11.1 A 4-Channel 4-Beam 24-to-26GHz Spatio-Temporal RAKE Radar Transceiver in 90nm CMOS for Vehicular Radar Applications

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The promise of *ambient intelligence* is a future environment that is adaptive and responsive to the objects and human beings that occupy it. Wideband RF and mm-Wave radar and imaging sensors will play a key role for indoor and outdoor surveillance, search and rescue, intelligent transportation and automotive active-safety systems, and wireless health monitoring [1].

Much like wireless-communication systems, radar and imaging sensors are adversely affected by multipath reflections caused by the presence of multiple targets. However, similar to wireless-communication systems, multi-antenna radar transceivers, or *MIMO radars*, may be envisioned that mitigate, and even *harness,* multipath for improved performance. For example, multipath reflections potentially enable a radar to probe an object from directions not visible from the line of sight (LoS) [2], or even probe an "invisible" object that is blocked in the LoS by other objects. Two categories of MIMO radars have been investigated – *linear beam-forming radars*, such as phased-array radars [3,4], and *spatial-diversity radars* [5].

This paper describes a new MIMO-radar architecture called the Spatio-Temporal RAKE (ST-RAKE) radar that uses waveform diversity in conjunction with multi-beam beam-forming to isolate LoS reflections and multipath to glean more information about the scene being imaged (Fig. 11.1.1). An $N \times B$ multi-beam matrix forms B simultaneous beams across N antennas. At transmit time, orthogonal codes are generated in baseband, modulated onto the carrier frequency and transmitted along the spatially-independent beams. If multipath were absent, each coded signal would return only along the direction in which it was sent. However, due to multipath, codes may return from other directions as well. At receive time, the radar "listens" for the return of *all* codes along *all* directions (i.e., beams). This is done by employing a baseband processor on each beam that consists of a bank of baseband correlators matched to delayed versions of *all* the transmitted codes. This enables isolation of LoS reflections and multipath. The correlation data can then be processed by a digital computational unit running multipath-based image-reconstruction algorithms [2,6,7]. This architecture is called an ST-RAKE radar because the multiple beams constitute spatial rake fingers and the correlation with varying delays constitutes temporal rake fingers. It is inspired by the ST-RAKE architectures that have been proposed for multi-user access in CDMA base-station receivers [8].

A prototype 4-channel, 4-beam, 24-to-26GHz, ST-RAKE radar transceiver is implemented in 90nm CMOS for vehicular radar applications (Fig. 11.1.7). A highly bi-directional architecture is employed that enables the sharing of several blocks across the transmitter and receiver, greatly conserving chip area (Fig. 11.1.2). An all-passive, bi-directional, 4×4 Butler matrix based on branch-line hybrids constructed from coupled CPWs used in differential mode is used for multi-beam beam-forming. Figure 11.1.3 depicts the synthesized normalized array patterns for the 4×4 Butler matrix based on measured S-parameter data for a pulsed-sinusoidal waveform with 500ps pulse width, 25GHz center frequency and approximately 2GHz -3dB bandwidth. The antenna spacing is assumed to be half-wavelength at 25GHz and an energy detector is assumed to gauge the output strength. At the antenna interface, a balun is employed for single-ended to differential conversion. Each front-end T/R module consists of an LNA and a PA with switches at both ends. The front-end T/R switch that follows the balun employs $\lambda/4$ transmission lines to eliminate the series transistor that is required in conventional designs. Together, the balun and front-end T/R switch contribute a simulated 3dB of insertion loss to the enabled branch. The PA is a single-stage, cascoded, pseudo-differential pair that is designed for class A operation to support the linear superposition of the codes being transmitted on the different beams. The PA is designed to consume 72mW and, based on FCC specifications as applied to the ST-RAKE architecture, deliver an output power of 0dBm/>5.5dBm at -1dB compression/ saturation including the balun and input and output switches. The LNA is a four-stage design, with current sharing employed in the first and second pair of stages. Each stage employs a differential pair with a dummy pair for C_{gd}-cancellation (Fig. 11.1.4). The LNA is designed to consume 21.6mW and has a measured gain of 14.8dB including the balun and input and output switches to a single-ended output (17.8dB inferred gain to the differential output). Both the LNA and PA include additional internal shunt switches that reduce their gain during the functioning of the other to ensure stability.

A power- and area-efficient baseband implementation in multi-beam transceivers is critical due to the large number of baseband processing units, especially in mm-Wave systems with multi-GHz signal bandwidth. The baseband processor of each beam consists of a Wilkinson power divider that feeds the I and Q sub-blocks. Each I/Q sub-block employs a doubly-balanced passive mixer that is bi-directional and hence shared between the transmitter and receiver. For the transmitter, a modulator is used that is essentially a hard-switching differential pair with controllable current (1.78 to 10.78mA) to provide 16dB of transmitter power control, and is driven by the digital code sequence of that beam. In this prototype, digital, amplitude-modulated, two-level code sequences are supported and provided by GHz-speed, programmable shift registers. This enables flexible testing with a variety of code families. On the receiver side, prior studies by the authors reveal that for vehicular-radar specifications, a mixed-signal baseband implementation based on analog correlators is more power-efficient than an all-digital one by roughly two orders of magnitude due to the Nyquist ADC that is required in the all-digital realization [1,9]. Therefore, the passive mixer drives a bank of four analog correlators, which are implemented as Gilbert-style, current-commutating mixers (0.5mA each) with variable gain followed by analog integrators (3.08mA each). The timing signals for the transmission of pulses and range-gated received-signal correlation are obtained from an off-chip controller.

