Overview of mmWave Radar and Antenna Advances in Contactless Vital Signs Monitoring

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***Abstract*— Remote Vital Signs Monitoring (RVSM) using Doppler radar provides a non-invasive, contactless solution for applications such as chronic care, emergency triage, and elderly monitoring. This paper reviews recent advances in mmWave Frequency Modulated Continuous Wave (FMCW) radar and high-performance antennas, such as Multiple Input Multiple Output (MIMO) and leaky-wave designs, which improve the detection of subtle cardiopulmonary signals in complex environments. Unlike prior reviews, we offer a comparative analysis of system architectures and antenna configurations, emphasizing their trade-offs in sensitivity, robustness, and scalability. Challenges such as respiratory harmonics, motion artifacts, and multi-target interference still hinder reliability. We highlight key radar and antenna setups that enhance detection sensitivity and robustness. With growing interest in smart healthcare across Asia, particularly in Malaysia, we also discuss regional deployment prospects. Future directions include adaptive signal processing, reconfigurable antennas, and low-power architectures for scalable, real-time RVSM systems.**

Keywords— Remote Vital Signs Monitoring (RVSM), Doppler Radar, mmWave, and Multi-Target Detection

I. INTRODUCTION

The increased burden of chronic diseases and the demand for efficient healthcare have fueled developments like Remote Patient Monitoring (RPM), which harnesses wireless technologies to track patient health remotely. [1].

RPM enables healthcare providers to manage diseases proactively, particularly for patients with chronic illnesses, while lowering hospitalizations and encouraging self-care at home. Traditional vital sign monitoring technologies, such as electrocardiograms (ECG) and photoplethysmography (PPG), rely on contact-based sensors, which can cause discomfort, limited mobility, and skin sensitivities in patients. In contrast, Doppler radar provides a contactless option for Remote Vital Signs Monitoring (RVSM) by detecting cardiopulmonary activity (e.g., heart rate (HR) and breathing rate (BR) without the use of physical probes. Operating at mmWave frequencies, this technology delivers great resolution and sensitivity, enabling through-wall monitoring that respects patient privacy—a characteristic useful in healthcare, emergency services, security, and military [2], [3], [4].

The Asia-Pacific region, particularly Malaysia, is experiencing a surge in demand for scalable and contactless healthcare solutions. With an aging population, limited access to reliable in-person healthcare in rural areas, and rising incidence of chronic illness, remote health monitoring has emerged as a critical strategic priority. Malaysia's national digital health efforts and smart hospital frameworks are looking into the integration of IoT and radar-based technologies. RVSM systems are ideal for community health centers, home-care settings, and aged care facilities around the region because they are non-invasive and protect privacy [5], [6].

Despite its potential, RVSM faces significant challenges. The tiny amplitude of vital signs (e.g., ~0.2 mm for HR) might be hidden by interference from BR harmonics, ambient noise, or multi-target settings, making reliable identification challenging. High-performance antennas and modern radar systems are therefore crucial for improving signal clarity and dependability. Frequency Modulated Continuous Wave (FMCW) radar is a key point in RVSM research because to its high range resolution and ability to identify numerous targets [7], [8]. This paper reviews the state-of-the-art in Doppler radar technologies and antenna designs at mmWave frequencies, exploring how they address these challenges and enable contactless healthcare. By surveying current approaches—from radar configurations to antenna innovations—we aim to highlight their potential, limitations, and implications for real-world deployment in diverse settings.

The rest of the paper is organized as follows. Section II reviews Doppler radar technologies for RVSM. Section III assesses the required antenna configurations for detection accuracy. Section IV addresses RVSM challenges, including noise and multi-target issues, and suggests future directions. Section V concludes with key findings and implications for contactless monitoring.

