Groundbreaking Millimeter-Wave Research Enabling 100 Gigabit-per-Seconds Wireless Communications

Payam Heydari
NCIC Labs, University of California, Irvine

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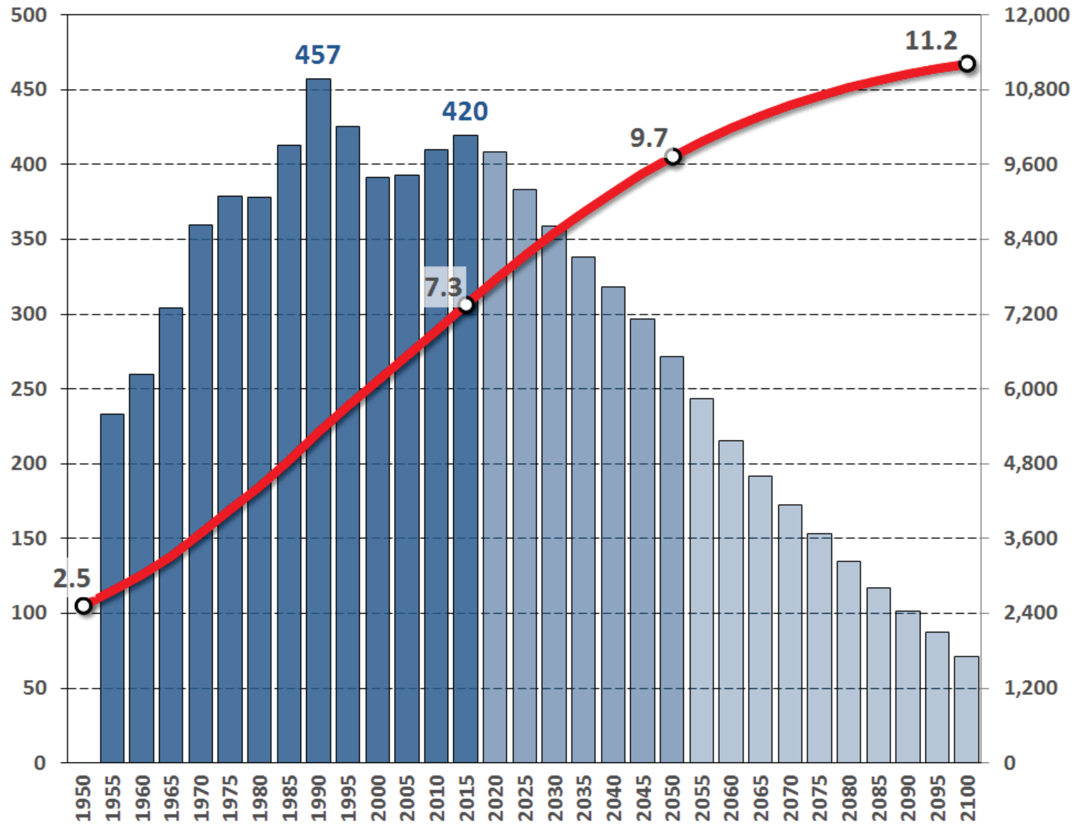
NANOSCALE COMMUNICATION IC LAB

University of California, Irvine

General Trends

- **Global forces in advancing communication technology**
  1. World population, communication users, continues to grow



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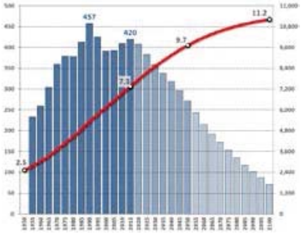
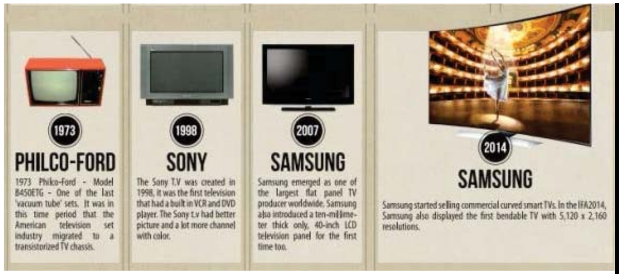
  1. World population, communication users, continues to grow
  2. Users constantly demand for larger multimedia contents
  3. New applications are more content-intensive → high data rates





1973

PHILCO-FORD

1973 Philco-Ford - Model B450ETG - One of the last 'vacuum tube' sets. It was in this time period that the American television set industry migrated to a transistorized TV chassis.

1998

SONY

The Sony T.V was created in 1998, it was the first television that had a built in VCR and DVD player. The Sony t.v had better picture and a lot more channel with color.

2007

SAMSUNG

Samsung emerged as one of the largest flat panel TV producer worldwide. Samsung also introduced a ten-millimeter thick only, 40-inch LCD television panel for the first time too.

2014

SAMSUNG

Samsung started selling commercial curved smart TVs. In the IFA2014, Samsung also displayed the first bendable TV with 5,120 x 2,160 resolutions.

General Trends

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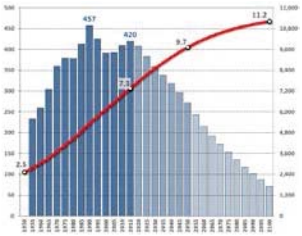


What does theory say?

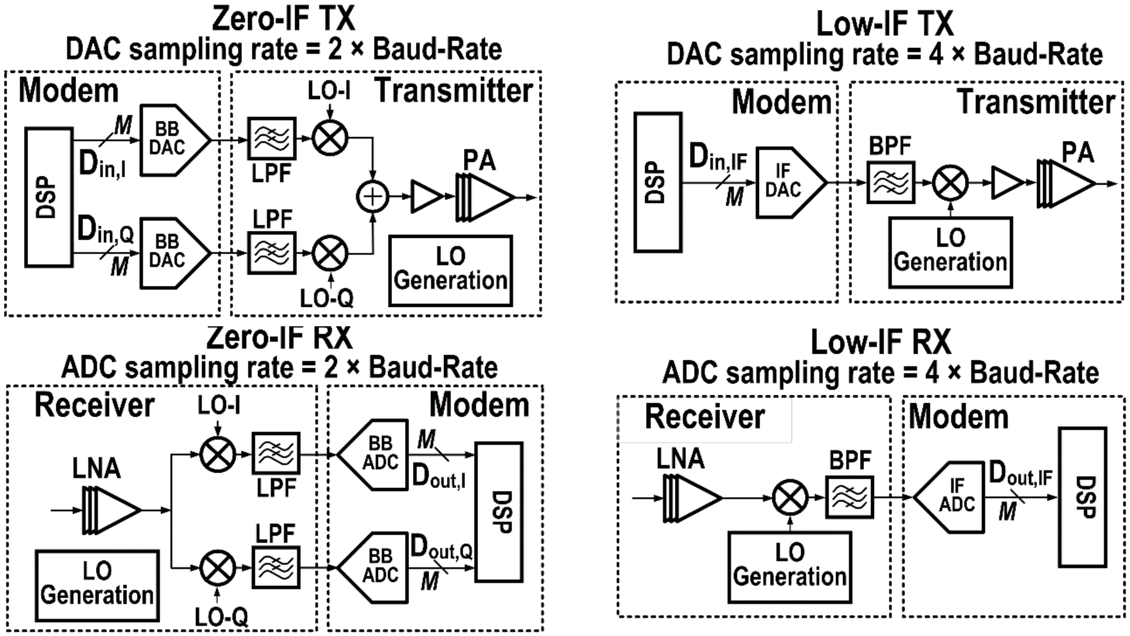
RF Power ↖ Noise Power ↗

Spectral Capacity $C = BW \log_2(1 + S/N)$ AWGN Channel

- **The wider the bandwidth (BW), the higher the capacity**
- **How about increasing bandwidth per user?**
  - What are the exiting challenges?
  - Can higher data-rate only be achieved by increasing BW?

Challenges in Wideband Design

Conventional TX and RX Architectures



- **TX/RX RF chains must satisfy target performance over wide BW, i.e.,**
  - **TX:** high gain, high TX power and efficiency, high linearity, low EVM
  - **RX:** low RX sensitivity, low noise and high gain, high blocker tolerance

☹ **Difficult to maintain high performance over wider BW**

- In-band noise integration → low SNR
- Device frequency-dependent characteristic and nonlinearity → large distortion

High Data-Rate over Smaller BW

Modulation/Demodulation

- **Digital modulation involves transforming the binary bits to digital switching of a signal attribute**
  - **Amplitude:** on-off-keying (OOK) → switching time is T_b
  - **Phase:** phase shift-keying (PSK) → constant amplitude
  - **Frequency:** frequency shift keying (FSK) → constant amplitude
- **To preserve signal quality, the DAC/ADC sampling rate should be**
  - Twice the baud-rate ($1/T_b$) for direct conversion architecture
  - Four times the baud-rate for low-IF architecture
- **Example:** For an OOK modulation to achieve 10 mega-bit-per-second data communication, the single-sideband baseband bandwidth should be 10 MHz
- **Basic binary modulations are not very BW efficient**

Question 1: how about defining a symbol represented by multi-bit binary code?

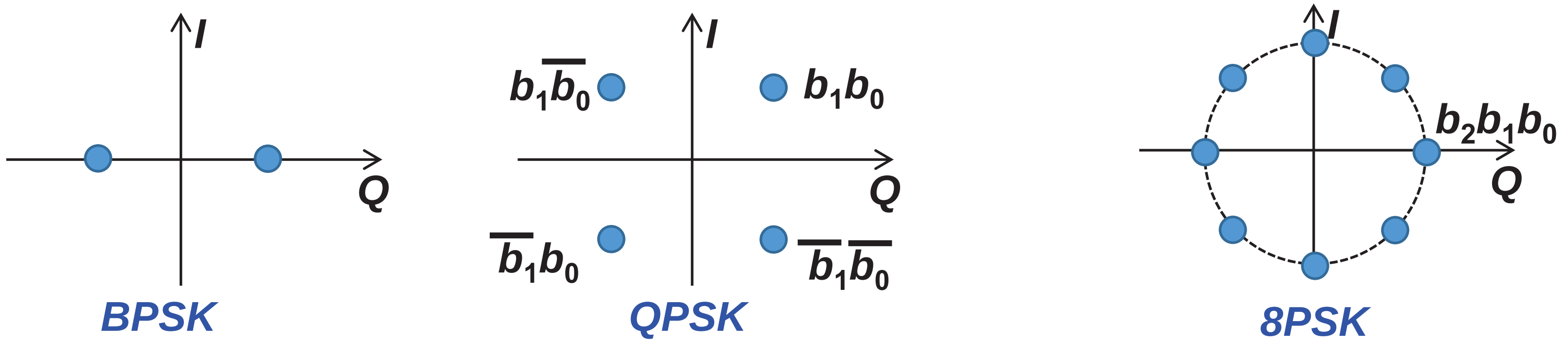
Question 2: how about using both amplitude and phase to generate these multi-bit binary codes?

