In this study, a low-cost continuous wave (CW) radar system with 3D-printed high-gain horn antennas called VitRad is proposed for human vital sign detection. The CW radar consists of 3D-printed high-gain horn antennas, commercially available low-cost surface-mounting devices, and monolithic ICs. The CW radar system operates at a frequency band of 5.8 GHz, and the backscattered I/Q data are collected using a digital storage oscilloscope (DSO). The data is processed on MATLAB to determine vital sign information such as respiratory and heartbeat rates. It is demonstrated that the proposed CW radar system for vital-sign monitoring can effectively measure respiratory and heartbeat rates.

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Specifications table

| Hardware name           | 3D printed horn antenna and CW radar system |
|-------------------------|-------------------------------------------|
| Subject area            | Engineering and materials science         |
| Hardware type           | Field measurements and sensors            |
|                         | Electrical engineering and computer science |
| Closest commercial analog | Radar                                     |
| Open-source license     | CC BY-SA 4.0                               |
| Cost of hardware        | $140.53 USD                                |
| Source file repository  | https://doi.org/10.17605/OSF.IO/8D429      |

1. Hardware in context

The global average life expectancy has increased owing to the advancement of medical services and health care systems. The increase in the life expectancy of people has led to significant research on the treatment and diagnosis of chronic diseases such as heart and lung diseases, cancer, stroke, and sleep disorders [1]. Although the requirement for monitoring vital
Signs in the contemporary lifestyle has increased, employing workforce or labor for healthcare is a challenging and expensive task. Several studies have been conducted on indoor short-range remote sensing of human health conditions using advanced technology [1–8]. Several remote biomedical sensing technologies such as radar-, camera-, and sound-based sensors have been developed. The radar-based indoor short-range remote sensing system is the most extensively adopted technology for remote biomedical sensing owing to its versatility and high reliability. It can detect objects obscured by obstacles and has low privacy issues. Additionally, critical vital signs such as breathing rate and heartbeat can be monitored remotely using the radar-based sensor platform. Radar-based indoor short-range remote sensing technology is widely utilized in household and disaster-control applications because of those advantages.

The different types of radar include continuous wave (CW) Doppler, frequency-modulated continuous wave (FMCW), and pulse radars [9]. CW and FMCW radars are suitable for short-distance indoor applications. Although FMCW radar has the advantage of obtaining range information compared with that of CW Doppler radar, the system configuration is relatively complex and there is a loss in the Doppler resolution for range resolution [10]. However, the cost of high-performance radar systems is relatively higher compared with that of alternative indoor short-range remote sensing technologies. A low-cost radio frequency front-end (RFFE) of the FMCW radar system was reported in [11], but the reported system took a modular approach for the design simplicity. Each functional module should be connected through surface mount adapter (SMA) connectors. In this work, all the components for the CW radar system are integrated in a single printed circuit board (PCB) for the better system integrity.

This study proposes a low-cost CW Doppler radar system for remote vital sign detection for indoor applications. The RF FE system of the proposed radar system was fabricated on a 1-mm-thick 2-layer FR-4 PCB. In addition, a horn type antenna was selected for radiating electromagnetic waves generated by the proposed radar system. Since indoor environments are typically more susceptible to path-loss and multipath fading than open areas [12], the horn antenna with high gain value is used in order to obtain higher signal-to-noise ratio (SNR) to detect relatively weak vital signs. Meanwhile, 3D printing technology was adopted in this paper for the manufacturing of the horn type antenna. Many studies have been conducted on the application of 3D printing technology because of its light-weight, low-cost, and fast-prototyping properties [13–19].

The proposed 3D-printed coax-fed pyramidal horn antenna optimized at 5.8 GHz was fabricated using a commercial-off-the-shelf (COTS) component. Although several 3D-printed horn antenna designs have been reported [20–23], they require professional equipment or an additional process for metallization. In this study, a simple metallization method using copper tape was proposed to ensure easy implementation of the system. The fabricated 3D printed horn antenna demonstrated high gain. Therefore, it is suitable for detecting micro-Doppler signature such as vital signs. The proposed antenna and radar system were verified through vital sign measurement. The proposed CW radar system exhibited an equivalent isotropic radiated power (EIRP) value of 36 dBm in the C-band, which is compliant with the regulations of the Federal Communications Commission (FCC).