II. Doppler Radar Technologies for RVSM

Doppler radar detects vital signs using two antennas: one transmits a signal to the subject's chest, while the other receives the reflected signal, modulated by chest wall vibrations caused by cardiac activity. The small amplitude of these signals ($\approx$0.2 mm) and interference from breathing harmonics require high-directional Tx and Rx antennas for accurate detection. Additionally, multi-target scenarios, target movement, and environmental noise complicate detection. Thus, antennas must have high gain, wide bandwidth, directive patterns, and be compact, lightweight, and compatible with other systems [9]. For this low-amplitude signal, the mm-wave frequency band is preferred due to the optimal resolution and high sensitivity of its short wavelengths. This will improve the radar detection and signal transmission and reception, which in turn will reduce the strong clutter and noise interference signals. At mmWave frequencies, the antenna will be small in scale, lowering the total system size and offering compatibility for implanting multiple antennas (MIMO antennas, for example) into a monolithic integrated circuit, which will improve the detection accuracy. This makes the RVSM radar system small and portable, which provides flexibility in its placement. The higher frequency and broader BW in mmWave offer great sensitivity, resolution, and accuracy in detecting sub-millimeter movements such as those induced by cardiopulmonary activity, allowing for long-term and continuous monitoring [2], [3], [10]. Additionally, the mmWave radar is insensitive to environmental and illumination changes [11]. Accurate retrieval of low-amplitude HR and BR signals in mmWave systems requires an efficient digital signal processing (DSP) algorithm. Such algorithms, combined with high-performance antennas, are essential to mitigate high path loss caused by atmospheric attenuation and to enable robust radar detection [12].

RVSM based on Doppler radar causes the received signal to differ in frequency from the transmitted signal, allowing it to be identified by filtering out the transmitted frequency. Transmitting powerful short pulses or continuous EM waves with stable frequency, radar can be categorized into pulsed-wave/UWB and Continuous-wave (CW) radars, efficient for RVSM applications. UWB measures the time delay between transmitted UWB pulses and received echoes to determine the range. Although the UWB impulse radar (UWB-IR) offers higher SNR and exhibits fewer harmonics, it requires specialized hardware (high-speed analog-to-digital converters) and complex signal processing. Also, for high-resolution applications, the pulse should be reduced, which is limited. Due to its simple filters and straightforward DSP, CW is considered the simplest, cheapest, and most commonly used for RVSM, in which it transmits and receives a known stable carrier frequency of continuous wave radio energy from any reflecting objects. However, CW radar can't change its operating frequency during the measurement, so the target range can’t be determined, which makes it inefficient for monitoring multi-stationary or moving targets. Additionally, its in-phase-quadrature (I-Q) detection suffers from DC offset and low-frequency noise. To solve these problems, CW can be frequency modulated (FMCW) where the transmitted signal frequency increases or decreases periodically or it can be transmitted using multi frequencies (MFCW) and this will offer a timing reference to accurately measure the time of the transmit and receive cycle and to convert this into the range [12]. In the FMCW radar system, Tx-Rx leakage, AC-DC coupling effect, RF nonlinearities, and the requirement of a high sampling rate should be addressed. In the literature, the different mmWave Doppler-based vital signs detection radars such as single tone CW (STCW) [2], [9], pulsed coherent radar (PCR) [3], FMCW [11], [13] and are proposed with different antenna types, DSP and performance enhancement techniques.

For RVSM, FMCW radar at mmWave frequency band is preferred among others due to the following factors: (1) high isolation is provided between the collocated radars due to the high attenuation at mmWave (tiny displacements in mm are comparable to the wavelength thus they can be detected), (2) multi-target detection due to its inherent range-gating ability to differentiate between multiple targets in different frequency bins, and (3) less prone to noises compared to impulse radar because FM signals are more robust to thermal noise compared to AM signals [8]. According to the number of antennas used in the radar system, it can be divided into SISO (single input (Tx) and single output (Rx)), SIMO (single input (Tx) and multiple output (Rx)), MIMO (multiple input (Tx) and multiple output (Rx)) radar. Most CW and UWB-IR are SISO, while FMCW, SFCW, MFCW, and STCW are either SISO or MIMO-based. MIMO is preferred for estimating the available angular coordinates for a single moving target, and for stationary or moving multiple targets [14]. This suggests that future developments in radar technology could prioritize hybrid SISO-MIMO configurations to balance complexity and performance, particularly for multi-target RVSM applications in dynamic environments. Figure 1 shows a typical mmWave FMCW radar system for RVSM.