High Data-Rate over Smaller BW

Modulation/Demodulation

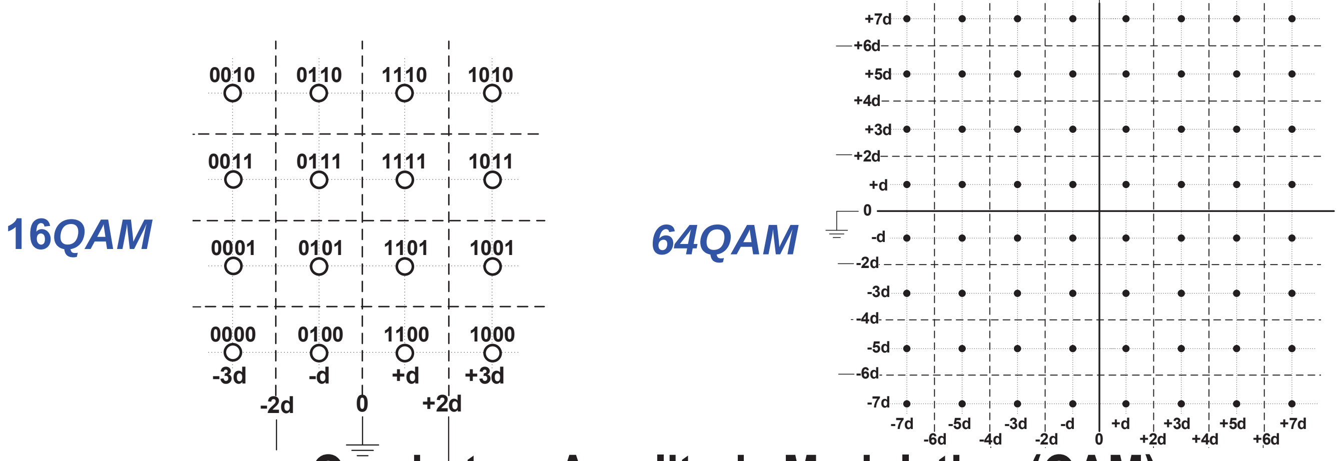
Question 1: how about defining a symbol of multi-bit binary code?

Question 2: how about using both multi-levels of amplitude and smaller phase angles than 0-180 to generate these multi-bit binary codes?



BPSK QPSK 8PSK

Constant Amplitude Modulations



16QAM 64QAM

Quadrature Amplitude Modulation (QAM)

High Data-Rate over Smaller BW

Modulation/Demodulation

☺**Increasing the modulation complexity (order) results in more spectrally efficient communication**

- ➢ Now, the data rate can be increased for given specific bandwidth

- **Example:** 16QAM modulation scheme is four times more spectrally efficient than BPSK or OOK

☺**More bang for the buck** → broadcasting larger content over a given BW

Question: If so effective, why can't we keep increasing the modulation order?

- ➢ 1024QAM, 2048QAM, and so on!

Challenges:

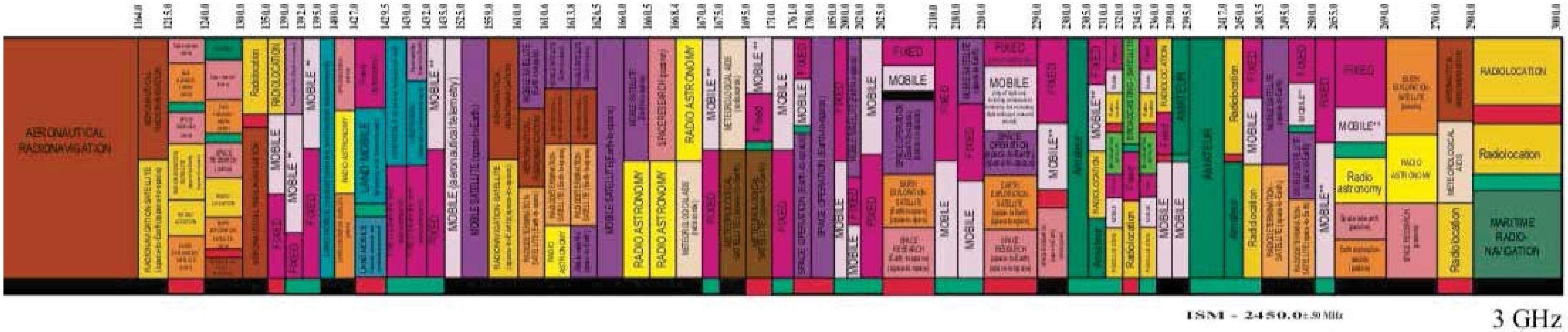
- **Increasing the modulation order requires**
  1. Lower local oscillator phase noise
  2. Higher resolution data converters
  3. Higher linearity RF chain

Observation: extremely difficult to increase modulation order beyond 1024QAM

Higher Carrier Frequency for Higher Capacity

Observation 1: Impractical to increase modulation order beyond 1024QAM

Observation 2: the RF band 700 MHz – 6 GHz is heavily congested

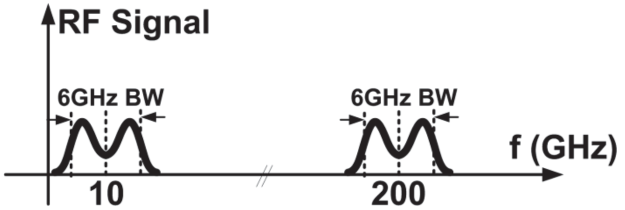


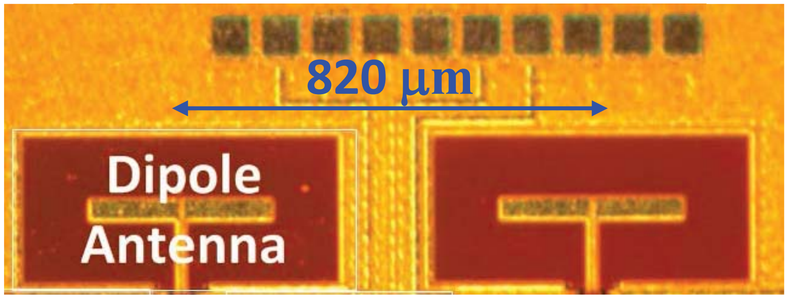
<u>Question:</u> **How can we further increase the data rate for emerging data intensive applications?**

- **How about increasing the carrier frequency?**

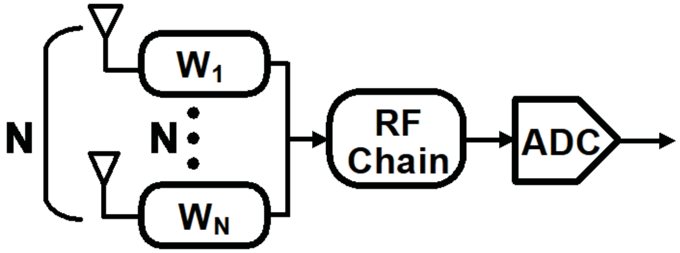
Higher Carrier Frequency for Higher Capacity

- **Increasing frequency towards mm-wave frequency range 30 – 300 GHz**
  - ☺ Wide BW with small fractional BW
  - ☺ The passive size decreases proportionally
  - ☺ The antenna size and spacing decreases, enabling larger array size
    - ☺ Multi-antenna architectures

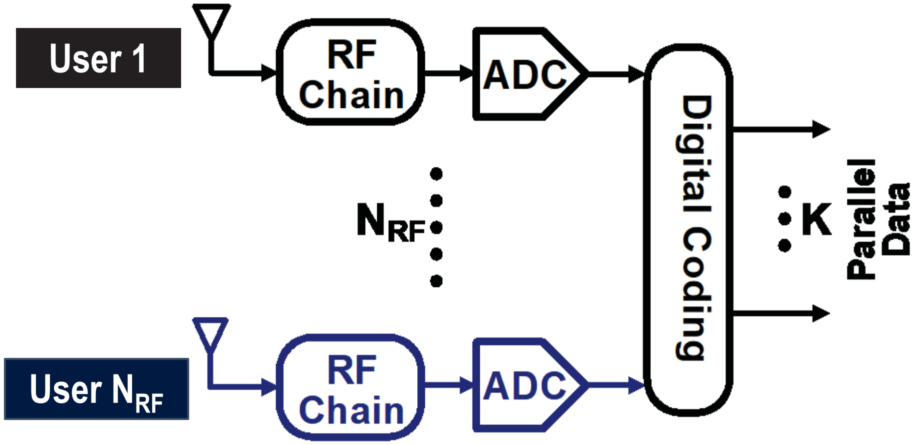




1x2 dipole antenna array at 210 GHz
[Wang- ISSCC 2013] and [Wang - JSSC2014]



All Analog Phased Array



All-Digital MIMO Multiplexing

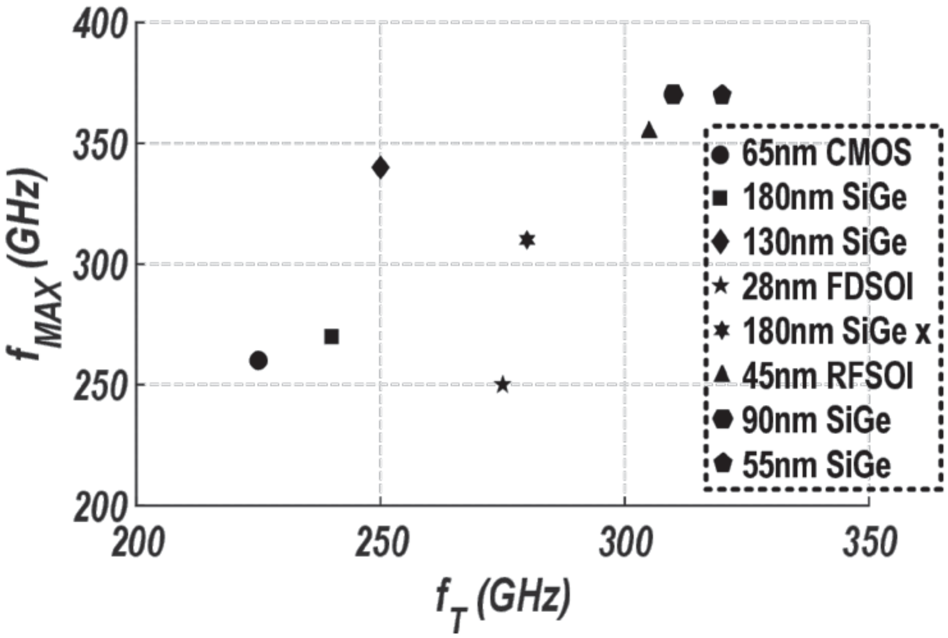
Challenges and Opportunities

- **Wider Instantaneous Bandwidth (BW)**
  - 30-300 GHz mm-Wave (EHF) band
  - Which part of the band to target for?
  - How to fully utilize the BW ?

- **High-Order Modulation**
  - OOK, ASK, BPSK, QPSK: low spectral efficiency
  - 8PSK, 16QAM, 64QAM, etc: high complexity
  - What are the bottlenecks ?

