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A 77 GHz FMCW MIMO radar system based on 65nm CMOS cascadable 2T3R transceiver

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In recent years, many studies on millimeter-wave (mm-wave) radar have been published [1–3]. Compared with other traditional vision sensors like ultrasound, camera, and laser radar, mm-wave radar is more attractive owing to its low cost, high resolution, high integration, and strong robustness against bad weather. Frequency-modulated continuous-wave (FMCW) radar is the most widely studied mm-wave radar because of its simple structure, easy realization, and powerful function. At present, the research of mm-wave radar mainly focuses on two frequency bands, 24 GHz and 77 GHz. Between them, the research on 24 GHz radar has started earlier and is more mature now. It is mainly used in car's advanced driving assistant systems (ADAS). Compared with 24 GHz, the 77 GHz radar has a smaller size (including chips and antennas) because of its higher frequency. In addition, the 77 GHz radar is able to achieve wider bandwidth, leading to a higher range resolution, because the range resolution is inversely proportional to the radar's sweep bandwidth.

In this study, a 77 GHz FMCW MIMO radar system is presented. Based on the 65 nm CMOS 2T3R radar transceivers that proposed in [4], a RF module is presented. A data collection module is also involved in the radar hardware to collect the information of targets. A Capon beamformer based radar algorithm is developed in this study to process the data and identify the target [5]. Employing the proposed radar hardware and algorithm, several measurements are also accomplished in this study.

Radar hardware. Figure 1 illustrates the block diagram of the proposed FMCW MIMO radar hardware. A radio frequency (RF) module is employed to generate, transmit, and receive the FMCW waves, as well as produce intermediate frequency (IF) signals. These IF signals contain the distance, velocity and angle information of the targets. The RF module is controlled by an micro controller unit (MCU) through SPI. The MCU also generates a tx_sync signal to mark the working transmitter (TX) channel for MIMO. The produced IF signals are sent to buffers and ADCs to be sampled and converted into digital signals. An FPGA is utilized to package the digital data, tx_sync and the ramp_sync signals from RF module. Ramp_sync indicates the beginning and end of FMCW chirps. A DDR chip is employed to cache the packaged data. To transfer the data from the hardware to PCs for further processing, an USB 3.0 chip is used in this design.

The RF module contains two 65 nm CMOS cascaded FMCW radar transceivers, a TX antenna array and a RX antenna array. The employed radar transceiver is able to generate sawtooth FMCW chirps with reconfigurable duration and bandwidth, which achieve 100 µs and 4 GHz, respectively. To estimate targets' directions of the arriving (DOA), the transceiver has 2 TXs and 3 RXs, and supports MIMO by utilizing on/off keying (OOK) and binary phase shift keying (BPSK). To further improve the angular resolution, multiple chips can work in master-slave mode, which offers more TX and RX channels. In the employed RF module, two transceivers are utilized to achieve 4 TXs and 6 RXs, which contributes to 24 virtual MIMO channels. The master one is configured to generate sawtooth chirps and share the local oscillator signal with the slave one. OOK based MIMO is used due to its simpler structure, control logic and data processing algorithm.

Non-uniform excited series-fed microstrip patch antennas that are fabricated on RO3003 Printed Circuit Board (PCB) are utilized to present the TX and RX antenna arrays [6]. The gain, bandwidth, and the side lobe lever (SLL) of the single antenna achieve 11.2 dB, 2 GHz, and −20 dB by simulation, respectively. The direction of the target is evaluated by