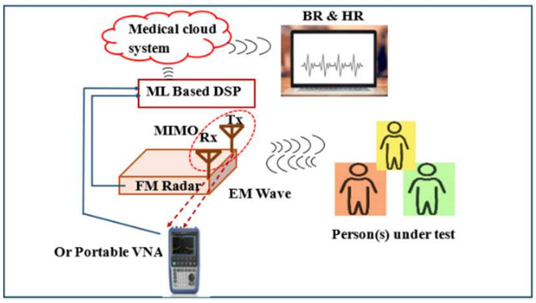

Figure 1. Typical mmWave FMCW radar system for RVSM.

III. Antenna Configurations for Enhanced RVSM

The efficiency of RVSM radar depends on its antenna performance in terms of gain, wide BW, beamforming scanning, steerability, and size for compatibility and integration with other circuits. This basically may change according to antenna type, configuration (SISO, SIMO, MIMO, arrays (phased)), and characteristics. To detect the small magnitude of vital signs among the clutter of other signals and noise, hardware noise, and external interference, the sensitivity of the radar system should be enhanced using a high directive and narrow beamwidth antenna. Additionally, to increase the detection range, a wide BW antenna is preferred. To increase the detection ability in the case of moving targets, an antenna with wide beam scanning ability is required [8].

To avoid bulky RVSM radar and provide efficient detection of multitarget or moving subjects, STCW radar using SISO system based on a Leaky Wave antenna (LWA) at 60 GHz band [2] is proposed. The LWA is selected due to its steering ability, simplicity, low cost, and low power consumption compared to other beamforming techniques, including sparse array, compressive sensing, path sharing, and MIMO. The LWA's beam steering allows it to have multiple angular locations, which helps collect effective information sets to extract the HR and BR with the largest peak. For further performance enhancement of LWA, many techniques are used. The directivity of 62–65 GHz LWA in [12] is improved using partially reflective surface (PRS) unit cells. In [9], improved frequency scanning and radiation control of (50-65 GHz**)** LWA are achieved using a dielectric image line (DIL). The gain and efficiency are improved using 2 top dielectric materials; however, the lower dielectric material is used to prevent higher-order modes. Open stopband (OSB) is mitigated using a periodic array of small metallic square patches between the dielectric layers. Broadside radiation at 57.5 GHz is achieved using 42 cylindrical holes. The BW and gain of (58- 66 GHz) LWA fed by a printed dipole antenna (PDA) in [2] are enhanced using multilayers of PRS, high impedance surface (HIS), and plain dielectric. The plain dielectric is used to increase the gain (24 dBi) and the beam scanning range (30^{o}), which helps increase the testing distance. The rectangular shape of the antenna was selected to achieve a highly directive beam at the E-plane.

