Spectrum-Efficient Multi-target Vital Sign Detection based on Space-Time-Coding Direct Antenna Modulation

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***Abstract*—With the significant advancement in the field of remote human health monitoring in recent years, the demand for simultaneous detection of multiple target vital signs is growing, especially in hospitals and assisted living environments. The development of space-time coding has enabled the generation and modulation of multiple harmonics, which can be directed toward different targets for sensing. Concurrently, direct antenna modulation (DAM) is applied to antenna elements to simplify the array control, making the entire system digitally controlled, applicable across a wider bandwidth, and reducing system complexity. This report summarizes my recent research on multi-target vital sign detection using space-time-coding (STC) direct antenna modulation radar, emphasizing innovations such as ease of design, deployment, and control, along with its narrow spectrum occupancy. The research further explores the potential of STC-based radar for shaping future applications in smart homes and environmental sensing systems, particularly in signal-dense environments.**

***Index Terms*—Direct antenna modulation (DAM), space-time-coding (STC), spectrum efficiency, vital sign detection**

I. Introduction

THE rapid advancement of the medical Internet of Things (IoT) has driven a growing demand for remote health monitoring, particularly for continuous and non-invasive vital sign monitoring. In clinical settings such as hospitals, assisted living facilities, and home care environments, the demand for systems capable of simultaneously monitoring the vital signs of multiple individuals is steadily increasing. Space-time coding (STC) has emerged as a promising solution to the limitations of conventional radar systems, facilitating the concurrent detection of multiple targets. By modulating different harmonic frequencies toward distinct spatial locations, STC enables effective target separation and detection. The integration of direct antenna modulation (DAM) further simplifies array control and reduces hardware complexity, resulting in a digitally controlled radar system with enhanced spectrum efficiency. In this report, we summarize our recent research involving the implementation of STC DAM-enabled radar for multi-target vital sign detection.

II. Metamaterial-Integrated STC DAM Array for Multi-Target Sensing

We propose an STC transmitting array integrated with DAM and metamaterials (MTMs) to monitor multiple-target vital signs, such as respiration and heartbeat rates. The array utilizes a serial MTM power divider to distribute the carrier signal to each antenna element evenly. The infinite wavelength

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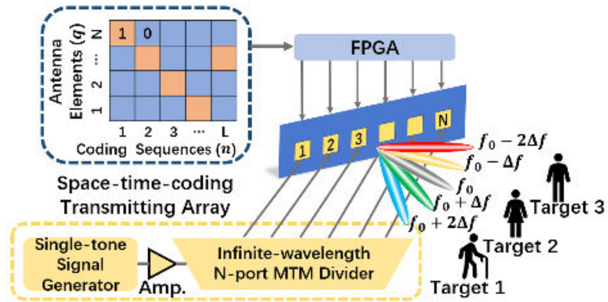
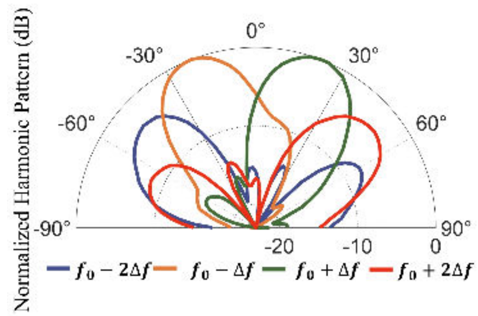
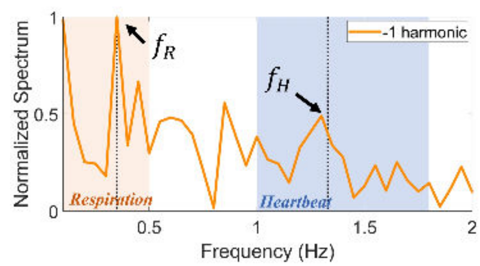


Fig. 1. Block diagram of STC array-based radar with DAM.



(a)



(b)

Fig. 2. (a) Measured STC harmonic patterns (b) Normalized FFT results of measured vital signs signal extracted from -1st harmonic when the target is positioned in the corresponding direction. The typical respiration rate range (0-0.5 Hz) and the heartbeat rate range (1-1.8 Hz) for adults are highlighted in orange and blue, respectively.

characteristics of the 0th-order resonant metamaterial ensure the theoretical scalability of the array without limitations. DAM is applied to each patch antenna element, inducing a 180° phase shift in the far field, which serves as the digital element of STC. This configuration simplifies the overall system, eliminating the need for additional phase shifters. The block diagram of the proposed STC array-based radar system is illustrated in Fig.1 [1]. By appropriately implementing the STC matrix, different harmonic beams can be steered in various directions to interrogate different targets.