2. Hardware description

2.1. 3D-printed horn antenna

Horn antenna is extensively used owing to its high gain, robust radiation pattern over the frequency, and high cross-polarization suppression ratio [24]. However, commercially available horn antennas have a high cost (greater than USD 1500). Therefore, a low-cost high-gain horn antenna operating at a frequency band of 5.8 GHz was designed using 3D printing technology. The design of the horn antenna was based on the pyramid horn antenna described in [24]. The 3D-printed horn antenna exhibited an acceptable antenna performance, which was comparable with that of commercial antenna (Pasternack, PE9860-15 [25] and PEWCA1054 [26]). Commercial antenna consist of two discrete components of coax-to-waveguide transition and pyramidal horn. In contrast, the proposed antenna design has an integrated structure. The integrated horn antenna has a simple design that is suitable for 3D printing. The antenna geometry is shown in Fig. 1(a), and the specific antenna design parameters are shown in Table 1. Unlike the conventional horn antennas (Fig. 1(b)), only outer surface is metallized as shown in Fig. 1(c). For the 3D printed horn antenna structure, single-sided metallization features better performance compared to the double-sided metallization because of the long return current path as shown in Fig. 1(d).

The proposed antenna was printed using polyactic acid filament (PLA, $\varepsilon_r$: 3.55, tan $\delta$: 0.001 [27]) with a thickness of 2 mm, and the infill ratio was set to 50%. The outer surface of the 3D printed horn antenna was metallized by wrapping it with copper tape. The 3D-printed horn antenna was excited by a coaxial connector and probe as shown in Fig. 1. The radiation performance and antenna matching were sensitive to the probe length ($l_b$) and distance from the wall ($h_3$). Therefore, these critical design parameters were analyzed and optimized using a full-wave 3D finite element method (FEM) simulator (Ansys HFSS 2022 R1). The probe length exhibited an optimal radiation performance at $l_b = 11$ mm, and the reflection coefficient ($|S_{11}|$) and realized gain values at 5.8 GHz were $-16.7$ dB and 15 dBi, respectively, as shown in Fig. 3. It should be noted that 90% of the signal power is radiated from the antenna when the $|S_{11}|$ value is lower than $-10$ dB. The radiation patterns measured at 5.8 GHz are shown in Fig. 4. The measurement of the horn antenna was performed in an anechoic chamber as shown in Fig. 2. The operation bandwidth ($|S_{11}| < -10$ dB) covered the target ISM frequency band (5.725–2.4 GHz).
5.875 GHz), and the coupling level between Tx and Rx antennas (\(|S_{21}|\)) was lower than −50 dB when the distance between the antennas was 12 cm as shown in Fig. 3(a). The measured peak antenna gain value was 14.7 dBi at 5.8 GHz (Fig. 3(b) and Fig. 4). It should be noted that the antenna gain pattern includes the directivity pattern as the antenna gain (\(G\)) is the dot product of the directivity (\(D\)) and the radiation efficiency (\(\eta\)). The simulation results exhibited a good agreement with that of the measured values. The difference in cross-pol gain values between the simulation and measurement is due to fabrication error. The copper tapes attached to the 3D printed horn antenna enforces current flow along the copper tapes. The proposed horn antenna was modeled as a solid metal in the simulation for simplicity of design.

### 2.2. CW radar system

The CW radar consists of a voltage-controlled oscillator (VCO), power amplifier (PA), mixer (MXR), and low noise amplifier (LNA) as shown in Fig. 5 [11]. The radio frequency front-end (RFFE) system was integrated to a 1-mm thick FR-4 PCB substrate (\(\varepsilon_r: 4.4, \tan \delta: 0.02 [28]\)) as shown in Fig. 6. The size of the PCB used for the CW radar system was 48.5 × 37 mm². The RFFE of the CW radar had a 20-dB coupled line coupler instead of the widely adopted 3-dB half power
Wilkinson power divider. The designed coupler captured only 1 % of the RF power (output RF power of PA2) and directed the coupled power to the down-converting mixer. The remaining 99 % of the power was radiated through the Tx antenna.