SFCW and FMCW can determine the absolute distances (range information) and vital sign parameters of multiple subjects only if they are in different range bins, however, they cannot resolve targets in the angular dimension (2-D localization). So, MIMO and phased arrays can be used at the cost of higher power consumption, larger size, complex design and control, and a greater amount of data to be processed [15]. The main challenges in RVSM radar are the difficulty in extracting vital signs, eliminating the related noise, and monitoring different targets simultaneously. Compared to SISO radar, MIMO radar is preferred in this case due to its spatial diversity and ability to acquire more important information about the echo signal using its different channels, which reduces the interference from other targets and increases the signal-to-noise ratio (SNR) [10], [11]. In a MIMO-based radar system, the signals radiated by distinct Tx antennas are orthogonal. The simplest strategy to synthesize orthogonal waveforms is by using time-division multiplexing (TDM). Adopting this strategy means that distinct Tx antennas are activated over disjoint time intervals so that the signals they radiate do not overlap in the time domain, allowing for independent views of the targets [14]. This method is used to enhance the efficiency of 77 GHz FMCW radar [10], [16] to locate multiple targets and their vital signal. Additionally, a deep learning (DL)-based classification framework using a convolutional neural network (CNN) is used in [10] to reduce the HR estimation error by selecting the high SNR MIMO channel. High-precision RVSM radar for multiple targets is obtained in [13] by proposing a TDM-phased MIMO approach based on 76-81 GHz FMCW radar. This approach helps in steering the beam to the required direction very fast and enables the formation of the virtual receiving array with a longer aperture, which enhances the SNR. This long aperture virtual array is used to separate the close targets, then a Capon Beamformer (CB) is used at the receiver for angle estimation to concentrate the beam in the desired direction while minimizing the others. Then, at the Tx, analog beamforming is used to direct the beam to the detected target. Due to the large distance between Txs, grating lobes will occur and can be alleviated using the CB. For more detection accuracy of the 60 GHz PCR radar system in [3], the gain of its antenna-in-package (AiP) is enhanced by 64.15 % using 3D printed lenses based on fused deposition modeling (FDM) and polylactic acid (PLA) filament. The improvement in gain increases the SNR of H and R signals (HS and RS) by 2.91 dB and 4.24 dB, respectively. For indoor monitoring, the static and non-static multipath propagation for the proposed 24 GHz FMCW radar in [17] is reduced due to the ability of reconfigurable intelligent surfaces (RISs) in controlling and directing the incident beam, and this will enhance the radar's ability to detect multiple targets for line of sight (LOS) and non-line of sight (N-LOS) situations. Additionally, two high-directivity horn antennas are used for Tx and Rx.

The ability of the microstrip antenna to tune at high frequencies (to get high sensitivity in detecting the vital signs), low cost, easy fabrication, easy integration with on-chip die, and low profile make this a good candidate for RVSM [18]. The proposed (57.24–65.88 GHz) microstrip array in [19] provides a small size and high gain, low side lobe level (SLL), and narrow beamwidth. Also, using dual microstrip antennas for Tx and Rx extends its detection range. To facilitate the integration between the CMOS radar chip with portable devices (microstrip patch antenna array) (at 60 GHz [20] and W band (100 GHz) [18]) for RVSM in healthcare applications, low-cost wire bonding is used to avoid additional processing (cavity etching of the carrier board) and outperforming the V-band cable (with 7-dB loss). Gain and detectability are improved using a microstrip patch array. As compared to [20] low fabrication cost and enhanced BW are obtained in [18] using a single PCB layer and CPW-fed, respectively. The tapered patches with Taylor amplitude distribution in [20] are used to reduce the SLL. The wire bonding effect is reduced using the LCL structure. To enhance the robustness of the impedance-matching bandwidth to withstand possible bonding length variations, additional series and shunt transmission lines are also deployed [20]. For compactness, and to eliminate possible losses and impedance mismatches caused by the mmWave cable and adapters, the Tx and Rx microstrip linearly polarized 2 x 4 array in the proposed 24 GHz [21] radar sensor for long-period sleep monitoring were printed on the same PCB layer as the radar device mmWave integrated circuit (MMIC). Future antenna designs could explore the integration of RIS with microstrip arrays to further enhance beam steering and detection accuracy, especially for non-line-of-sight (N-LOS) scenarios.

IV. CHALLENGES AND FUTURE DIRECTIONS

While RVSM using Doppler radar at mmWave frequencies offers transformative potential for contactless healthcare, several challenges hinder practical deployment. The small amplitude of vital signs (e.g., 0.2 mm for HR) is often masked by stronger BR harmonics (~1–2 mm) and distorted by environmental clutter, body motion, and multi-target interference, reducing detection accuracy. Hardware limitations—such as noise from system non-idealities, Tx-Rx leakage in FMCW radar, and the power demands of MIMO and phased arrays—add complexity and cost, limiting portability and scalability. Although advances in radar types (e.g., FMCW) and antenna designs (e.g., MIMO) have improved resolution, atmospheric attenuation at mmWave frequencies reduces operational range. Real-world validation remains limited, with most studies conducted in controlled environments, leaving performance across different demographics and settings untested.