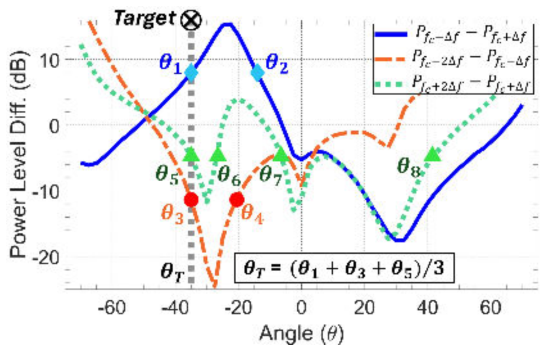


Fig. 3. Power level difference between harmonics over azimuth angles calculated with the measured pattern.

All harmonic beam patterns are radiated simultaneously, with each beam directed in a distinct direction, highlighting the array's versatile, multidirectional capabilities. Notably, the modulation frequency (Δf) is significantly smaller than the carrier frequency (f_0), ensuring efficient spectrum utilization. The measured radiation patterns from the -2nd to the +2nd order harmonics are shown in Fig.2 (a) [2]. The measured FFT result of the vital sign signal extracted from -1st harmonic is shown in Fig.2 (b), which shows good agreement with the ground truth as indicated by the black dotted line.

III. Multi-Harmonic Amplitude Analysis of STC for Target Angle Estimation

By utilizing the STC array as the receiving terminal and leveraging the characteristics of spatio-spectral mapping, the amplitude of the received harmonics can be analyzed to determine the direction of arrival (DOA) of the signal in the approach of the received signal strength indicator (RSSI). An omnidirectional or wide-beam antenna is deployed as the transmitting terminal to radiate a single-tone signal across an area. The target's angle can be estimated by analyzing the direction of the received signal reflected from the target. Fig.3 illustrates the proposed concept using the power level difference between harmonics calculated from the measured patterns [3]. The estimated angle θ_T is computed as $(\theta_1 + \theta_3 + \theta_5)/3$. Once the estimated target angle is obtained, the target's vital signs can be detected by analyzing the STC harmonics in the corresponding direction, enabled by the spatio-spectral mapping feature.

IV. Asynchronous STC-based Automated Beam-Scanning for Multi-Target Sensing

The automatic one-dimensional half-space beam scanning with a controllable scanning period is achieved by implementing the asynchronous STC (ASTC) code into the array, facilitated by the frequency offset between the adjacent antenna elements. By isolating data points corresponding to each target within each scanning period and applying Fourier analysis, the vital signs of multiple targets can be precisely differentiated and extracted. The block diagram of the ASTC-based multi-target radar system is shown in Fig.4 (a) [4]. The time-relevant far-field radiation of the purified +1st harmonic with a scanning period of 125 μs are depicted in Fig.4 (b). As shown in Fig.4 (c), the +1st harmonic beam angles over time cover the half-azimuth range from -90 to +90 degrees within one scanning period.

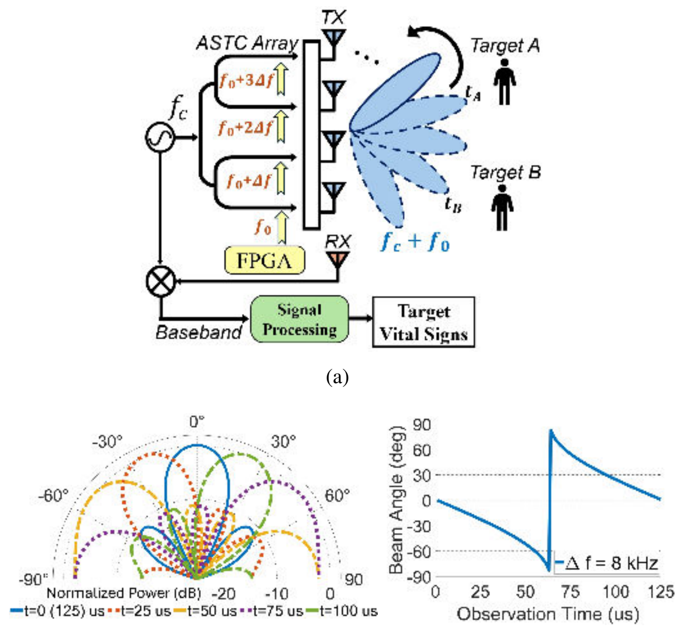


Fig. 4. (a) Block diagram of the ASTC-based multi-target radar system, where f_c, f_0 and Δf represent the carrier frequency, reference modulation frequency, and additional modulation frequency offset, respectively. (b) Automatic time-dependent scattering patterns of the +1st order harmonic ($f_c+\Delta f$). (c) The beam angle of +1st harmonic pattern over time in one scanning period.

V. Fellowship Impact and Career Plan

I am honored and grateful to be a recipient of the IEEE Microwave Theory and Techniques Society (MTT-S) Graduate Fellowship Award. This recognition has greatly boosted my confidence and further motivated me to pursue research in this field. Looking ahead, I plan to begin my career in industry to gain a broader perspective of the field, with the possibility of returning to academia in the future to further contribute to this area of research. The IMS conference offered a valuable opportunity to expand the perspectives of young scholars, allowing me to meet leading experts in the field and engage with scholars from around the world. The professional academic atmosphere left a lasting impression on me.

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