$$\sin\theta = \frac{\lambda \cdot \Delta\phi}{2\pi d}, \tag{1}$$

where θ is the direction of the target. λ is the wavelength

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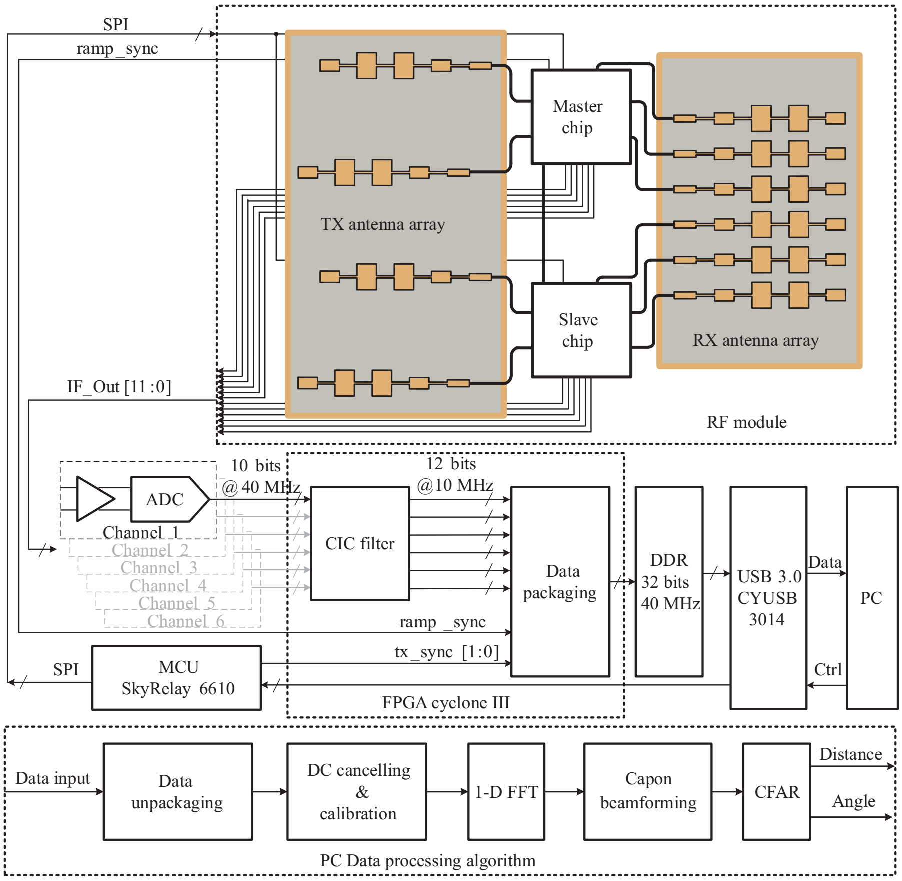

Figure 1 (Color online) Block diagram of the proposed FMCW MIMO radar hardware and the employed data processing algorithm.

of the radar wave. $\Delta\phi$ and d are the phase difference and spacing between adjacent antennas, respectively. As the definition domain of $\Delta\phi$ is $[-\pi/2, \pi/2]$, with a designed d of 2.2 mm, the field of view (FOV) (value domain of θ) is calculated as $[-55^\circ, 55^\circ]$. The relationship between angular resolution of the MIMO system and the number of antennas is defined by

$$\Delta\theta = 0.88\frac{\lambda}{D_{\text{array}}} = 0.88\frac{\lambda}{Nd}, \tag{2}$$

where $\Delta\theta$ is the angular resolution, D_{array} is the antenna aperture, and N is the number of virtual RX antennas. In this study, there are 2 TXs and 6 RXs on the horizontal plane, leading to 12 virtual antennas. The theoretical angular resolution is 7.2°.

Six 10-bit differential ADCs are utilized to sample IF signals. The sampling clock of ADCs is 40 MHz, which is synchronized with the crystal oscillator in the RF module. In the following Cyclone III FPGA, a CIC decimation filter is presented to downsample the converted digital signals. Then, these IF digital signals are expanded to 12 bits and packaged with ramp_sync, tx_sync, and chirp-tag bits into 32 bits data in the FPGA. A 4 MHz 32 bits DDR is employed to cache the packaged data. At last, a CYUSB 3014 USB 3.0 chip is used to connect the radar hardware with PC. It transfers the measured data from the hardware to PC and sends the hardware control codes that are received from PC.

