting from installation conditions such as position and angle, and from factors such as the in-cabin layout. Therefore, optimizing the installation conditions for each vehicle model is essential. One way to achieve such optimization is to acquire data under various radar installation conditions for all vehicle models and optimize those installation conditions and various parameters; yet when factoring in the time and cost required for development, this is not a realistic approach.

To address these issues, Mitsubishi Electric Corporation’s radio-wave visualization technology is applied to an in-cabin radar with this development to improve development efficiency. After outlining the radio-wave propagation environment of in-cabin radar and methods of modeling it, this paper presents experimental verification using measured data of human-body scattering taken in an electromagnetic anechoic chamber, as evaluation results of the developed radio-wave propagation analysis for in-cabin radar. Examples of examining installation conditions by creating an in-cabin detection feasibility map are also provided, thereby showing that radio-wave propagation analysis is effective for determining radar detection performance in the pre-product-development stage.

2. Applying Radio-wave Visualization Technology to In-cabin Radar

This chapter outlines the concept for applying Mitsubishi Electric Corporation’s radio-wave visualization technology to in-cabin radar.

2.1 Radio-wave propagation environment of in-cabin radar

In open space, the received power P_r of a reflected wave from an object located at a distance R from the transmit/receive antennas of a millimeter-wave radar is generally expressed by the radar equation as follows, where the transmit power is P_t , the transmit antenna gain is G_t , the receive antenna gain is G_r , the wavelength is λ , and the radar cross section (RCS) is σ .

$$P_r = \frac{G_t G_r \lambda^2 \sigma}{(4\pi)^3 R^4} P_t \dots\dots\dots (1)$$

However, the actual radio-wave propagation environment inside a vehicle is not open space and is extremely complex. For example, radar has directionality, and radio waves are radiated with different strengths depending on direction. That is, the transmit antenna gain and receive antenna gain in Equation (1) vary by direction. In addition, in a vehicle cabin, radio waves may not only reach an infant directly, but may also reach the infant via multipath directions, after passing through seats or other objects, or after being reflected by in-cabin structures. Therefore, designing an in-cabin radar requires not a simple radar equation, but a method to comprehensively evaluate and visualize whether radio waves reach throughout the vehicle cabin for each vehicle model and installation condition. That method is radio-wave propagation analysis technology, i.e., radio-wave visualization technology.

Mitsubishi Electric Corporation’s radio-wave visualization technology uses the ray tracing method, and this method is also used for analyzing radio-wave propagation for in-cabin radar. With the ray tracing method, radio waves are represented as rays as shown in Fig. 2; rays are emitted from the transmit antenna, and their trajectories are tracked. In addition, the physical phenomena of radio waves being reflected and diffracted by in-cabin structures is calculated by approximating them as reflection and diffraction of rays. Furthermore, changes in the electromagnetic field are calculated while taking into account the electrical characteristics and shapes of in-cabin structures, enabling calculations that reflect a wide variety of real environments.

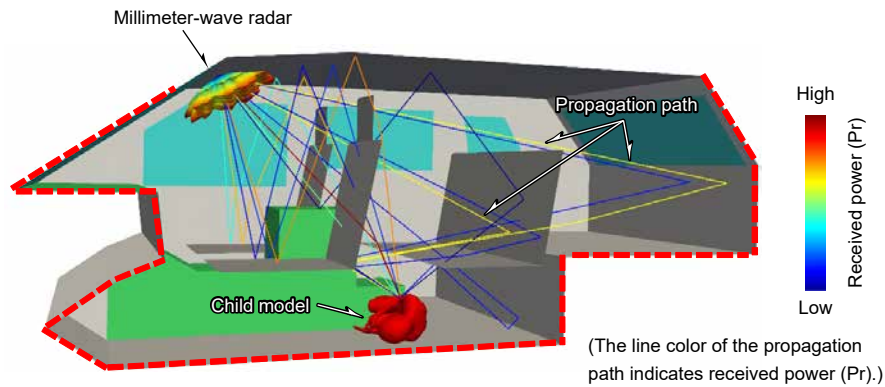


Fig. 2 Conceptual illustration of the ray-tracing method

A feature of the ray tracing method is that it is able to calculate electric field strength with a high level of accuracy based on a geometrical optics approximation for objects and spaces that are sufficiently large compared with the wavelength of the radio wave. In the case of a 60GHz-band millimeter-wave radar, the wavelength (λ) is approximately 5mm, so it can be said that the wavelength is sufficiently short relative to in-cabin structures. In addition, the ray tracing method has the feature of being able to perform calculations faster than complex electromagnetic field analyses such as the Finite-Difference Time-Domain (FDTD) method.