Future work could explore low-power antenna designs—such as RIS-enhanced microstrip arrays—for adaptive beam control in cluttered indoor environments. Enhancing radar performance through techniques like adaptive frequency hopping may improve noise resilience and multi-target detection. Field trials in Malaysian healthcare settings (e.g., rural clinics, elderly care homes) will help validate system reliability, while collaboration with local medical stakeholders can ensure ethical deployment aligned with patient needs and privacy standards.

V. CONCLUSIONS

This paper reviewed key advancements in mmWave Doppler radar and antenna technologies for contactless RVSM. The combination of FMCW radar with high-performance antennas—such as MIMO and leaky-wave designs—has enabled more accurate detection of small physiological signals in complex environments. Yet, challenges like noise interference, hardware limitations, and multi-target detection persist. Future work will focus on implementing these systems in real-world settings across Asia, starting with healthcare facilities in Malaysia. The goal is to validate the performance of RVSM solutions under real-life multi-target, motion, and noise scenarios typical of homes and hospitals in the region.

REFERENCES

[1] "Remote Health Monitoring - eHealth Ireland." Accessed: Jan. 29, 2024. [Online]. Available: https://www.ehealthireland.ie/ehealth-functions/community-health/telehealth-programme/remote-health-monitoring/

[2] S. Mingle, D. Kampouridou, and A. Feresidis, "Multi-Layer Beam Scanning Leaky Wave Antenna for Remote Vital Signs Detection at 60 GHz," *Sensors*, vol. 23, no. 8, Apr. 2023, doi: 10.3390/s23084059.

[3] J. Lai, Y. Sun, Z. Luo, and Y. Yang, "3D Printed Lens Antenna for Contactless Heartbeat and Respiration Detection Using mm-Wave Radar Sensing," in *2022 IEEE MTT-S International Microwave Biomedical Conference, IMBioC 2022*, Institute of Electrical and Electronics Engineers Inc., 2022, pp. 180–182. doi: 10.1109/IMBioC52515.2022.9790127.

[4] C. ; Ahmed, S. ; Abdullah, and M. Alouini, "mm-Wave Radar-Based Multiple Patients' Breathing and Heart Rates Measurement," 2023, doi: 10.21203/rs.3.rs-2966459/v1.

[5] "Innovating Malaysia's healthcare through 5G and digital solutions | Telekom Malaysia." Accessed: May 12, 2025. [Online]. Available: https://tm.com.my/news/tm-one-5g-innovating-healthcare?utm_source=chatgpt.com

[6] "The future of healthcare in Asia | McKinsey." Accessed: May 12, 2025. [Online]. Available: https://www.mckinsey.com/industries/healthcare/our-insights/the-future-of-healthcare-in-asia-digital-health-ecosystems?utm_source=chatgpt.com

[7] M. Alizadeh, G. Shaker, J. C. M. De Almeida, P. P. Morita, and S. Safavi-Naeini, "Remote monitoring of human vital signs using mm-Wave FMCW Radar," *IEEE Access*, vol. 7, pp. 54958–54968, 2019, doi: 10.1109/ACCESS.2019.2912956.

[8] A. Singh, S. U. Rehman, S. Yongchareon, and P. H. J. Chong, "Multi-Resident Non-Contact Vital Sign Monitoring Using Radar: A Review," *IEEE Sens J*, vol. 21, no. 4, pp. 4061–4084, Feb. 2021, doi: 10.1109/JSEN.2020.3036039.

[9] S. Mingle, D. Kampouridou, and A. Feresidis, "Bidirectional Leaky-Wave Antenna Based on Dielectric Image Line for Remote Vital Sign Detection at mm-Wave Frequencies," *IEEE Open Journal of Antennas and Propagation*, vol. 3, pp. 1003–1012, 2022, doi: 10.1109/OJAP.2022.3201630.