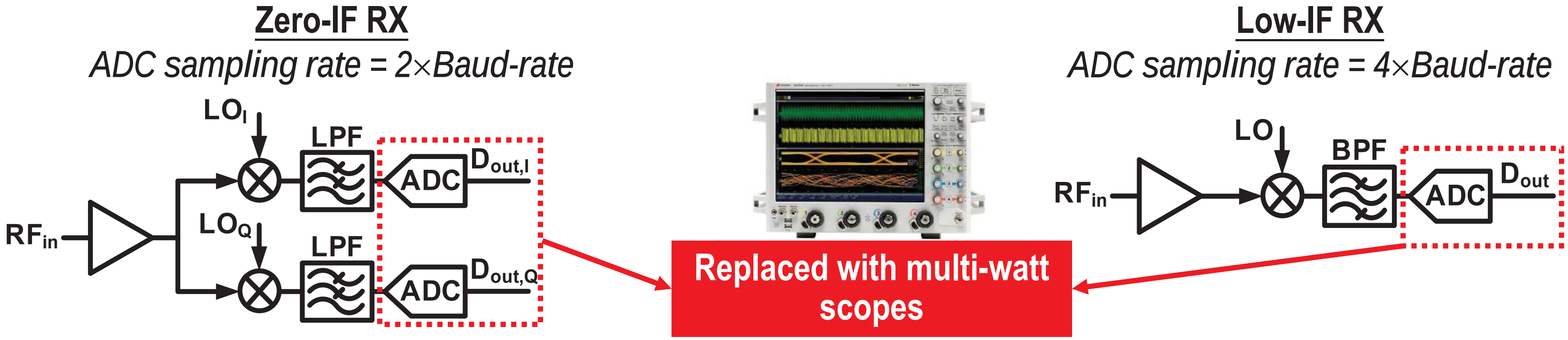
Bandwidth Availability

- **Continuous BW and Efficiency Trade-off**
  - Higher frequency for more BW
  - Limited by active devices
    - Low power-gain
    - High noise figure
    - High power consumption
  - Commercial Silicon Tech
    - f_{MAX}: 250 - 370GHz
    - Operate below $f_{MAX}/3$ - $f_{MAX}/2$



Prior-Art High-Speed Receivers

- **Conventional zero- or low-IF architectures**
  - ☹ incapable of addressing unresolved challenges in BB/mixed-signal parts
  - ☹ Require power-hungry high-speed high-resolution ADCs



Zero-IF RX

ADC sampling rate = 2×Baud-rate

Low-IF RX

ADC sampling rate = 4×Baud-rate

Replaced with multi-watt scopes

- **Current ADC-less receivers**
  - ☹ Only limited to basic modulations (OOK, QPSK)
  - ☹ For ultra-high-speed require very high center frequency and bandwidth

Prior-Art High-Speed Transmitters

- Conventional high-speed zero- or low-IF architectures
  - ☹ Incapable of addressing unresolved challenges in BB/mixed-signal
  - ☹ Require power-hungry high-speed-resolution (high SFDR) DACs

Zero-IF TX

DAC sampling rate = 2×Baud-rate

Low-IF TX

DAC sampling rate = 4×Baud-rate

☹ Replaced with multi-watt AWG

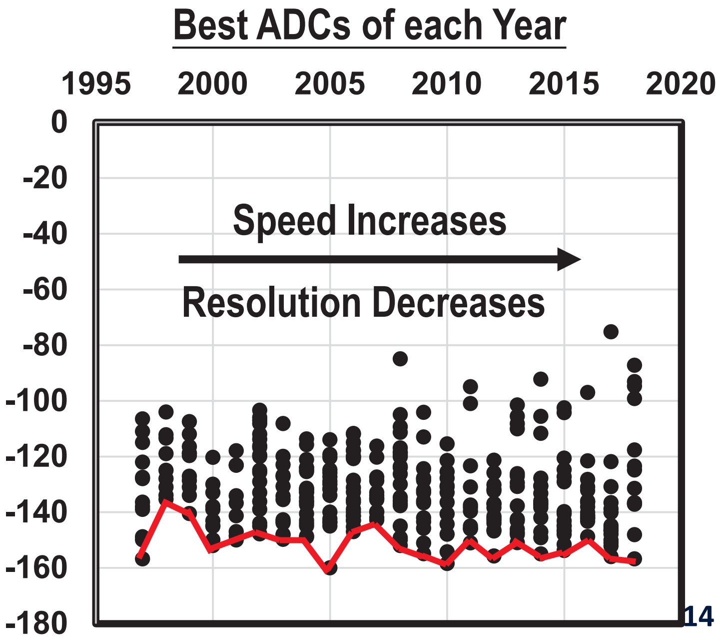
- Conventional DAC-less Transmitters
  - ☹ Only limited to basic modulations (OOK, QPSK)
  - ☹ For ultra-high-speed require very high center frequency and bandwidth

High-Speed Receivers: ADC/DAC Bottleneck

- Time-interleaving
  - For high sampling-rates (> 100+ MHz)
  - ☹ Inter-channel gain/timing mismatches
  - 64GSa/s, 5.95-ENOB, 1000 mW! [Cao - ISSCC 2017]

- Technology down-scaling
  - ☺ Energy efficiency improves
  - ☹ Resolution (SNDR) limited

☹ **Relative noise floor is saturated at –160dB/Hz**



Relative Noise Floor
= -(SNDR + 10log(BW))

Solution

High-Order Direct (De-)Modulation

***Statement*: Design of integrated ultra-high-speed RF-to-Bits TRXs using traditional architectures is nearly impossible**

A Paradigm Shift

High-order *direct* (de-)modulation in RF domain

- ☺**Removes power-hungry ADC and DAC**
- ☺**Relaxes the complexity of the BB unit**
- ☺**Achieves high spectral efficiency**

Solution

High-Order Direct (De-)Modulation

A Paradigm Shift

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- ☺ **Relaxes the complexity of the BB unit**
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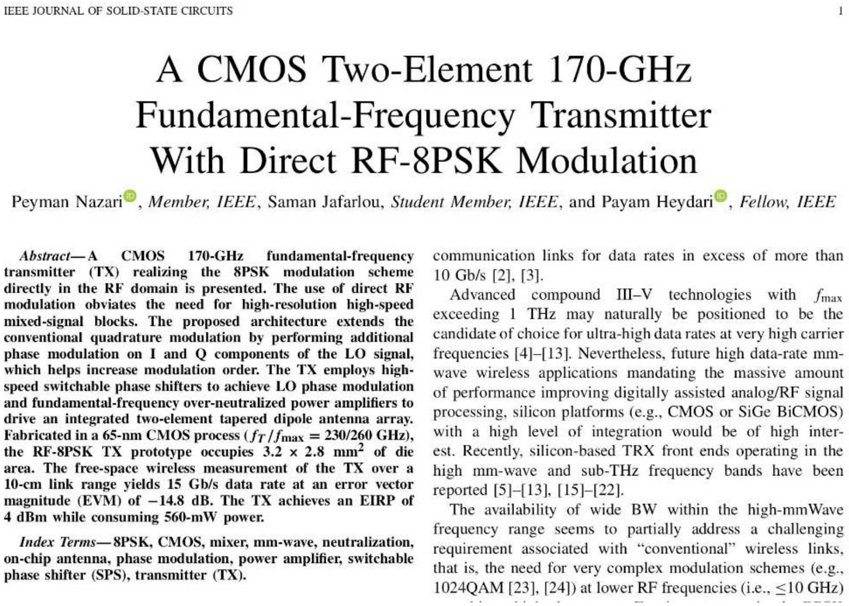
- Peyman Nazari, Saman Jafarlou, and Payam Heydari, "A CMOS Two-Element 170-GHz Fundamental-Frequency Transmitter with Direct RF-8PSK Modulation," to appear in *IEEE J. Solid-State Circuits*, vol. 55, 2020
- Huan Wang, Hossein Mohammadnezhad, and Payam Heydari, "Analysis and Design of High-Order QAM Direct-Modulation Transmitter for High-Speed Point-to-Point mm-Wave Wireless Links," *IEEE J. Solid-State Circuits*, vol. 54, no. 11, pp. 3161 – 3179, Nov. 2019
- Hossein Mohammadnezhad, Huan Wang, Andreia Cathelin, and Payam Heydari, "115-135 GHz 8PSK Receiver Using Multi-Phase RF-Correlation-Based Direct-Demodulation Method," *IEEE J. Solid-State Circuits*, vol. 54, no. 9, pp. 2435 – 2448, Sept. 2019



IEEE JOURNAL OF SOLID-STATE CIRCUITS 1

A CMOS Two-Element 170-GHz Fundamental-Frequency Transmitter With Direct RF-8PSK Modulation

Peyman Nazari, *Member, IEEE*, Saman Jafarlou, *Student Member, IEEE*, and Payam Heydari, *Fellow, IEEE*

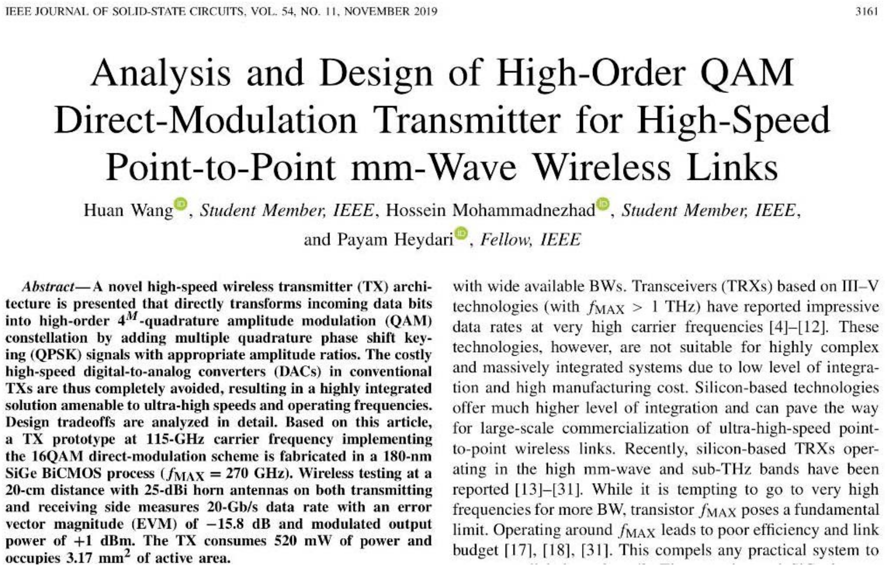
***Abstract*—A CMOS 170-GHz fundamental-frequency transmitter (TX) realizing the 8PSK modulation scheme directly in the RF domain is presented. The use of direct RF modulation obviates the need for high-resolution high-speed mixed-signal blocks. The proposed architecture extends the conventional quadrature modulation by performing additional phase modulation on I and Q components of the LO signal, which helps increase modulation order. The TX employs high-speed switchable phase shifters to achieve LO phase modulation and fundamental-frequency over-neutralized power amplifiers to drive an integrated two-element tapered dipole antenna array. Fabricated in a 65-nm CMOS process ($f_T/f_{\max} = 230/260$ GHz), the RF-8PSK TX prototype occupies 3.2×2.8 mm^2 of die area. The free-space wireless measurement of the TX over a 10-cm link range yields 15 Gb/s data rate at an error vector magnitude (EVM) of −14.8 dB. The TX achieves an EIRP of 4 dBm while consuming 560-mW power.**

***Index Terms*—8PSK, CMOS, mixer, mm-wave, neutralization, on-chip antenna, phase modulation, power amplifier, switchable phase shifter (SPS), transmitter (TX).**

communication links for data rates in excess of more than 10 Gb/s [2], [3].

Advanced compound III–V technologies with $f_{\max}$ exceeding 1 THz may naturally be positioned to be the candidate of choice for ultra-high data rates at very high carrier frequencies [4]–[13]. Nevertheless, future high data-rate mm-wave wireless applications mandating the massive amount of performance improving digitally assisted analog/RF signal processing, silicon platforms (e.g., CMOS or SiGe BiCMOS) with a high level of integration would be of high interest. Recently, silicon-based TRX front ends operating in the high mm-wave and sub-THz frequency bands have been reported [5]–[13], [15]–[22].