2.2 Modeling for radio-wave propagation analysis for in-cabin radar

As shown in Fig. 3, radio-wave propagation analysis for in-cabin radar requires modeling of the antenna radiation pattern, in-cabin structure, and the reflection strength of the human body. The following outlines the modeling methods for each.

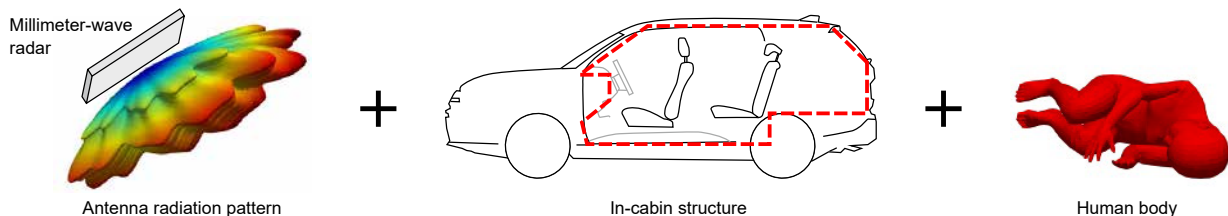


Fig. 3 Modeling elements for radio wave propagation analysis for in-cabin radar

(1) Modeling of antenna radiation pattern

The antenna radiation pattern is one of Mitsubishi Electric Corporation's radar design elements, and it can be quantified using measured data and electromagnetic field analysis results. In addition, if a structure exists near the position where the radar is installed, an antenna radiation pattern that includes the radar and the surrounding structures is derived as needed.

(2) Modeling of the in-cabin structure

One approach to modeling the in-cabin structure is to measure the positional relationships of each part and build a model based on the measurements. In recent years, it has also become possible to reflect detailed shapes using a 3D scanner. In addition to measurements, it is also possible to base the model on an in-cabin 3D model (a surface model is acceptable), and it can be applied even to vehicles in the pre-prototype stage. Note that fine parts may only increase analysis time while having little impact on the analysis results; therefore, the 3D model shape is modified while factoring in analysis time and analysis accuracy. The electrical characteristics of structures such as vehicle seats are tuned based on measured data and other factors.

(3) Modeling of the human body

The human body has features that are small relative to the wavelength (λ), and received power (P_r) cannot be calculated correctly using a simple ray tracing method. Therefore, we used two methods: (1) Calculate received power (P_r) as the composite wave of reflections from the entire human model, and (2) Assign a representative RCS of the human body as a point target.

Method (1) makes it possible to calculate the radar’s received power (P_r) according to the posture and size of the human model, but it increases the computational load accordingly. As a method for calculating received power (P_r) obtained from the human body, there is also a method that combines ray tracing and physical optics approximation; however, as a simpler calculation method used for this development, we adopted a method where virtual scattering point(s) are placed on the human body surface, the received power (P_r) at the radar is obtained according to the radar equation from the path loss to those points and their scattering characteristics, and then those contributions are combined.

Method (2) fixes the human body’s RCS to the set RCS; however, because it becomes a point target, it can be calculated with a simple ray tracing method, and it is suitable for comprehensively evaluating whether sufficient power reaches each area inside the cabin.

3. Evaluation Using Radio-wave Propagation Analysis for the In-cabin Radar

This chapter outlines the evaluation results obtained by applying Mitsubishi Electric Corporation’s radio-wave visualization technology to an in-cabin radar and verifies its effectiveness.