Data processing algorithm. A Capon beamformer based algorithm is employed in this study. Firstly, the series data from the USB are recovered into 12 matrixes. Data from each channel is divided into chirps according to the ramp_sync signal and each chirp takes a row. These matrixes are shown in

$$\boldsymbol{A}_i = \begin{bmatrix} a_{i11} & \cdots & a_{i1n} \\ \vdots & \ddots & \vdots \\ a_{im1} & \cdots & a_{imn} \end{bmatrix}_{m\times n}, \quad i = 1, 2, \ldots, p, \tag{3}$$

where p is the number of MIMO channels (12 in this study), m is the number of chirps, and n is the number of sample points in each chirps.

Due to the asymmetry layout of each TX/RX channels and the delay of LO signal between master and slave chips, offsets exist among IF signals from different channels. TO eliminates the offsets, and a calibration is involved in this study. The calibrated signal S_{jc} can be written as

$$\begin{aligned} S_{jc} &= \text{Amp}_{jc} \cdot S_{jo} \cdot \mathrm{e}^{-i\cdot 2\pi\cdot f_{jc}} \cdot \mathrm{e}^{-i\cdot p_{jc}}, \\ j &= 2, 3, \ldots, 12, \end{aligned} \tag{4}$$

where S_{jo} is the original data of the jth channel. Amp_{jc}, f_{jc}, and p_{jc} are amplitude, frequency, and phase offsets between the jth and the 1st channel. After calibration, 1-D FFTs are accomplished for each chirps of each channels. Then the spectrum matrixes $F_{i,m\times n}$ on distance can be derived.

The Capon beamformer technique is employed to estimate the directions of targets. The algorithm is firstly proposed by Capon [5]. For each distance point q $(1 \leqslant q)$, the output of the 1-D FFT can be derived as

$$\boldsymbol{X}=\begin{bmatrix} f_{1q1} & \cdots & f_{1qn} \\ \vdots & \ddots & \vdots \\ f_{pq1} & \cdots & f_{pqn} \end{bmatrix}_{p\times n}. \tag{5}$$

The steering vector for θ is

$$\boldsymbol{a}(\theta)=[1,\exp(-\mathrm{j}\pi\sin(\theta)),\ldots,\exp(-\mathrm{j}\pi(\mathrm{p}-1)\sin(\theta))]^{\mathrm{T}}. \tag{6}$$

For the signal in (5), the covariance matrix $\boldsymbol{R}_x=\boldsymbol{X}\boldsymbol{X}^{\mathrm{H}}/n$. Then, the Capon spatial spectrum on the distance q can be written as

$$\boldsymbol{w}_{\text{capon}}(\theta)=\frac{1}{\boldsymbol{a}(\theta)^{\mathrm{H}}\boldsymbol{R}^{-1}\boldsymbol{a}(\theta)}. \tag{7}$$

After getting a distance-angle map from Capon beamformer, a constant false alarm rate (CFAR) module is employed to identify targets from clutters.

Measurement. To verify the function and test the performance of the presented FMCW MIMO radar system, several measurements are completed. Static measurements are done with two corner reflectors which are used as targets. By fixing the position of one corner reflector and slightly moving the other one until the two reflectors are indistinguishable, the range resolution and angular resolution of radar can be measured. The measurements show that the radar achieves a range resolution of 5 cm and an angular resolution of 9°. The FOV of the radar is also verified and the result illustrates that ±55° FOV is achieved. Using chirps with 200 µs chirp-up time and 4 GHz bandwidth, the maximum detectable velocity is measured as ±4.7 m/s. To further test the radar in real scenery, a real-time measurement is accomplished. The Capon algorithm and display system are realized on PC with MATLAB. A scatter picture is used to illustrate the results. Tests are carried out on a square to detect people and bicycle, and on a road to detect cars. The measurement shows the radar system presented in this study is able to detect pedestrians, bicycles, flag-poles, and cars.

Supporting information Videos and other supplemental documents. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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