The availability of wide BW within the high-mmWave frequency range seems to partially address a challenging requirement associated with "conventional" wireless links, that is, the need for very complex modulation schemes (e.g., 1024QAM [23], [24]) at lower RF frequencies (i.e., ≤10 GHz)



IEEE JOURNAL OF SOLID-STATE CIRCUITS, VOL. 54, NO. 11, NOVEMBER 2019 3161

Analysis and Design of High-Order QAM Direct-Modulation Transmitter for High-Speed Point-to-Point mm-Wave Wireless Links

Huan Wang, *Student Member, IEEE*, Hossein Mohammadnezhad, *Student Member, IEEE*,
and Payam Heydari, *Fellow, IEEE*

***Abstract*—A novel high-speed wireless transmitter (TX) architecture is presented that directly transforms incoming data bits into high-order 4^M-quadrature amplitude modulation (QAM) constellation by adding multiple quadrature phase shift keying (QPSK) signals with appropriate amplitude ratios. The costly high-speed digital-to-analog converters (DACs) in conventional TXs are thus completely avoided, resulting in a highly integrated solution amenable to ultra-high speeds and operating frequencies. Design tradeoffs are analyzed in detail. Based on this article, a TX prototype at 115-GHz carrier frequency implementing the 16QAM direct-modulation scheme is fabricated in a 180-nm SiGe BiCMOS process ($f_{\mathrm{MAX}} = 270$ GHz). Wireless testing at a 20-cm distance with 25-dBi horn antennas on both transmitting and receiving side measures 20-Gb/s data rate with an error vector magnitude (EVM) of −15.8 dB and modulated output power of +1 dBm. The TX consumes 520 mW of power and occupies 3.17 mm^2 of active area.**

with wide available BWs. Transceivers (TRXs) based on III–V technologies (with $f_{\mathrm{MAX}} > 1$ THz) have reported impressive data rates at very high carrier frequencies [4]–[12]. These technologies, however, are not suitable for highly complex and massively integrated systems due to low level of integration and high manufacturing cost. Silicon-based technologies offer much higher level of integration and can pave the way for large-scale commercialization of ultra-high-speed point-to-point wireless links. Recently, silicon-based TRXs operating in the high mm-wave and sub-THz bands have been reported [13]–[31]. While it is tempting to go to very high frequencies for more BW, transistor f_{MAX} poses a fundamental limit. Operating around f_{MAX} leads to poor efficiency and link budget [17], [18], [31]. This compels any practical system to

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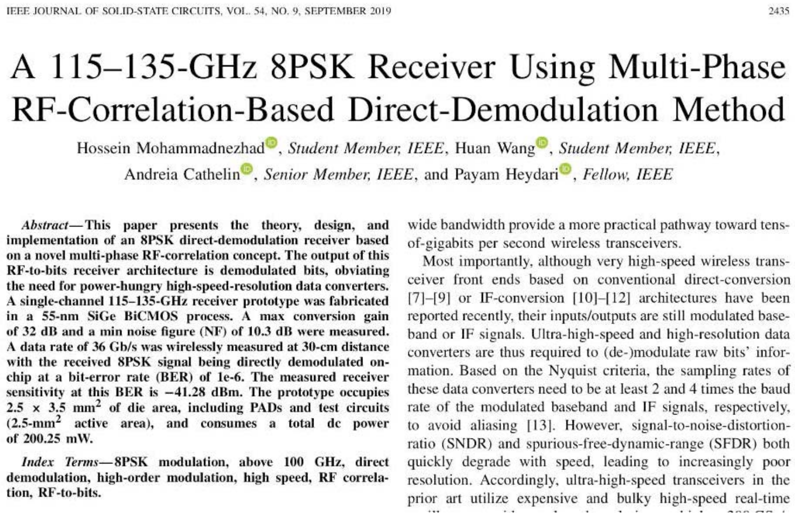


IEEE JOURNAL OF SOLID-STATE CIRCUITS, VOL. 54, NO. 9, SEPTEMBER 2019 2435

A 115–135-GHz 8PSK Receiver Using Multi-Phase RF-Correlation-Based Direct-Demodulation Method

Hossein Mohammadnezhad, *Student Member, IEEE*, Huan Wang, *Student Member, IEEE*,
Andreia Cathelin, *Senior Member, IEEE*, and Payam Heydari, *Fellow, IEEE*

***Abstract*—This paper presents the theory, design, and implementation of an 8PSK direct-demodulation receiver based on a novel multi-phase RF-correlation concept. The output of this RF-to-bits receiver architecture is demodulated bits, obviating the need for power-hungry high-speed-resolution data converters. A single-channel 115–135-GHz receiver prototype was fabricated in a 55-nm SiGe BiCMOS process. A max conversion gain of 32 dB and a min noise figure (NF) of 10.3 dB were measured. A data rate of 36 Gb/s was wirelessly measured at 30-cm distance with the received 8PSK signal being directly demodulated on-chip at a bit-error rate (BER) of 1e-6. The measured receiver sensitivity at this BER is −41.28 dBm. The prototype occupies 2.5×3.5 mm^2 of die area, including PADs and test circuits (2.5-mm^2 active area), and consumes a total dc power of 200.25 mW.**

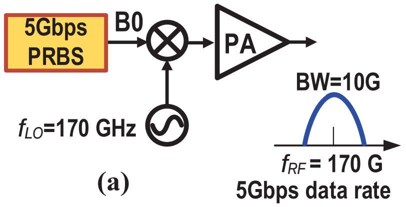
***Index Terms*—8PSK modulation, above 100 GHz, direct demodulation, high-order modulation, high speed, RF correlation, RF-to-bits.**

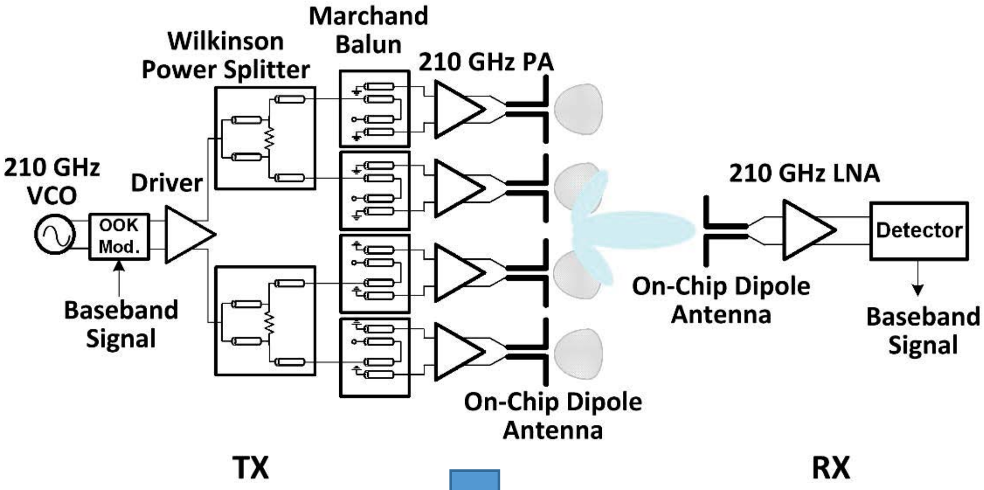
wide bandwidth provide a more practical pathway toward tens-of-gigabits per second wireless transceivers.

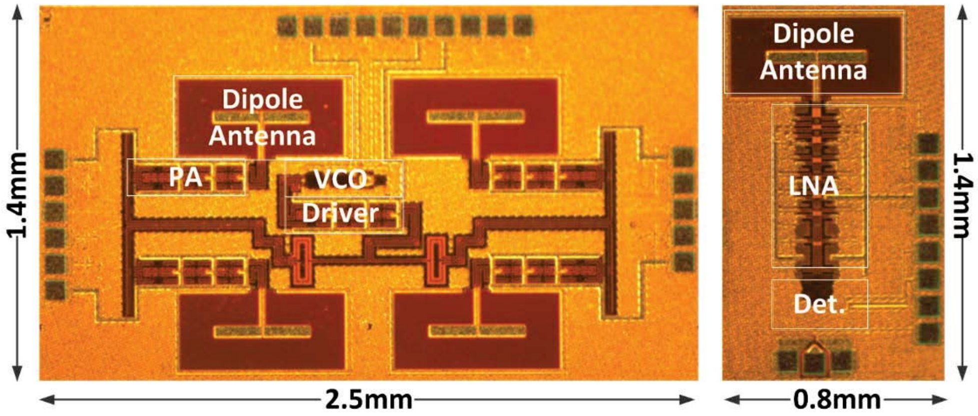
Most importantly, although very high-speed wireless transceiver front ends based on conventional direct-conversion [7]–[9] or IF-conversion [10]–[12] architectures have been reported recently, their inputs/outputs are still modulated baseband or IF signals. Ultra-high-speed and high-resolution data converters are thus required to (de-)modulate raw bits' information. Based on the Nyquist criteria, the sampling rates of these data converters need to be at least 2 and 4 times the baud rate of the modulated baseband and IF signals, respectively, to avoid aliasing [13]. However, signal-to-noise-distortion-ratio (SNDR) and spurious-free-dynamic-range (SFDR) both quickly degrade with speed, leading to increasingly poor resolution. Accordingly, ultra-high-speed transceivers in the prior art utilize expensive and bulky high-speed real-time

Conventional Direct Modulation

OOK







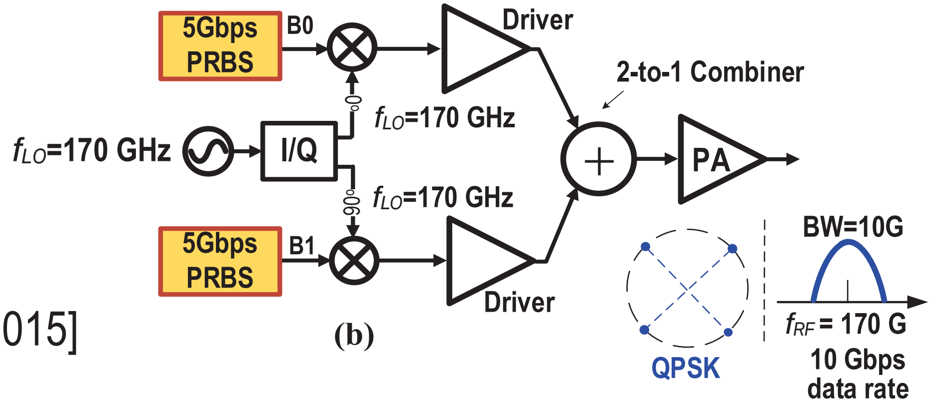
[Wang - ISSCC 2013] and [Wang - JSSC2014]

	[1]	[2]	[3]	[4]	This work
Proc.	32nm SOI CMOS	45nm SOI CMOS	0.13μm BiCMOS	65nm CMOS	32nm SOI CMOS
Freq.	291GHz	280GHz	380GHz	260GHz	210GHz
Topology	2×2 DAR	4×4 DAR	Quadruple r-based TRX	2×2 Quadruple r-based TRX	2×2 Fundamental TRX
Mod.	None	None	FMCW	OOK	OOK
EIRP [dBm]	-1	9	-13	5	5.13 (15.2 @ P_{sat})
P_{DCTX} [mW]	74.8	817	182	688	240
EIRP/P_{DCTX}	1.1%	1%	0.028%	0.46%	1.4% (>6.9%@P_{sat})
Area [mm^2]	0.64	7.29	4.18	6	3.5 (TX) + 1.12 (RX)

Z. Wang *et al.*, "A CMOS 210GHz fundamental transceiver with OOK modulation," *IEEE J. Solid-State Circuits*, vol. 49, no. 3, pp. 564-580, March 2014.