I/Q LO generation is performed through 25GHz I/Q coupled LC VCOs, each consuming 5.2mA. A bank of calibration varactors is included in each VCO to accommodate for process and layout mismatches to ensure good quadrature. The distribution of the I/Q LO signals to the various baseband blocks is a challenge in multi-beam transceivers due to the mm-range length of the distribution lines. The distribution lines are implemented using 100Ω conductor-backed coplanar striplines, and the I/Q LO buffers consume 15.4mA. Local LO buffers in each baseband block consuming 9mA are also used to ensure sufficient LO swing at the passive-mixer gates. The measured tuning range and phase noise of the I/Q VCO are summarized in Fig. 11.1.6.

The prototype transceiver has been tested as a single-channel radar in wired loopback configuration (Fig. 11.1.5). An Altera DSP Development Board is used to generate 10ns-wide (limited by the development board) transmitter timing pulses for beam #1, and delayed, 10ns-wide, receiver correlation timing pulses. The measured transmitter spectrum is depicted. The transmitted output from RF channel #1 is fed back to RF channel #4 through long RF cables to produce appreciable delay and mimic the propagation of the wave in space and reflection off an object. The measured, received, correlated and integrated signal from the Q-channel correlator for code #1 on beam#1 is depicted for multiple receiver range bins stepped at 10ns.

Acknowledgements:
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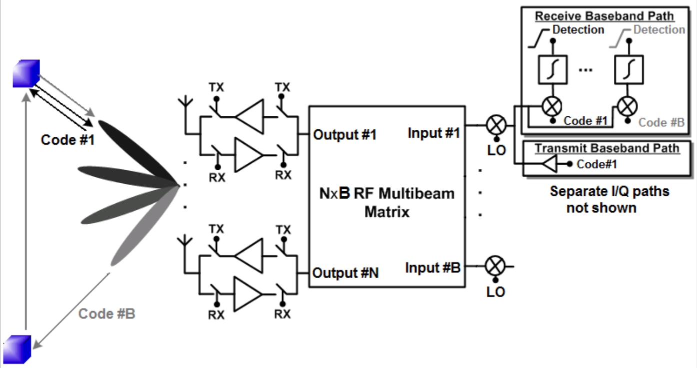

Figure 11.1.1: Spatio-Temporal RAKE radar concept.

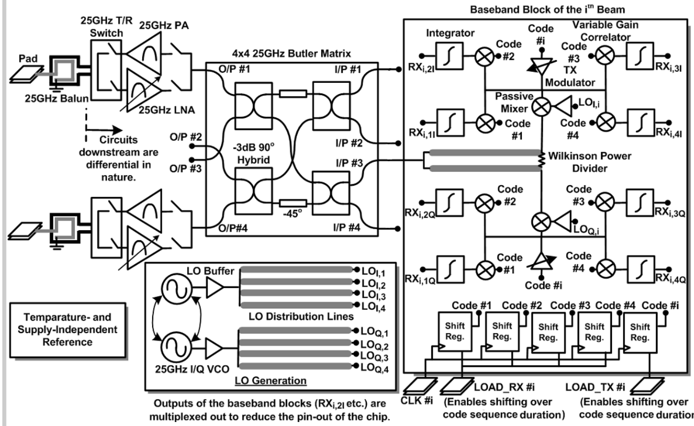

Figure 11.1.2: Block diagram of the 90nm CMOS, 4-channel, 4-beam, 24-26GHz, Spatio-Temporal RAKE radar transceiver.

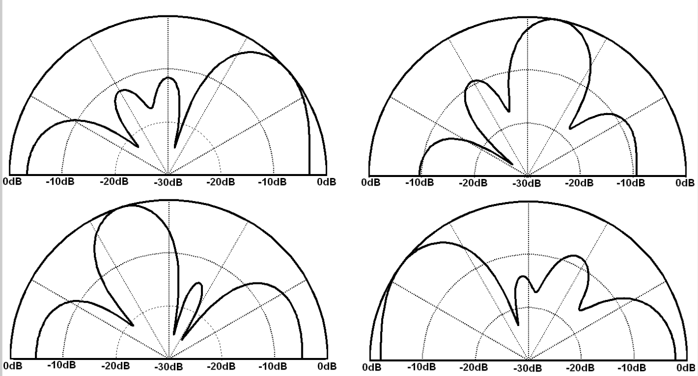

Figure 11.1.3: Synthesized normalized array patterns for the 4×4 Butler matrix based on measured S-parameter data.