The CW radar system operated on the direct conversion method. The Rx signal was directly down-converted to baseband I/Q signal using a commercially available mixer chip (HMC218BMS8GE, Analog Devices[29]). Fig. 7 depicts a remote vital sign sensing environment, wherein the transmission signal and movement of vibrating surface due to the vital signs are denoted by $T(t)$ and $DV(t)$, respectively.

$$T(t) = \cos(2\pi f_0 t)$$

$$DV(t) = D_{\text{max}} \sin(2\pi f_v t) = D_{\text{Heart}}(t) + D_{\text{Respiration}}(t)$$

where $f_0$ is the carrier frequency of the transmitted signal, $D_{\text{max}}$ is the maximum amplitude of vital sign, $f_v$ is the vibration frequency of the target, $D_{\text{Heart}}(t)$ is the displacement of heartbeat, and $D_{\text{Respiration}}(t)$ is the displacement of respiration.

The signal $S(t)$ reflected by the vibrating surface is directly down-converted by the mixer for the distance $R(t)$ between the radar and vibrating surface. The down-converted baseband signal $SB(t)$ can be expressed as (5).

$$R(t) = R_0 + D_{\text{max}} \sin(2\pi f_v t) = R_0 + DV(t)$$

$$S(t) \cong A_R \cdot \exp \left\{ j \left[ 2\pi f_0 t + \frac{4\pi R(t)}{\lambda} \right] \right\}$$

$$SB(t) = \text{LPF}[T(t) \times R(t)] \cong A_g \cdot \cos(\frac{4\pi R(t)}{\lambda}) = A_g \cdot \cos(\frac{4\pi}{\lambda} R_0 + \frac{4\pi}{\lambda} DV(t))$$

$R_0$ is the distance between the radar and vibrating surface, $\lambda$ is the wavelength, $A_R$ and $A_g$ represent amplitudes. The phase noise of the signals $S(t)$ and $SB(t)$ is neglected for simplicity of calculation. $SB(t)$ can be written as (7).

$$\frac{R(t)}{\lambda} = k\pi, (k = 0, 1, 2, \cdots)$$

$$SB(t) \cong 1 - \left[ \frac{4\pi}{\lambda} DV(t) \right]^2$$

When the condition shown in (6) is satisfied, $SB(t)$ can be approximated to (7). Additionally, the null point phenomenon of the $DV(t)$ sensitivity can be suppressed using a quadrature mixer with two channels (I- and Q-Channels) having a phase difference of $\pi/2$ [10]. If the quadrature mixer is used, the direct-down converted signal can be written as follows:
Eq. (10) can be derived by the arctangent quadrature demodulation for (8) and (9).

\[
S_{R_0}(t) \approx A_B \cdot \cos \left( \frac{4\pi}{\lambda} R_0 + \frac{4\pi}{\lambda} D_V(t) \right)
\]

(8)

\[
S_{R_0}(t) \approx A_B \cdot \sin \left( \frac{4\pi}{\lambda} R_0 + \frac{4\pi}{\lambda} D_V(t) \right)
\]

(9)

Hence, the vital sign, \(D_V(t)\), can be obtained without the null point phenomenon. The quadrature mixer (HMC951A, Analog Devices [30]) was used, and the baseband signals \((S_{R_0}(t), S_{R_0}(t))\) were collected using a digital storage oscilloscope (DSO) at a sampling rate of 125 kS/s. The collected data was post-processed on a PC.
Fig. 4. Antenna radiation patterns: (a) $\varphi = 0^\circ$ (XZ-plane) and (b) $\varphi = 90^\circ$ (YZ-plane).

Fig. 5. A block diagram of the proposed CW radar system.
3. Design files summary

3.1. Software

The signal processing method used in this study is shown in Fig. 8. The vital signs were determined by the arctangent quadrature demodulation of Equation (10), and the code provided in [10] was referenced. The code presented in [10] used the SDR Radar Kit for signal processing. Therefore, the code was slightly modified to ensure that it can be used with DSO.