Conventional Direct Modulation

QPSK



[Kang - JSSC 2015]

- **Using quadrature down- and up-conversion to perform QPSK (de-)modulation**
  - Inject BB PRBS data streams to an I/Q mixer with quadrature LO

Conclusion

- **Current ADC-less receivers**
  - ☹ **Only limited to basic modulations (OOK, QPSK)**
  - ☹ **For ultra-high-speed require very high center frequency and BW**

Examples of Higher-Order Direct (De-)Modulation in RF/Analog Domain

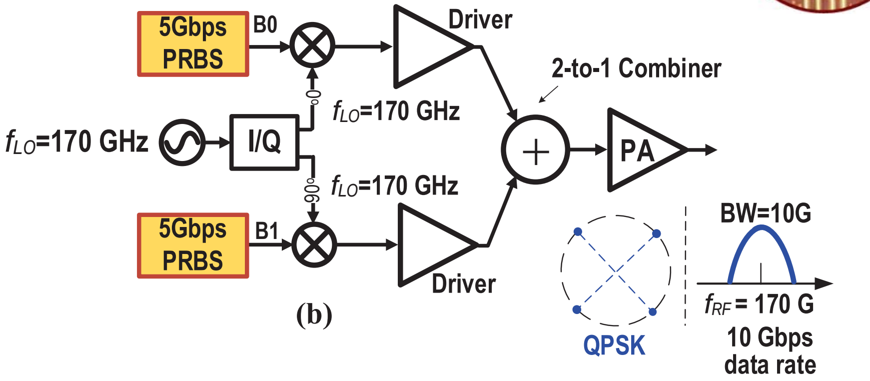
Case Study 1

mm-Wave Bits-to-RF RF-8PSK Transmitter in CMOS

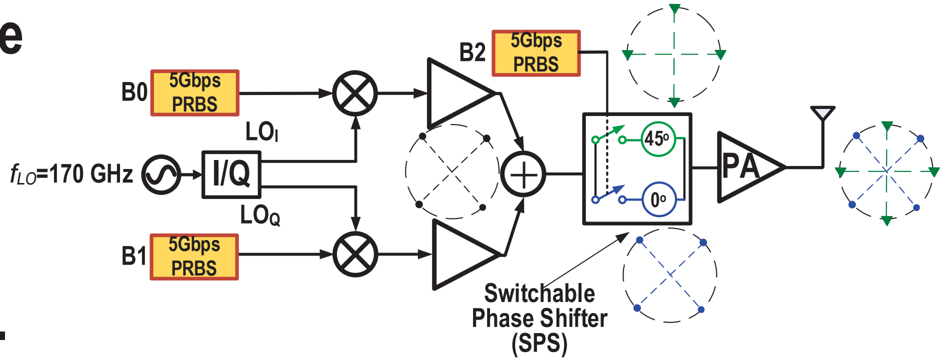
- Peyman Nazari, Saman Jafarlou, and Payam Heydari, " A CMOS Two-Element 170-GHz Fundamental-Frequency Transmitter with Direct RF-8PSK Modulation," to appear in *IEEE Journal of Solid-State Circuits*, vol. 55, 2020

Proposed RF-8PSK Modulation

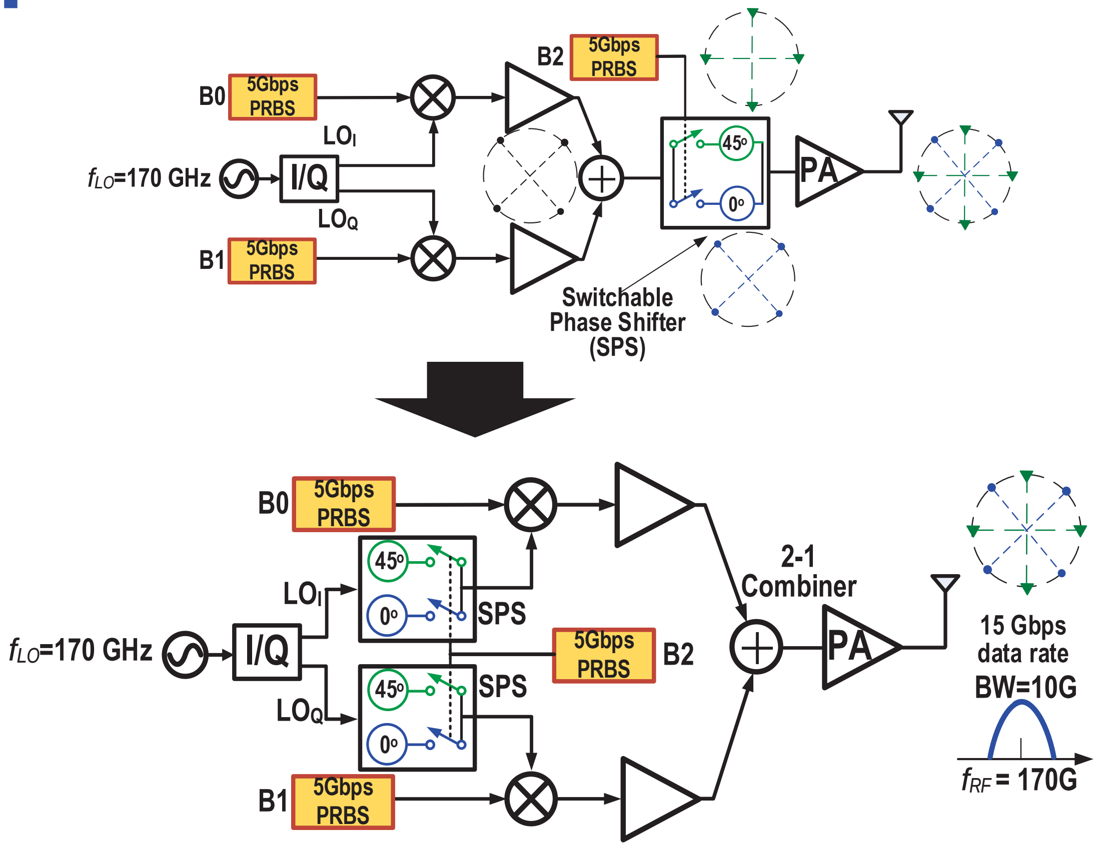
- **Starting with RF-QPSK TX architecture [Prior Work]**
  - Inject BB PRBS data streams to an I/Q mixer with quadrature LO



- **Add another level of modulation in the phase-domain to QPSK modulator's output**
- **Create two versions of QPSK constellation, itself and its 45° phase-rotated version, depending on the status of a 3rd input bit**

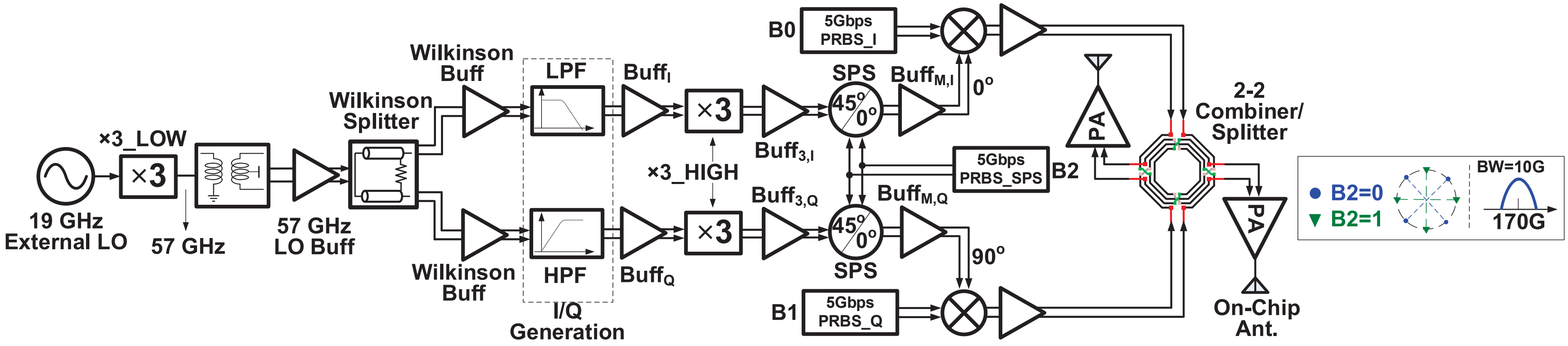


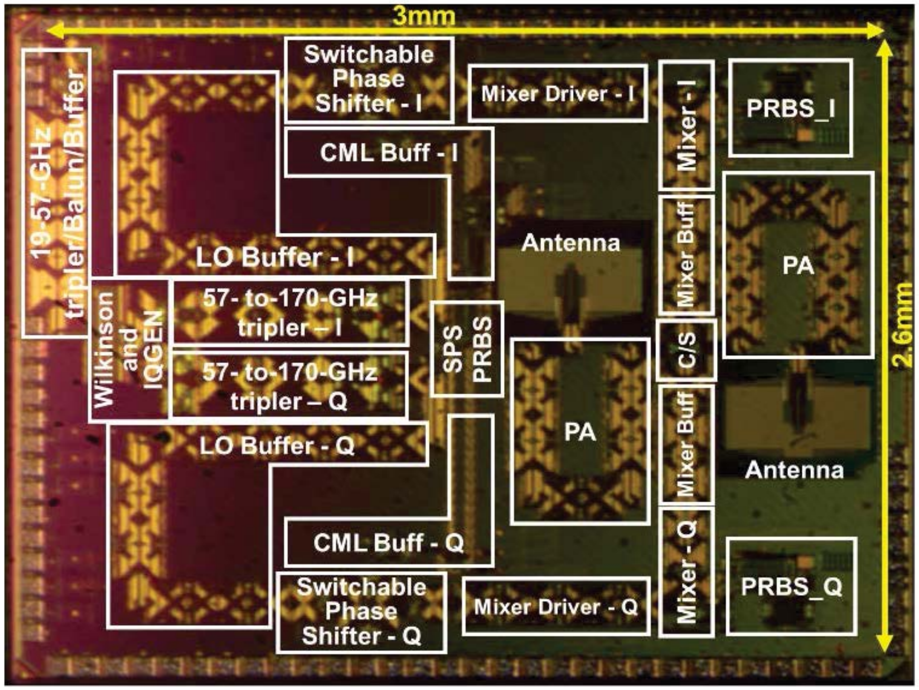
Proposed RF-8PSK Modulation



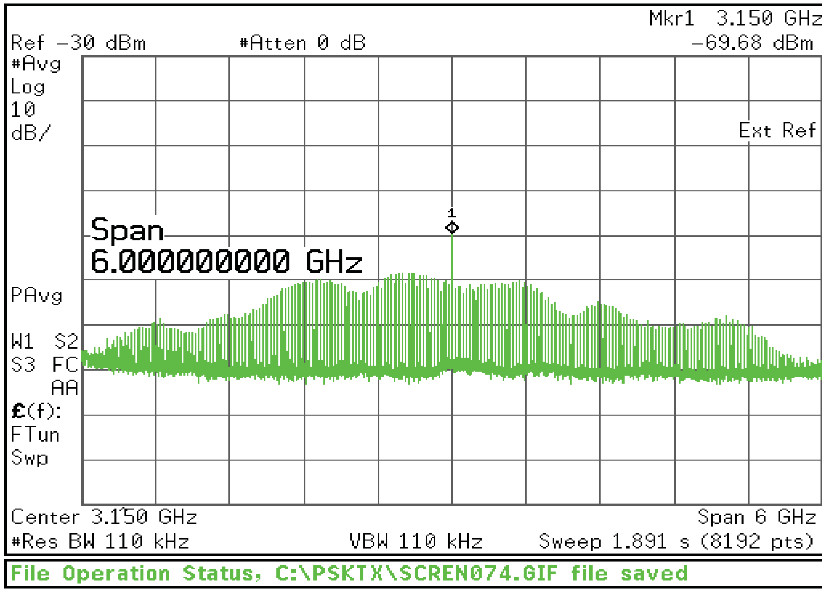
- To avoid the use of wide-band RF phase-shifters at 170 GHz, this additional phase-modulation can be moved to the LO path (before I/Q mixers)
- The phase of both I and Q signals are altered using two switchable phase-shifters (SPSs)