[10] T. K. V. Dai *et al.*, "Enhancement of Remote Vital Sign Monitoring Detection Accuracy Using Multiple-Input Multiple-Output 77 GHz FMCW Radar," *IEEE J Electromagn RF Microw Med Biol*, vol. 6, no. 1, pp. 111–122, Mar. 2022, doi: 10.1109/JERM.2021.3082807.

[11] S. Wang, C. Han, J. Guo, and L. Sun, "MM-FGRM: Fine-Grained Respiratory Monitoring Using MIMO Millimeter Wave Radar," *IEEE Trans Instrum Meas*, 2023, doi: 10.1109/TIM.2023.3334353.

[12] M. S. Rabbani, J. Churm, and A. P. Feresidis, "Fabry-Perot Beam Scanning Antenna for Remote Vital Sign Detection at 60 GHz," *IEEE Trans Antennas Propag*, vol. 69, no. 6, pp. 3115–3124, Jun. 2021, doi: 10.1109/TAP.2021.3049233.

[13] Z. Xu *et al.*, "Simultaneous Monitoring of Multiple People's VitalSign Leveraging a Single Phased-MIMO Radar," *IEEE J Electromagn RF Microw Med Biol*, 2022, doi: 10.1109/JERM.2022.3143431.

[14] G. Paterniani *et al.*, "Radar-Based Monitoring of Vital Signs: A Tutorial Overview," *Proceedings of the IEEE*, vol. 111, no. 3, pp. 277–317, Mar. 2023, doi: 10.1109/JPROC.2023.3244362.

[15] M. Mercuri *et al.*, "2-D Localization, Angular Separation and Vital Signs Monitoring Using a SISO FMCW Radar for Smart Long-Term Health Monitoring Environments," *IEEE Internet Things J*, vol. 8, no. 14, pp. 11065–11077, Jul. 2021, doi: 10.1109/JIOT.2021.3051580.

[16] S. Iyer *et al.*, "mm-Wave Radar-Based Vital Signs Monitoring and Arrhythmia Detection Using Machine Learning," *Sensors*, vol. 22, no. 9, May 2022, doi: 10.3390/s22093106.

[17] M. Mercuri, E. Arnieri, R. De Marco, P. Veltri, F. Crupi, and L. Boccia, "Reconfigurable Intelligent Surface-Aided Indoor Radar Monitoring: A Feasibility Study," *IEEE J Electromagn RF Microw Med Biol*, vol. 7, no. 4, pp. 354–364, Dec. 2023, doi: 10.1109/JERM.2023.3298730.

[18] T. Zhang, Z. Zhu, X. Ma, H. Xia, L. Li, and T. J. Cui, "A W-Band Integrated Tapered Array Antenna with Series Feed for Noncontact Vital Sign Detection," *IEEE Trans Antennas Propag*, vol. 69, no. 6, pp. 3234–3243, Jun. 2021, doi: 10.1109/TAP.2020.3030999.

[19] M. S. Rabbani and H. Ghafouri-Shiraz, "Ultra-Wide Patch Antenna Array Design at 60 GHz Band for Remote Vital Sign Monitoring with Doppler Radar Principle," *J Infrared Millim Terahertz Waves*, vol. 38, no. 5, pp. 548–566, May 2017, doi: 10.1007/s10762-016-0344-z.

[20] C. H. Chan, C. C. Chou, and H. R. Chuang, "Integrated Packaging Design of Low-Cost Bondwire Interconnection for 60-GHz CMOS Vital-Signs Radar Sensor Chip with Millimeter-Wave Planar Antenna," *IEEE Trans Compon Packaging Manuf Technol*, vol. 8, no. 2, pp. 177–185, Feb. 2018, doi: 10.1109/TCPMT.2017.2782342.

[21] S. Dong *et al.*, "Remote Respiratory Variables Tracking With Biomedical Radar-Based IoT System During Sleep," *IEEE Internet Things J*, 2024, doi: 10.1109/JIOT.2024.3367932.