3.1 Experimental verification using human-body scattering data

We verify the validity of the developed radio-wave propagation analysis for in-cabin radar using comparison with human-body scattering data measured in an electromagnetic anechoic chamber. Figure 4 shows an example comparison between the radio-wave propagation analysis results and the measured results for the relationship between received power (P_r) and distance when applying the human modeling method (1) outlined in Section 2.2 (method that calculates received power (P_r) as the composite wave of reflections from the entire human model). The human model was generated by capturing an actual human body with a 3D scanner so that the posture and shape would be equivalent. In the simulation, 28,796 virtual scattering points were placed on the human body surface, and the received power (P_r) at the radar was calculated according to the radar equation from the path loss to those points and their scattering characteristics. Note that the power on the vertical axis is normalized with the received power (P_r) near the head set to 0dB, and the measured data uses the average of two measurements set to 0dB. From Fig. 4, while the measured and analyzed results do not match completely, both show a tendency for higher power near the head and shoulders; thus, we confirmed that radio-wave propagation analysis can yield received power (P_r) trends similar to those of the measured results. Possible causes of the error include that the human model and the measurements do not match completely, and that the human body during measurement has some degree of sway even while the data is being acquired. Going forward, we will conduct verification with various postures and verification with occupants in the cabin, and confirm effectiveness in an environment closer to real-world conditions.

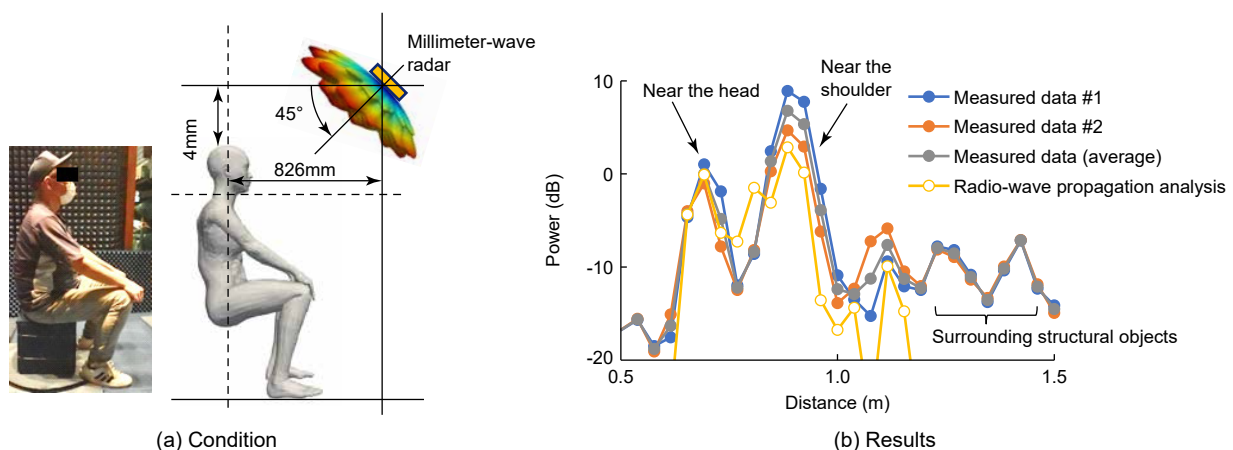


Fig. 4 Comparison between radio-wave propagation analysis and measured results for received power observed from the human body

3.2 Study of mounting conditions by creating a detection feasibility map

The following is an example where radio-wave propagation analysis is performed while changing the mounting angle to assess whether an in-cabin child can be detected. The radar is mounted near the overhead console above the rearview mirror, and the mounting position corresponds to Fig. 2 outlined in Section 2.1. In this simulation, we used human-body modeling method (2) (method that assigns a representative RCS of the human body as a point target).

Figure 5(a) shows the mounting position and angle conditions, and Fig. 5(b) shows the received power map and the radar detection feasibility map in the vicinity of the feet for mounting angles of 45° and 60°. The received power map represents with color shading the strength of received power (P_r) when a child-representative reflector is present at each point in the cabin, and is used to identify how many radio waves reach each region in the cabin. The radar detection feasibility map, which takes into account the radar hardware and signal processing performance, visualizes in white the range where the received power (P_r) is at or above the signal-to-noise ratio (SNR) required to detect a child, and in black otherwise—this is used to intuitively identify whether the desired detection range is covered. For reference, the figure also overlays child-representative objects at the feet of the first- and second-row seats; moreover, to make the cabin easier to see, the vehicle body is not drawn in the figure.