3.2. Hardware

The schematic of the CW radar hardware was divided into three types according to the VCO, Tx, and Rx functional groups as depicted in Fig. 9, Fig. 10, and Fig. 11, respectively. A power supply was used to supply power to the components. $V_{\text{tune}}$ required 3.8 V and the remaining devices required 3 and 5 V, respectively. A 5.8-GHz output signal was generated and amplified by the two-stage PA of the Tx chain when the appropriate voltage was applied to the VCO. The amplified output signal was connected to the antenna via the SMA connector and it radiated electromagnetic waves. The backscattered signal was amplified by the LNA of the Rx chain and performed I/Q demodulation by the MXR. The components and the models of the SMA connector and pin header are listed in the “Bill of materials summary”.

| Design file name | File type | Open-source license         | Location of the file          |
|------------------|-----------|-----------------------------|-------------------------------|
| Horn antenna     | STL-File  | Elsevier User License       | https://doi.org/10.17605/OSF.IO/8D429 |
| CW radar         | BRD-File  | Elsevier User License       | https://doi.org/10.17605/OSF.IO/8D429 |
Program process Vital Sign Detection:
read the raw dataset x, y
j = image unit;
K = x + y*;
DO Signal conditioning
   DC cancellation of the K;
   Real and image signal imbalance correction of the K;
   Smooth the K;
   Decimation of the K;
END DO
Q = image signal of the K;
I = real signal of the K;
Angle = arctan demodulation of (Q/I);
CASE 1: Heartbeat signal processing
   Heart = bandpass filtering for heartbeat (Angle);
   Heart_wd = Hamming window * Heart;
   Heart_zp = zero padding of the Heart_wd;
   Heart_ft = compute fourier transform of the Heart_zp;
   Heart_ft = Heart_ft * 60;
   DISPLAY Heart_ft
      x-axis('BPM');
      y-axis('Magnitude');
END DISPLAY
END CASE 1
CASE 2: Respiratory signal processing
   Resp = bandpass filtering for respiratory rate (Angle);
   Resp_wd = Hamming window * Resp;
   Resp_zp = zero padding of the Resp_wd;
   Resp_ft = compute fourier transform of the Resp_zp;
   Resp_ft = Resp_ft * 60;
   DISPLAY Resp_ft
      x-axis('BPM');
      y-axis('Magnitude');
END DISPLAY
END CASE 2
END.

Fig. 8. Pseudo code algorithm for digital signal processing.

Fig. 9. VCO circuitry schematic.
4. Bill of materials summary

| Designator | Component | Number | Cost per unit in USD | Total cost in USD | Source of materials | Material type |
|------------|-----------|--------|----------------------|-------------------|---------------------|---------------|
| Copper tape | ST003CU100 | 1 | 4.1 | 4.1 | Mouser.com | Metal |
| Coax Connector | 901-9892-RFX | 2 | 9.86 | 19.72 | Mouser.com | Electronics |
| U1 | HMC431LP4ETR | 1 | 20.63 | 20.63 | Mouser.com | Electronics |
| U2 | GRF2505 | 1 | 2.4 | 2.4 | Mouser.com | Electronics |
| U3 | HMC407MS8GE | 1 | 17.33 | 17.33 | Mouser.com | Electronics |
| U4 | QPL9503TR7 | 1 | 5.33 | 5.33 | Mouser.com | Electronics |
| U5 | HMC951ALP4E | 1 | 38.99 | 38.99 | Mouser.com | Electronics |
| C1,C20,C23 | GCM188R71H103KA37J | 3 | 0.1 | 0.3 | Mouser.com | Electronics |
| C2,C19,C24 | 298D475X0016M2T | 3 | 1.84 | 5.52 | Mouser.com | Electronics |

(continued on next page)
The total amount of cost shown in the Bill of Materials (BoM) is $140.53, and it includes the radar system (antenna, Tx, Rx, and signal mixing). The signal processing setup and data acquisition (DAQ) tools for vital sign detection presented in this paper, such as a computer and DSO are not included in the BoM. The Doppler frequency shift of vital signs is relatively low enough to be acquired by other DAQ tools such as FPGA, computer audio port or even Arduino [11].

5. Build instructions

5.1. Antenna

In this study, a 3D printer (MOMENT m350 [31]) was used to fabricate the horn antenna. The output obtained after the stl file attached to the design file was printed is shown in Fig. 12(a). Subsequently, the copper tape was attached to the outer surface of the 3D printed horn antenna. The axial connector was adjusted to a length of $l_5 = 11$ mm after attaching the tape. The axial connector was fixed using super glue at a height of $h_3 = 7.4$ mm, which was determined in the simulation as shown.
in Fig. 12(b). The key performance parameter of the fabricated antenna, such as S-parameter ($|S_{11}|$) and linear gain were measured by vector network analyzer (VNA).

