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Recent Advances in Intermodulation and Harmonic Radar Sensing and Tracking

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***Abstract*—This paper reviews recent advances in intermodulation and harmonic radar utilizing the nonlinear behavior of electronic components for improved target detection, classification, and tracking. The studies explore applications in multiple target tracking, healthcare monitoring, and insect tracking. Techniques such as multi-baseline millimeter-wave interferometric radar and optimized implementations are discussed for their capabilities to enhance accuracy and mitigate signal distortion. Hardware advancements include germanium (Ge) FinFET fabricated and verified on a GeSOI platform for radio-frequency (RF) applications with a harmonic radar tag, showing improved detection range compared to a commercial Schottky diode. Discussed research also includes designs of passive nonlinear tags, frequency-selective surfaces, and integration with other radar systems covering various applications.**

Keywords—Detection, harmonic radar, intermodulation radar, monitoring, tracking.

I. INTRODUCTION

Intermodulation and harmonic radar systems have undergone significant advancements, revolutionizing tracking, sensing, and monitoring applications. Intermodulation radar, known for its superior sensitivity and accuracy compared to traditional radar systems [1-10], detects and tracks targets using intermodulation products. Harmonic radar excels at tracking small, nonlinear targets like insects by analyzing harmonic frequencies generated during radar interaction [11-19]. Both radar techniques possess advantageous capabilities in target detection and tracking.

Significant progress has been made in the development of intermodulation radar systems. Hardware improvements, focusing on antennas, transmitters, and receivers, have enhanced system performance [1]. The miniaturization of intermodulation radar systems has become feasible with the development of more efficient and compact components. Signal processing techniques have advanced with the development of advanced algorithms for signal detection, analysis, and target information extraction [4]. These advancements have improved target detection and tracking capabilities and sensitivity, creating opportunities for applications in healthcare, security, environmental monitoring, and transportation [3,4,6-10].

Harmonic radar system development has also witnessed notable progress. Hardware advancements have focused on miniaturization and increased portability, enabled by advances in microelectronics [11,14]. Lightweight and compact components, including improved antenna designs and materials, have enhanced system performance and range capabilities [11,16,17,19]. The application areas of harmonic radar systems have expanded beyond entomology, finding utility in wildlife monitoring, environmental studies, and precision agriculture [14,18]. The ability to track and study small targets at low altitudes has been instrumental in these domains.

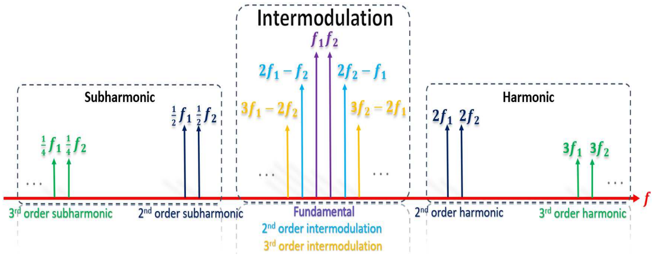

Figure 1. Nonlinear responses of intermodulation and harmonic.

This paper is structured as follows: Section II (A) provides an overview of the fundamentals of intermodulation and harmonic radar in (B). Section III (A) presents the recent advances in intermodulation, and (B) presents harmonic radar. Finally, Section IV concludes the paper, summarizing the essential findings and implications.

II. FUNDAMENTALS

A. Intermodulation Radar

Intermodulation radar uses the intermodulation phenomenon to extract target information. It transmits signals at different frequencies, producing intermodulation products when interacting with the target. These products reveal important details such as range, velocity, and position. The radar system requires a wide frequency range, high linearity, and optimized frequency response to detect and analyze these products accurately. This response determines the system's sensitivity to target characteristics and ability to resolve closely spaced targets. By optimizing the frequency response, intermodulation radar systems achieve enhanced target detection, localization, and tracking capabilities in various applications.