RF-8PSK TX in CMOS





Measurement Results



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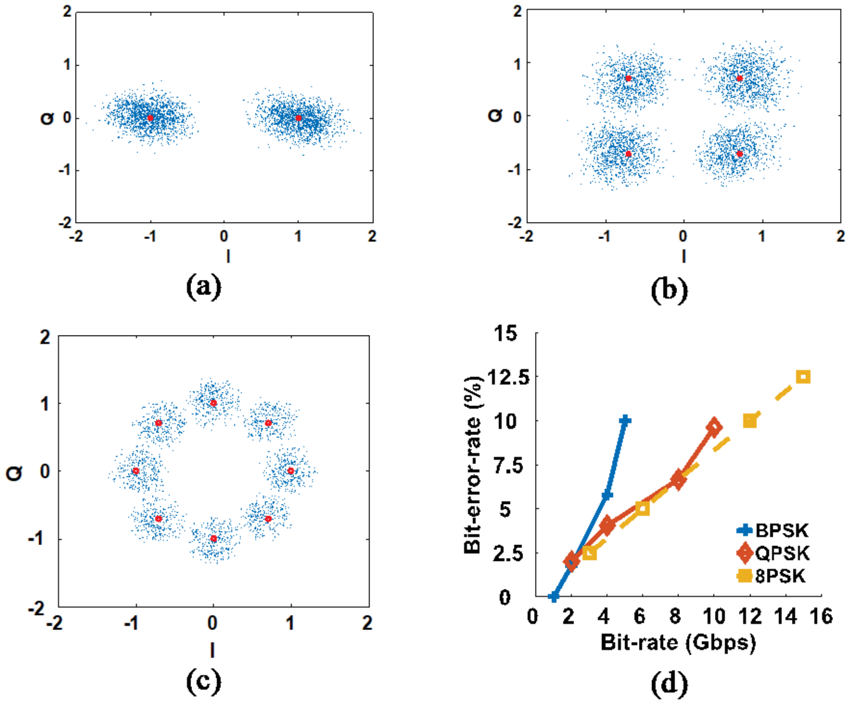
Spectrum measurement of TX output signal at 3GSymbol/s



Measured constellations for (a) BPSK (5Gbps), (b) QPSK (10Gbps), (c) 8PSK (15Gbps). (d) Measured bit-error-rate vs. bit-rate for BPSK, QPSK, 8PSK constellations

Examples of Higher-Order Direct (De-)Modulation in RF/Analog Domain

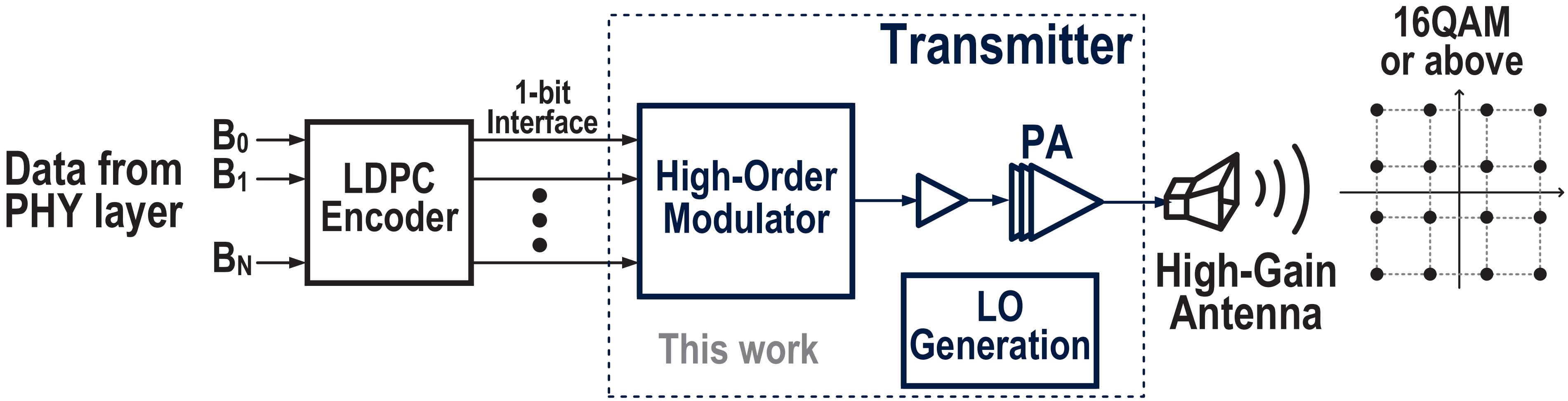
Case Study 2

mm-Wave Bits-to-RF High-Order QAM Transmitters Using 1-bit Digital-to-Analog Interface Enabling 20+ Gbps Data Rate

- H. Wang, H. Mohammadnezhad, and P. Heydari, "Analysis and Design of High-Order QAM Direct-Modulation Transmitter for High-Speed Point-to-Point mm-Wave Wireless Links," *IEEE Journal of Solid-State Circuits*, vol. 54, Nov. 2019
- H. Wang, H. Mohammadnezhad, D. Dimlioglu and P. Heydari, “A 100-120GHz 20Gbps Bits-to-RF 16QAM Transmitter Using 1-bit Digital-to-Analog Interface,” *IEEE Custom Integrated Circuits Conference (CICC)*, Austin, TX, 2019.

Desired System Architecture

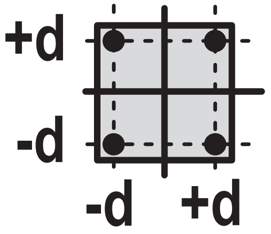
- **Direct Modulation with 1-bit Interface**
  - 1-bit data stream interface, no high-speed DACs
  - Increase modulation order beyond OOK, QPSK, etc



Core Idea

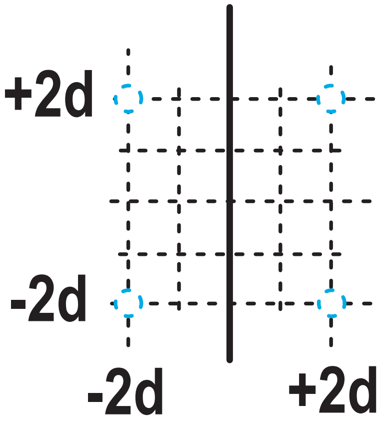
From QPSK to 16QAM

- **Combining QPSK to Form 16QAM**
  - QPSK2 defines center in each quadrant of 16QAM
  - QPSK1 adds on top to form 16QAM symbols
  - Only constant envelope signals + linear combiner



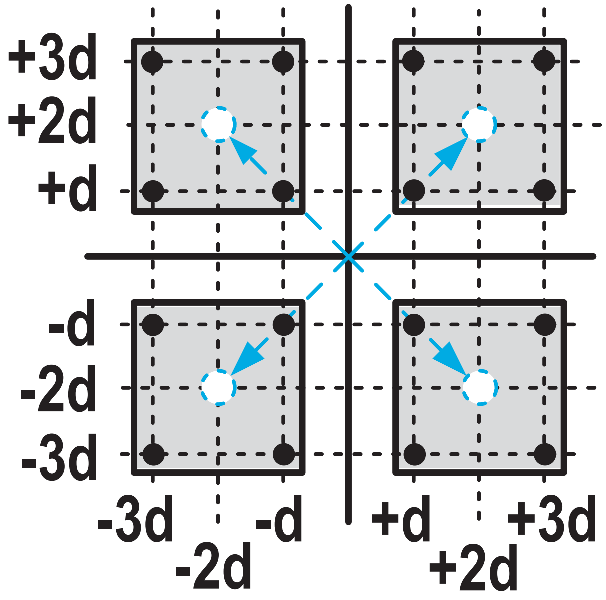
QPSK1
(Spacing = 2d)
EVM_1

$+$



QPSK2
(Spacing = 4d)
EVM_2

$=$



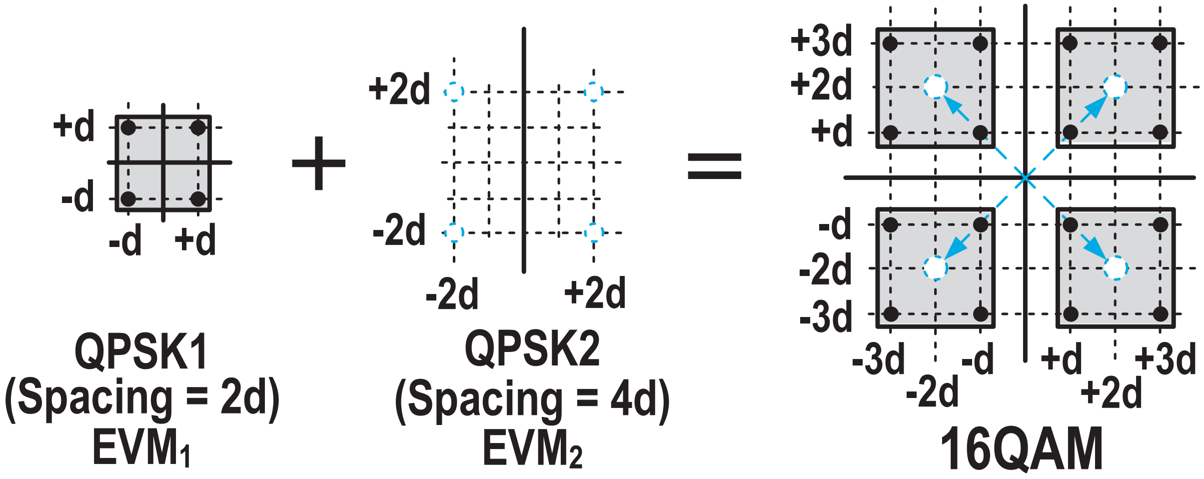
16QAM

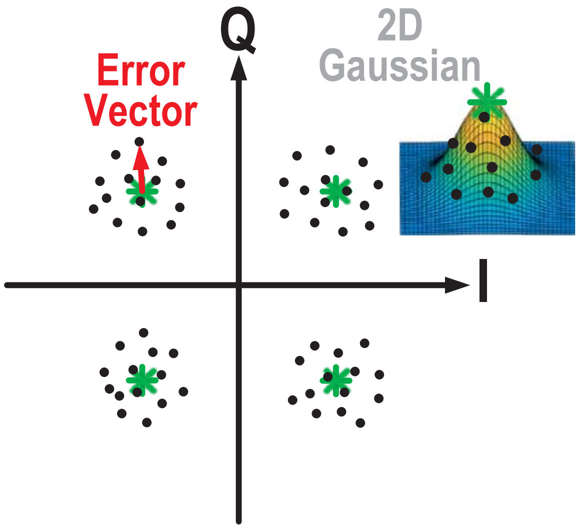
Core Idea

From QPSK to 16QAM (cont'd)

- **Combining QPSK to Form 16QAM**
  - Error vectors in QPSK1 and QPSK2 random, independent
  - 16QAM EVM ≈ QPSK EVM
  - Low EVM QPSK much easier

$$EVM_{16QAM} = \sqrt{\frac{EVM_1^2 + 4EVM_2^2}{5}}$$

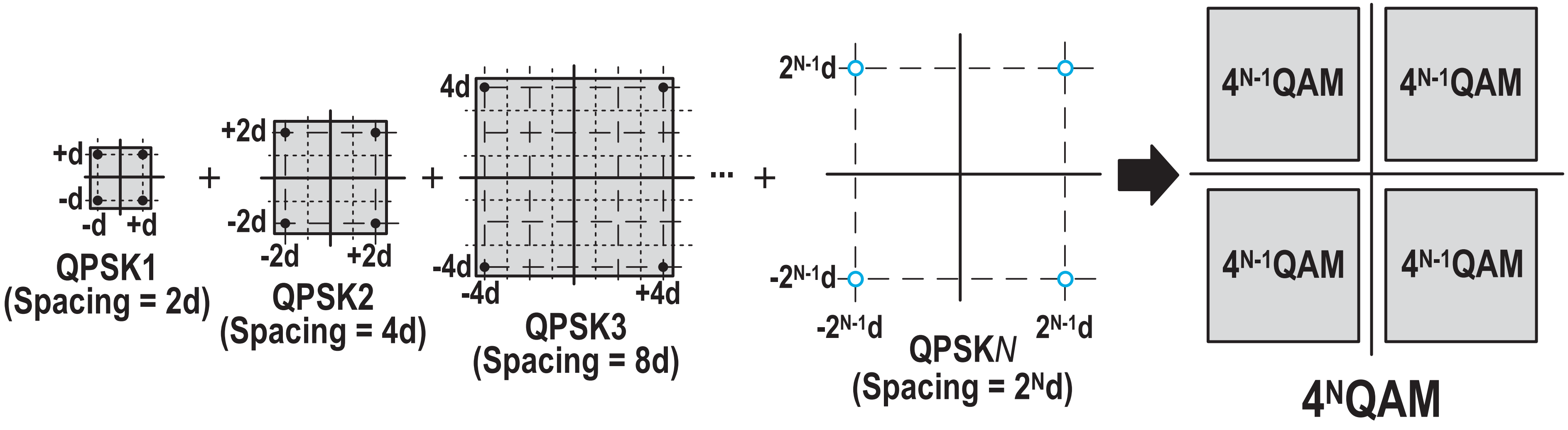




Extension of Core Idea

From QPSK to 4^N-QAM

- **Extend to Higher Order Modulation Easily**
  - 3 or 4 QPSK combining leads to 64QAM or 256QAM
  - LO I/Q mismatch and phase noise become bottleneck
  - Burden on D/A interface greatly relaxed