5.2. Radar

The proposed radar system was built on two-layer FR-4 substrate because it is widely adopted low-cost material for PCB fabrication. The assembled radar board is verified by a spectrum analyzer. The output frequency of VCO depending on $V_{\text{tune}}$ and Tx power are measured in the operating frequency band. It is important to keep the EIRP value (Antenna gain + Tx power) less than 36 dBm according to the FCC regulations.

6. Operation instructions

The isolation level between the Tx and Rx antennas is a critical factor for the CW radar system as it ensures continuous transmission of electromagnetic waves. The Tx RF power can be coupled to the Rx antenna to decrease the SNR. To determine whether such Tx leakage power affects the Desired signal, calculate the received power for transmission power $P_t = 21$ dBm, antenna gain $G_t = G_r = 14.7$ dB, wavelength $\lambda = 0.052$ m using the radar equation in Eq. (11),

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

When the distance to the target is $R = 1$ m, Radar cross section $\sigma = 1 m^2$, the received power $P_r \approx -8.3$ dBm is calculated, and the Tx leakage power should be less than this. Therefore, when the center-to-center distance between Tx and Rx is 12 cm, the isolation level was measured to be $-50$ dB, and the Tx leakage power was $-29$ dBm, indicating that it is a very small value compared to the desired signal. The isolation level was measured using VNA as shown in Fig. 13. A DC power supply was connected to the radar, and appropriate DC voltage was applied to the CW radar system. The VCO generated an RF signal at 5.8 GHz when the radar system was switched on, and it was amplified by the PA. The Tx horn antenna radiated the amplified RF signal, and the Rx antenna captured the backscattered signal from the target. The Rx signal was amplified by the LNA to improve SNR and down-converted to the baseband by the mixer. The baseband signals were collected via DSO and were post-processed on Matlab (MathWorks, USA) to extract vital signals such as heartbeat and respiratory rates. These operation process is briefly shown in Fig. 14. Although this measurement process satisfies the EIRP regulations of the FCC, it is recommended that the measurement time be shortened after a certain distance from the radar system because someone may be sensitive to electromagnetic waves depending on their health condition.

7. Validation and characterization

The vital signs of an adult male located at a distance of 40 cm from the antennas were measured using the proposed radar system. The down-converted baseband I/Q voltage signals were collected by the DSO at a sampling rate of 150 kS/s for 8 s. The collected data were saved and transmitted to a computer for post-signal processing on Matlab. The measured heartbeat and respiratory rates were 69.58 and 14.65 BPM, respectively, as shown in Fig. 15. These values indicated high accuracy of
96.6 % and 97.3 % for the actual heart and respiratory rates of 72 and 15 BPM. The accurate heart rate of 72 BPM and the respiratory rate of 15 were measured by direct contact. Furthermore, to verify the performance of the proposed radar system, comparison with other radar systems is shown in Table 2. There are CW, FMCW, and UWB radar types used for vital sign detection. Among the reported cutting-edge vital sign detection radar systems, CW radar features low-complexity and low-cost system. The proposed 3D printed horn antenna has simple design and ease of fabrication compared to other reported antennas, such as horn, patch and phased array antennas. The accuracy of the proposed radar system is similar or better than other reported research efforts.
8. Conclusion

The hardware design of the VitRad CW radar for remote human vital sign sensing application was described. Instructions were provided to determine the location of its open-source design files, fabricate the PCB for CW Doppler radar, and validate the processes required after hardware assembly. VitRad can be used for various indoor short-range remote sensing applications such as human motion, localization, and imaging. VitRad is a scalable design owing to its cost-efficient and simple structure. It is a potential low-cost radar system that can enhance the quality of life.

CRediT authorship contribution statement

Hyunmin Jeong: Methodology. Sangkil Kim: Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ohx.2022.e00361.