Fig. 1 illustrates the intermediated frequency tones that appear when two-frequency tones. f_1 and f_2 pass through a nonlinear device as $nf_1 \pm mf_2$, where n and m are integers, 2nd and 3rd intermodulation frequencies are commonly used for

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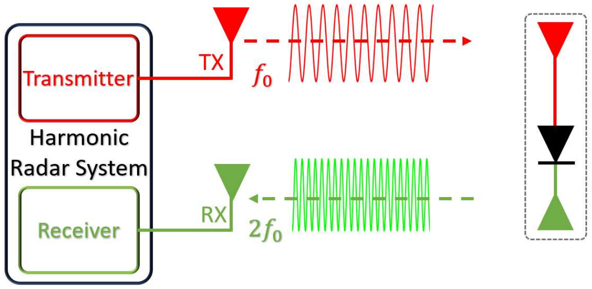

Figure 2. Illustration of 2nd order harmonic radar operation with nonlinear tag.

wireless health monitoring, such as vital sign tracking and human location detection [9, 10].

B. *Harmonic Radar*

Harmonic radar is a radar technology that transmits continuous wave signals at specific frequencies and detects the harmonic frequencies emitted by targets. It takes advantage of the target's nonlinearity, generating harmonic frequencies during the interaction. These harmonics provide valuable information about the target's range, velocity, and size.

Harmonic radar operation is illustrated in Fig. 2. The transmitter (TX) radiates a fundamental frequency at f_0, when the electromagnetic (EM) wave hits a nonlinear (NL) tag; depending on the design of the NL tag, it would reflect back n^{th} order $(n \times f_0)$ harmonic EM wave transmitted by the TX antenna. Passive nonlinear tags are often used as the NL element [16,17], with their small sizes and longevity advantages compared to active tags.

Harmonic radar excels in outdoor tracking, as most objects reflect the fundamental frequency, allowing clutter rejection. Nonlinear tag designs commonly employ second-order harmonics $(2 \times f_0)$ due to higher harmonic orders reducing the power of reflected waves. This approach improves target detection, precision measurements, and reliable tracking in harmonic radar applications.

III. RECENT ADVANCEMENTS

A. *Intermodulation Radar*

Intermodulation radar has been investigated among researchers aiming to improve target signal detection, overcome clutter challenges, and enhance vital sign estimation techniques.

The investigation in [2] delved into intermodulation and electromagnetic induction (EMI) sensors as potential solutions to distinguishing target signals from clutter in harmonic radars. The study primarily focused on designing and implementing a hybrid scan head for harmonic radar sensors, encompassing transmit and receive antennas in conjunction with an EMI sensor. Another research effort [4] also tackled linear continuous-wave sensors' challenges in distinguishing target signals from environmental clutter. This study uses passive intermodulation response in microwave sensors as a potential solution.

Intermodulation-based Frequency-Modulated Continuous Wave (FMCW) systems for ranging purposes were investigated in a research endeavor, highlighting their improved target mapping and clutter rejection capabilities compared to conventional FMCW sensors. This research aimed to demonstrate the potential of intermodulation-based FMCW systems in range estimation and clutter mitigation [4].

An issue called reverse intermodulation distortion (RIMD) in phased-array transmitter systems, particularly in 5G and radar applications, was analyzed in [3]. RIMD occurs when signals from one transmitter are coupled to the output ports of nearby transmitters, resulting in intermodulation distortion. The study utilized RIMD modeling and estimation methods, emphasizing their potential applications in higher power operation and simplified pre-distortion in multi-tone array systems.

The impact of multi-frequency intermodulation electromagnetic interference (EMI) on radar systems was investigated in [5]. This research underscored the importance of studying the interference caused by multi-frequency intermodulation EMI to understand the behavior and characteristics of false alarm signals in radar systems.