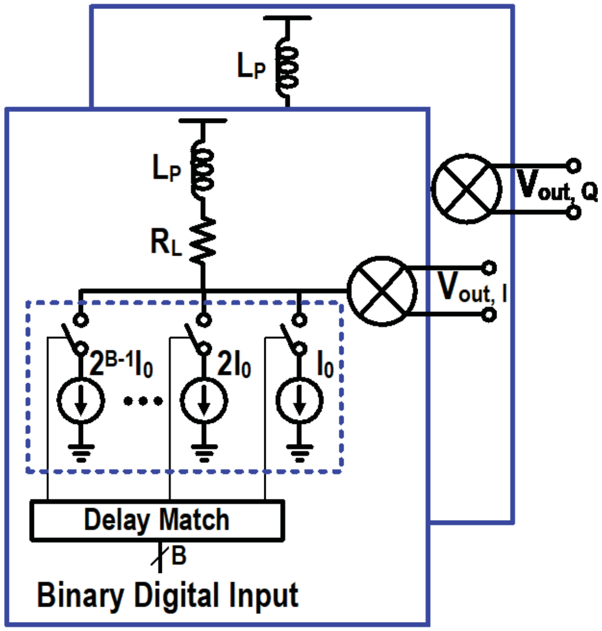
Example: Direct Modulation 16QAM Technique

- **Generation of high-order QAM modulations**
  - ☹ High-speed well-matched switches (THD degrades with parasitics)
  - ☹ High-speed precise timing control
  - ☺ DC bias tuning instead of high-speed RF switching

☹ **Conventional**

RF switching

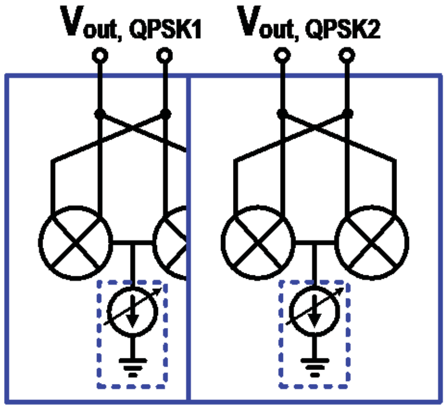
Multi-bit DAC



☺ **Proposed**

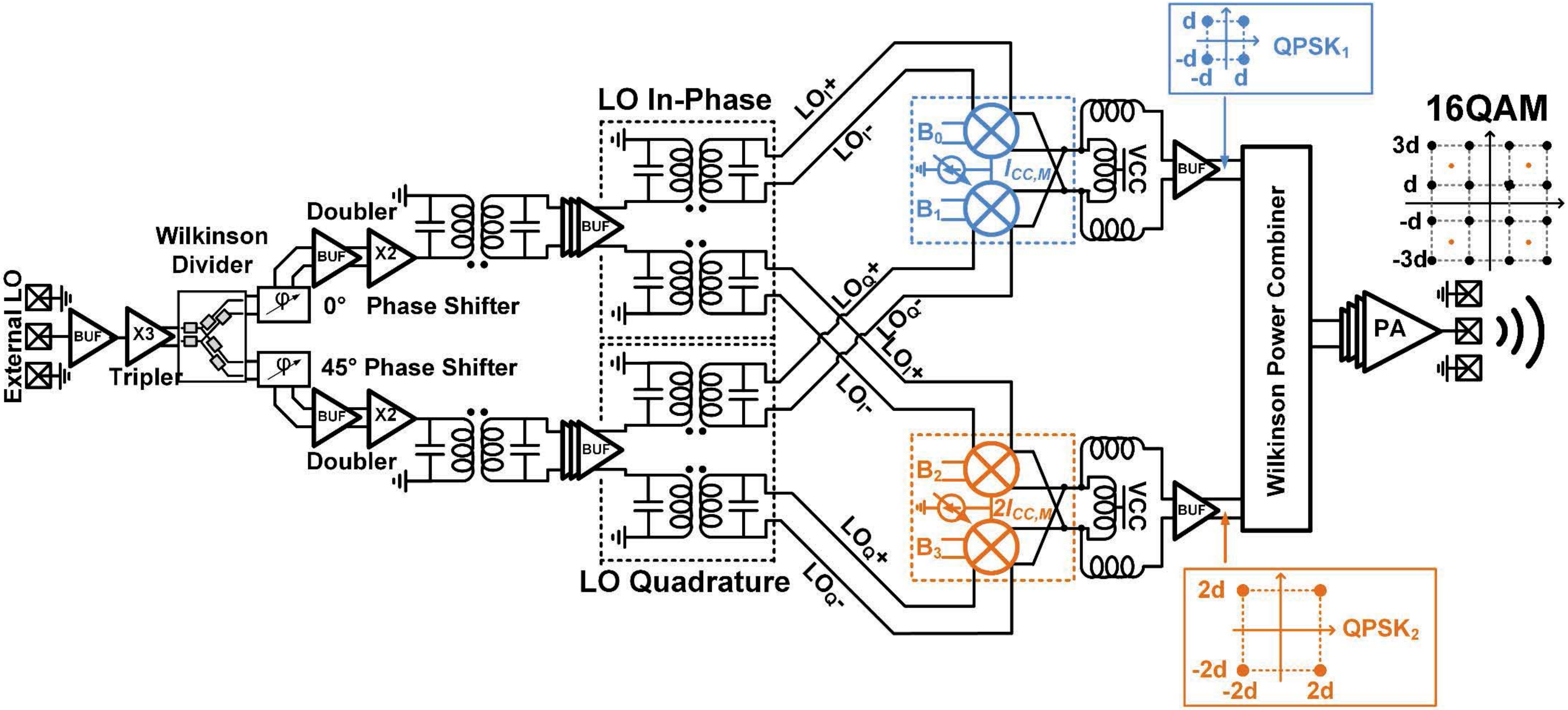
DC tuning

1bit DAC

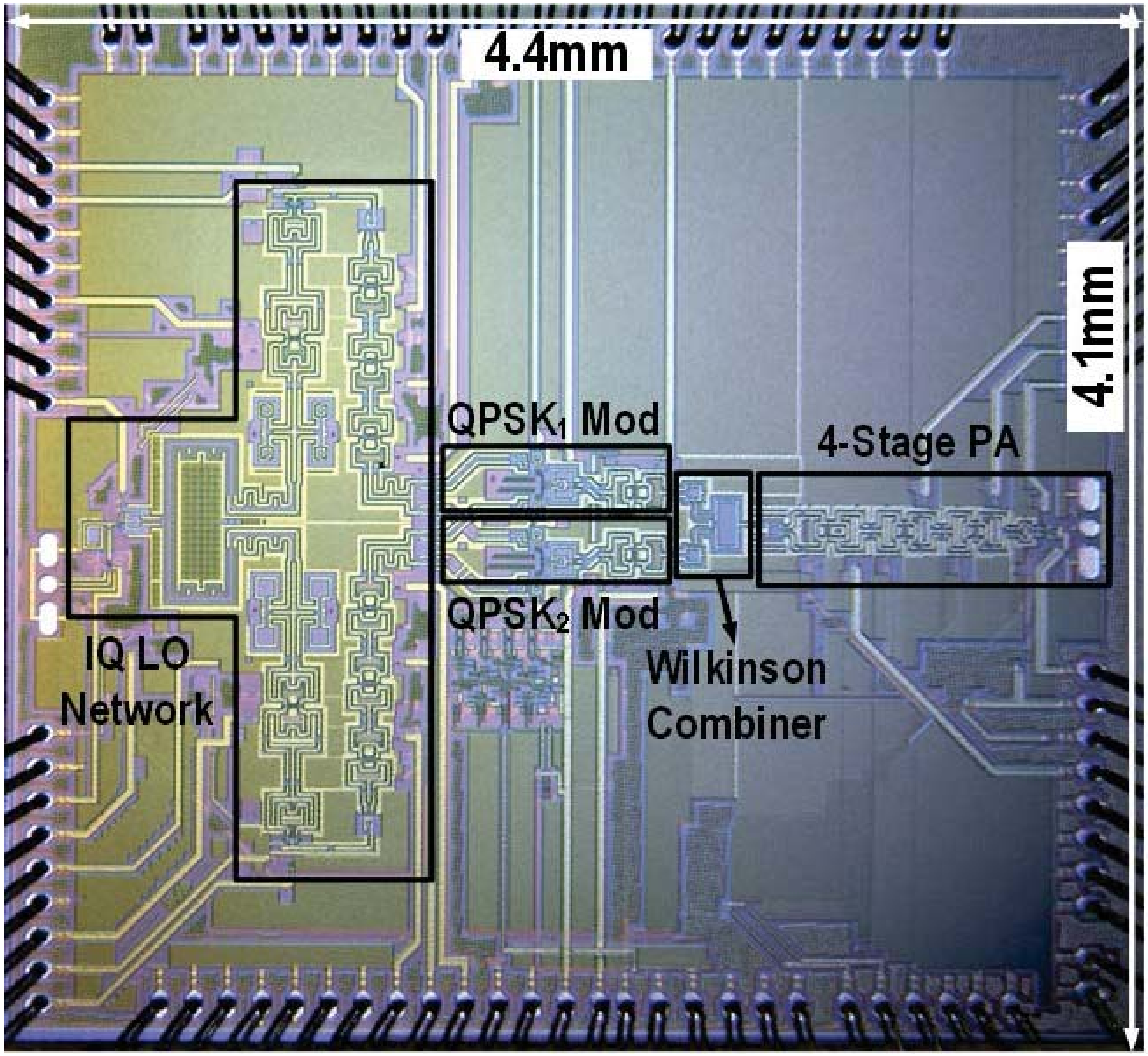


TX Architecture for 16QAM

- LO multiplier chain + I/Q Generation
- QPSK modulator with tunable amplitude
- Linear combiner