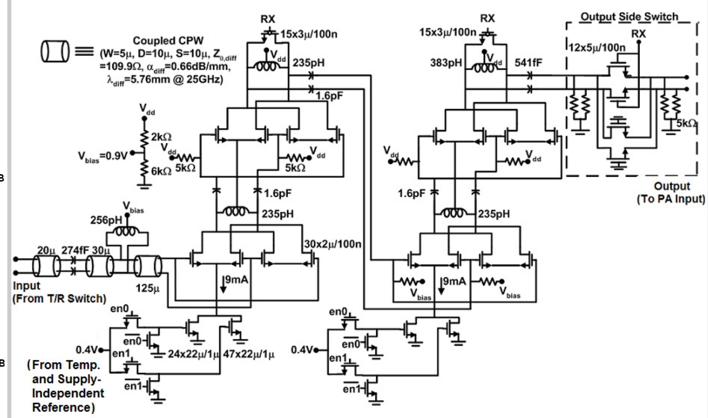

Figure 11.1.4: Schematic of the 90nm CMOS, 25GHz, front-end LNA.

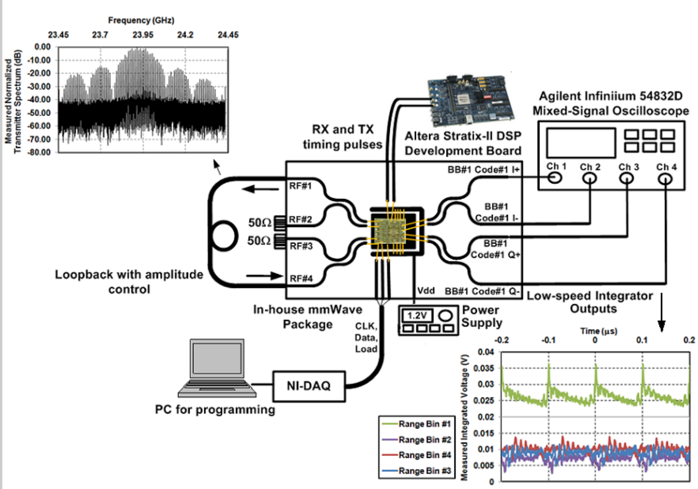

Figure 11.1.5: Wired loopback radar testing.

Implementation	
Technology	90nm CMOS
Die Area	4.2mm × 3.4mm
Supply Voltage	1.2V
RF-Path Performance	
Measured LNA Gain	14.8dB to 50Ω single-ended output (17.8dB to differential 100Ω)
PA Output at -1dB Comp./Saturation (sim)	0dBm/>5.5dBm
LO-Path Performance	
Measured I/Q VCO Tuning Range (all cal. bits 0)	23.5-25GHz
Measured I/Q VCO Tuning Range (all cal. bits 1)	24.3-25.8GHz
Measured I/Q Phase Noise at 1MHz Offset	-93.7dBc/Hz
Array Performance	
Number of Beams	4
Number of Antenna channels	4
RF-Path Power Consumption	
PAs	4 × 60mA × 1.2V=288mW
LNAs	4 × 18mA × 1.2V=86.4mW
LO-Path Power Consumption	
I/Q VCO and Buffers	49.4mW
Baseband-Path Power Consumption	
TX Modulators (max. setting)	8 × 10.75mA × 1.2V=103.2mW
Analog Correlators (mixer portion)	32 × 0.5mA × 1.2V=19.2mW
Analog Correlators (integrator portion)	32 × 3.08mA × 1.2V=118.3mW
I/Q Local LO Buffers	8 × 9mA × 1.2V=86.4mW
Total Power Consumption	(all TX and RX circuitry enabled) 751mW

Figure 11.1.6: Performance Summary.

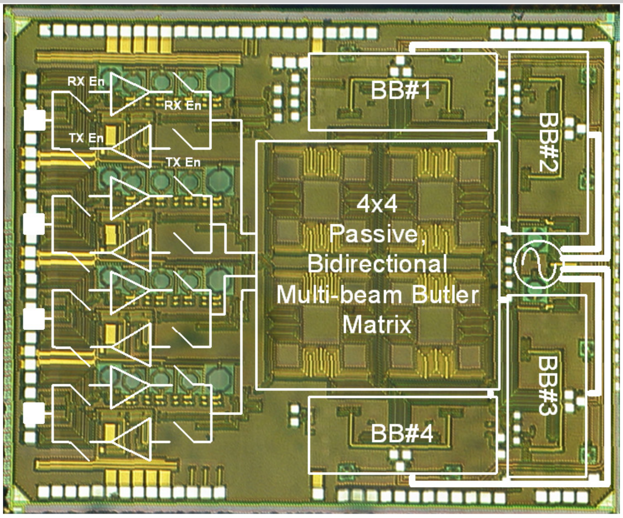

Figure 11.1.7: Chip micrograph of the 90nm CMOS, 4-channel, 4-beam, 24-26GHz, Spatio-Temporal RAKE radar transceiver. The radar chip consumes an area of 3.4mm×4.2mm.

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