To improve signal analysis for vital sign estimation, a research study [6] introduced the harmonics and intermodulation product-based fuzzy logic (HIPBFL) algorithm utilizing ultra-wideband (UWB) radar. This algorithm employed the Chirp Z-Transform (CZT) to analyze vital signs and extract the spectrum. It demonstrated its accuracy and noise tolerance for robust vital sign estimation using UWB radar technology.

A novel technique was presented in [7], involving the multiplication of normalized frequencies from different baselines using interferometric radar. This method aimed to mitigate nonlinear intermodulation products and accurately capture the angular velocities of multiple targets. It offered a low-complexity and cost-effective solution using continuous wave radar systems.

Another notable approach in intermodulation radar [8] operated in the same frequency band for transmission and reception. This system effectively rejected undesired reflections from passive clutters while detecting nonlinear targets, providing a promising alternative to traditional harmonic radars. Passive nonlinear tag-assisted vital sign detection using intermodulation radar was explored [9]. This approach demonstrated clutter suppression capabilities and successful vital sign measurements. Moreover, the utilization of intermodulation response was investigated in the development of a passive-intermodulation-based FMCW radar system for target detection and tracking in complex indoor environments [10]. This study leveraged third-order intermodulation products (IMP3s) for range estimation, and performance improved through calibration to compensate for range offsets caused by phase delays.

Recent advancements in intermodulation radar systems show improved target signal detection, mitigating clutter, and advancing vital sign estimation through innovative techniques, impacting its development and application across diverse domains.

B. *Harmonic Radar*

Harmonic radar systems have been the focus of extensive research, addressing various challenges and exploring their potential applications in different domains.

One notable challenge in [11] revolves around harmonic radar detections in cluttered environments with Frequency-Modulated Continuous Wave (FMCW) radar. The study proposes the utilization of harmonic reflectors or tags as a solution to overcome this challenge. This study presents a detailed tag circuit design and evaluation specifically tailored for millimeter-wave radar. The design demonstrates high conversion gain, power efficiency, and stable operation. Furthermore, the range resolution capabilities of the tag are showcased through experiments conducted in a harmonic radar setup and on a linear track.

In [12], a maritime search and rescue system (SRS) is introduced, incorporating both the ship's navigation radar and harmonic radar (HR) technology. Utilizing low-cost, low-power passive and active HR tags surpasses previous HR systems' performance. Integrating an X-band navigation radar enables sensor data fusion, enhancing SAR capabilities for more efficient rescue missions. Harmonic radar systems significantly benefit maritime rescue and insect tracking [12, 14, 18]. Notably, the effectiveness of an active harmonic tag is highlighted in [12], achieving an impressive 5.8 km range with 100 W feed point power, even for targets situated just 7 meters above sea level.

The study described in [13] explores a technique that harnesses the power of harmonic radar and power-swept signals for the classification of electronic devices. This technique showcases accurate classification results, even in scenarios characterized by low signal-to-noise ratios. Statistical and Fourier-based features are employed to achieve this accurate classification, providing a valuable contribution to electronic device classification.

The utilization of harmonic radar systems for insect tracking is investigated in [14,18]. Focusing on both S-band and X-band frequencies, the study discusses developing and evaluating FMCW harmonic radar prototypes designed explicitly for insect tracking. These studies showcase advancements in harmonic radar, overcoming clutter, insect tracking, extending detection range, and maritime rescue operations.

IV. CONCLUSION

In recent years, intermodulation and harmonic radar advancements and their sensor integration have improved electronics detection. Incorporating electromagnetic induction sensors enhances performance, while the algorithm based on harmonics and intermodulation improves heart rate estimation accuracy. Intermodulation radar detects nonlinear targets, rejects noise, and identifies unauthorized devices. Harmonic radar in insect tracking advances ranges, flexibility, and usability. Research explores electronic circuit classification and methods to enhance range. These advancements highlight the progress and versatility of harmonic and intermodulation radar technology across diverse fields.

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