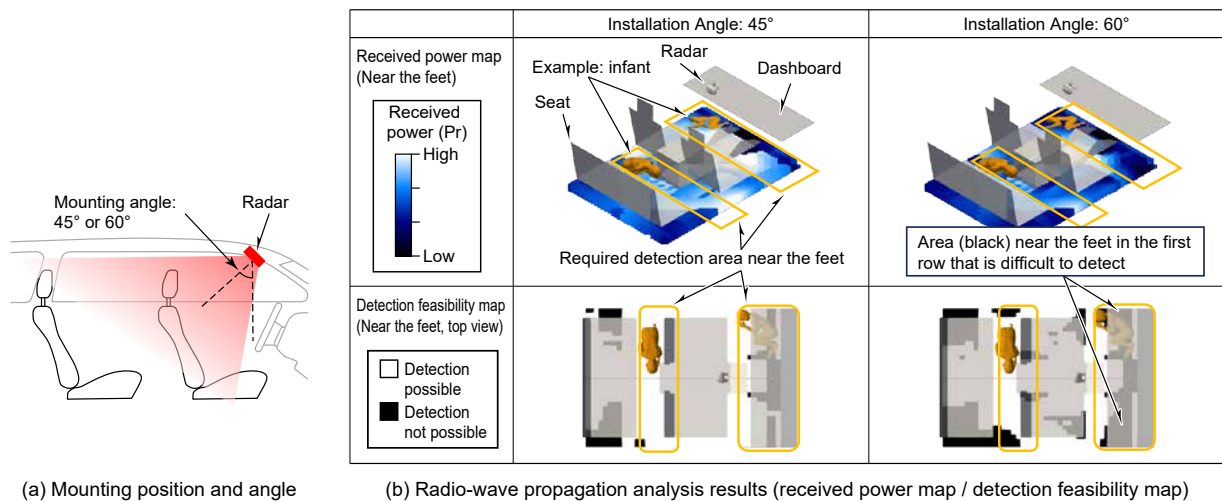


Fig. 5 Example of mounting (installation) conditions and radio-wave propagation analysis results

From Fig.5(a), it can be seen that received power (P_r) decreases due to the effects of shielding objects such as seats and attenuation with distance. From Fig. 5(b), it can also be seen that for both mounting angles of 45° and 60°, even in the radio attenuation region in Fig. 5(a), it is generally possible to detect a child. However, for a mounting angle of 60°, we also confirmed that there are areas where it is difficult to detect some children in the first-row footwell; under these conditions, it can be said that a mounting angle of 45° is more appropriate. As outlined above, by leveraging radio-wave propagation analysis, it is possible to confirm the appropriateness of design parameters such as “radar unit specifications” and “radar mounting position and angle” at the pre-prototype stage. This makes it possible to optimize the design at an early stage, and is expected to improve development efficiency.

4. Conclusion

Mitsubishi Electric Corporation’s radio-wave visualization technology was applied to in-cabin radar, and its effectiveness was demonstrated.

Going forward, we will evaluate the validity of analysis results in an actual vehicle and establish radio-wave propagation analysis technology for in-cabin radar; moreover, by leveraging not only radio-wave propagation analysis technology but also a variety of Mitsubishi Electric’s radar technologies, we will contribute to developing a CPD system capable of more reliably detecting infants left behind in the cabin.

References

- (1) Euro NCAP: Child Presence Detection Test and Assessment Protocol Ver.1.3(2024)
<https://www.euroncap.com/media/83740/euro-ncap-cpd-test-and-assessment-protocol-v13.pdf>
- (2) Mitsubishi Electric Corporation: Development of “Radio-wave Visualization Technology” that Supports IoT by Assisting Optimal Placement of Wireless Equipment (2017)
<http://www.mitsubishielectric.co.jp/news/2017/pdf/0524-c.pdf>
- (3) In-cabin Occupant Detection Technology Using Camera and Millimeter Wave Radar, Mitsubishi Denki Giho, 97, No. 1, 71 (2023)