References

[1] M. Mercuri, I.R. Lorato, Y.H. Liu, F. Wieringa, C. Van Hoof, T. Torfs, Vital-sign monitoring and spatial tracking of multiple people using a contactless radar-based sensor, Nat. Electron. 2 (2019) 252–262.
[2] A. Saffari, S. Y. Tan, M. Katanbaf, H. Saha, J. R. Smith, and S. Sarkar, “Battery-free camera occupancy detection system,” in Proceedings of the 5th International Workshop on Embedded and Mobile Deep Learning, 2021, pp. 13–18.
[3] Ni, B.; Nguyen, C.; Moulin, P. RGBD-camera based get-up event detection for hospital fall prevention. In Proceedings of the International Conference on Acoustics, Speech and Signal Processing (ICASSP), Kyoto, Japan, 25–30 March 2012; pp. 1405–1408.
[4] S. Lyra, L. Mayer, L. Ou, D. Chen, P. Timms, A. Tay, P.Y. Chan, B. Gans, S. Leonhardt, C. Hoog Antink, A Deep Learning Based Camera Approach for Vital Sign Monitoring Using Thermography Images for ICU Patients, Sensors 21 (2021) 1495.
[5] Y. He, C. Gu, H. Ma, J. Zhu, C.V. Eleftheriades, Miniaturized circularly polarized Doppler radar for human vital sign detection, IEEE Trans. Antennas Propag. 67 (11) (2019) 7022–7030.
[6] C. Gu, R. Li, H. Zhang, A. Fung, C. Torres, S. Jiang, C. Li, Accurate respiration measurement using DC-coupled continuous-wave radar sensor for motion-adaptive cancer radiotherapy, IEEE Trans. Biomed. Eng. 59 (11) (2012) 3117–3123.
[7] C. Li, V.M. Lubecke, O. Boric-Lubecke, J. Lin, A review on recent advances in Doppler radar sensors for noncontact healthcare monitoring, IEEE Trans. Microw. Theory Techn. 61 (5) (2013) 2046–2060.
[8] S. Pisa, E. Pittella, E. Piuzzi, A Survey of Radar Systems for Medical Applications, IEEE Aeros. Electron. Syst. Mag. 31 (2016) 64–81.
[9] B.R. Mahafza, Radar systems analysis and design using MATLAB, Chapman & Hall, 2013.
[10] V.C. Chen, The Micro-Doppler Effect in Radar; Artech House: Boston, MA, USA, 2019.
[11] H. Jeong and S. Kim, “Educational low-cost C-band FMCW radar system comprising commercial off-the-shelf components for indoor through-wall object detection,” Electronics, vol. 10, no. 22, p. 2758, 2021. [Online]. Available: https://www.mdpi.com/2079-9292/10/22/2758.
[12] A. Goldsmith, Wireless Communications, Cambridge Univ. Press, New York, NY, USA, 2005.
[13] E.S. Keneth, A. Kamyschy, M. Totoro, L. Beccai, S. Magdassi, 3D printing materials for soft robotics, Adv. Mater., Nov. Art. no. 2003387 (2020), https://doi.org/10.1002/adma.202003387.
[14] O. Ozioko, H. Nassar, R. Dahiya, 3D printed interdigitated capacitor based tilt sensor, IEEE Sensors J. 21 (23) (Dec. 2021) 26252–26260.
[15] A. Shastri, B. Sanz-Izquierdo, A. Eliiaby, E.A. Parker, Manufacturing, Developments, and Constraints in Full 3-D Printing of Frequency-Selective Surface Using Low-Cost OpenSource Printer, IEEE Transactions on Components, Packaging and Manufacturing Technology 11 (12) (Dec. 2021) 2193–2200, https://doi.org/10.1109/TCPM.2021.3123985.

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Table 2

Radar system comparison with the literature.

| Research Group | Radar Type | Antenna Type | Accuracy | Operation Frequency |
|----------------|------------|--------------|----------|---------------------|
| This work      | CW         | 3D printed Horn | >95 %     | 5.8 GHz             |
| [32]           | CW         | Horn          | >95 %     | 5.8 GHz             |
| [33]           | CW         | Horn          | 95–90 %   | 24 GHz              |
| [34]           | FMCW       | Patch         | >95 %     | 5.46–7.25 GHz       |
| [35]           | FMCW       | Patch         | >95 %     | 24–24.25 GHz        |
| [36]           | UWB        | Phased Array  | >95 %     | 0.5–5.5 GHz         |
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