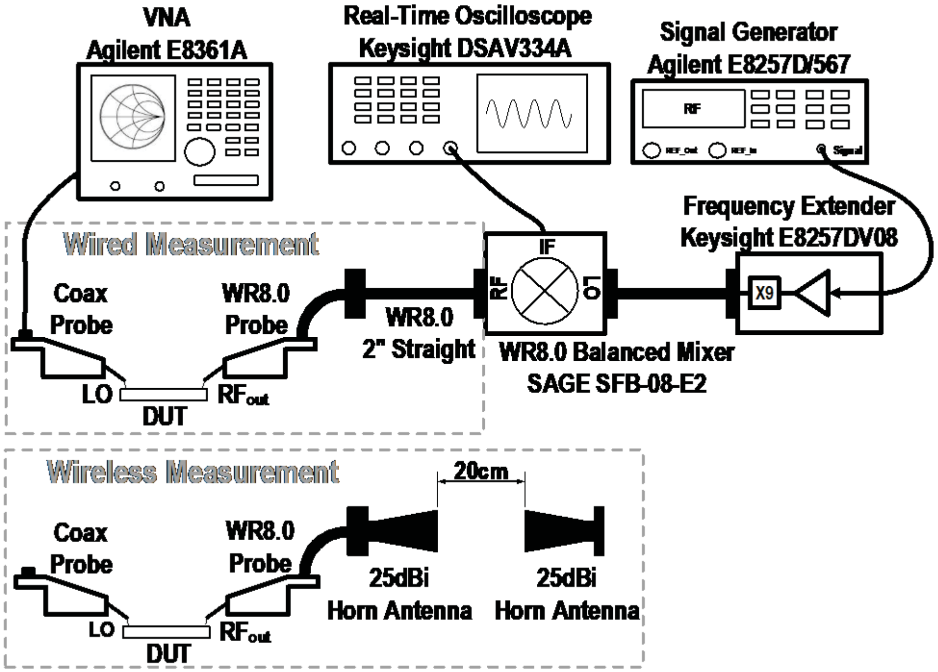


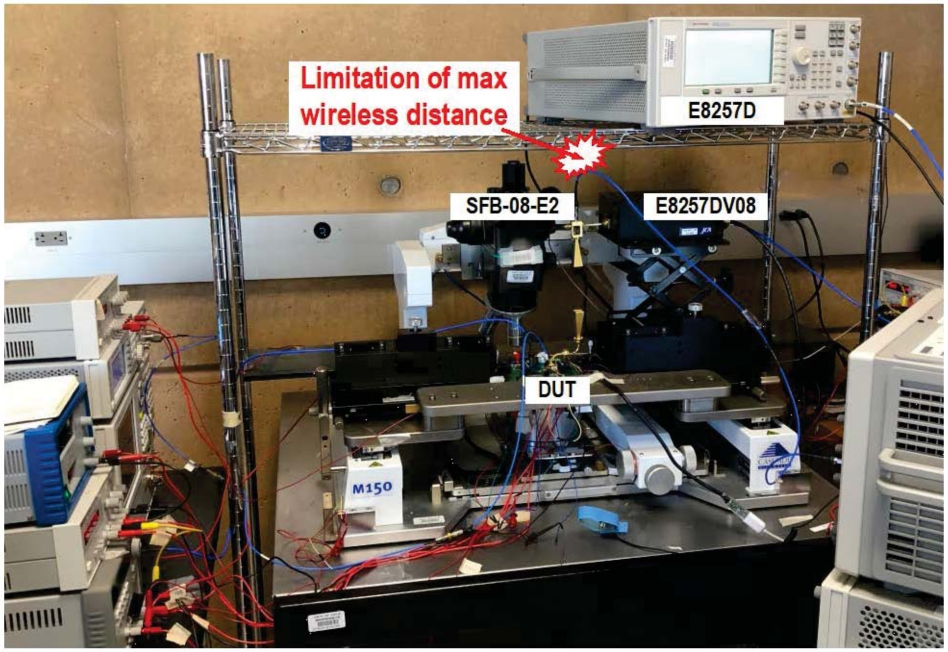
Chip Micrograph



- 180nm SiGe BiCMOS f_{MAX} ~ 270GHz; 3.17mm^2 active area- On-chip PRBS
- Wafer probe mm-Wave I/O

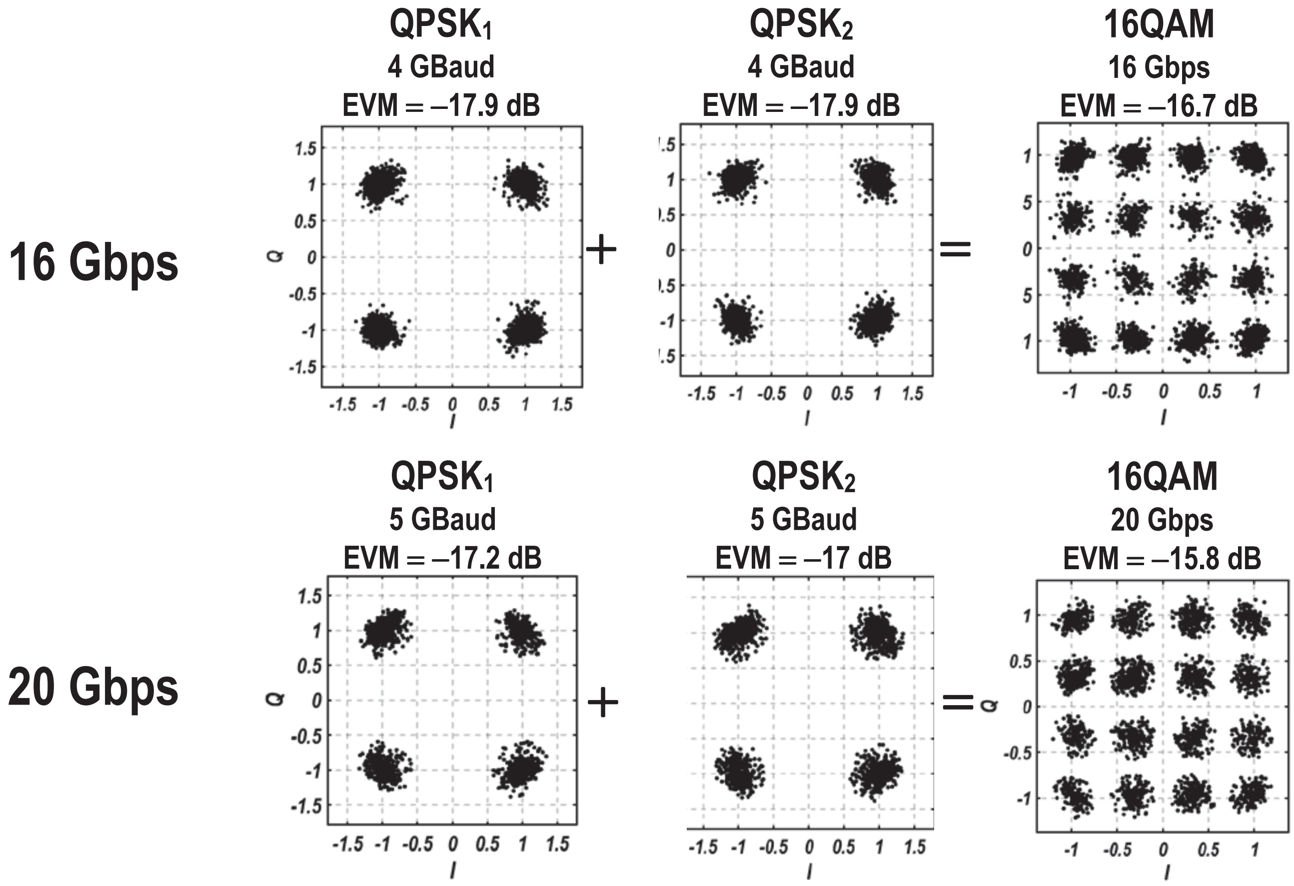
Wireless Measurement Setup





Limitation of max wireless distance

Modulation Measurements



16 Gbps

QPSK$_1$
4 GBaud
EVM = –17.9 dB

QPSK$_2$
4 GBaud
EVM = –17.9 dB

16QAM
16 Gbps
EVM = –16.7 dB

20 Gbps

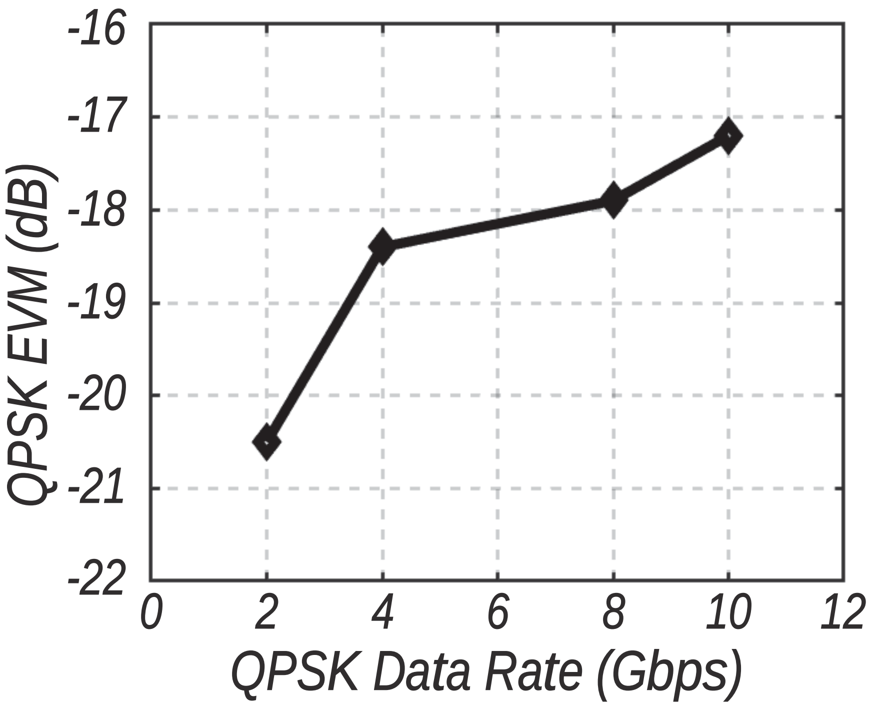
QPSK$_1$
5 GBaud
EVM = –17.2 dB

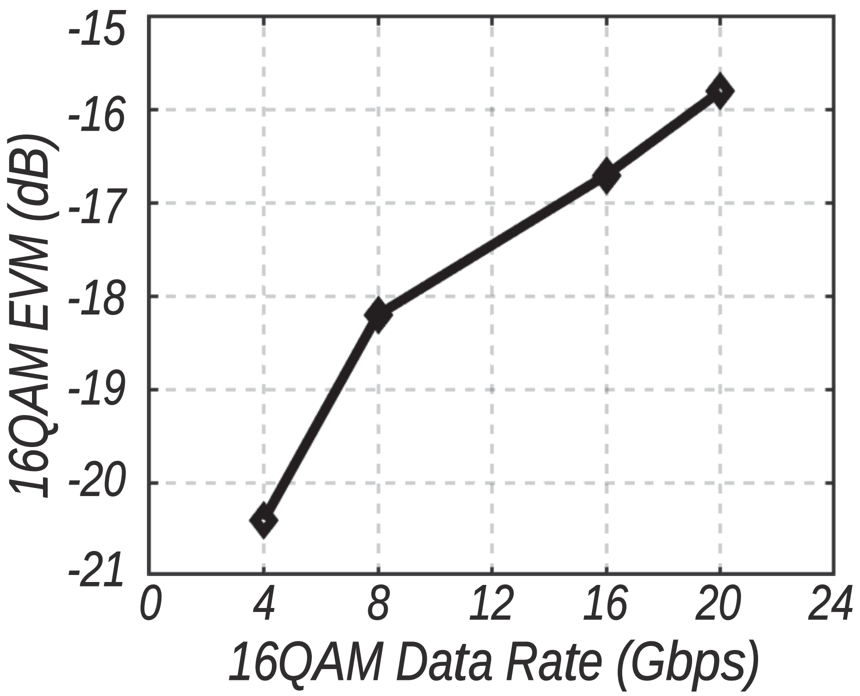
QPSK$_2$
5 GBaud
EVM = –17 dB

16QAM
20 Gbps
EVM = –15.8 dB

- **Wireless measurement of 16QAM direct-modulated signal at 20cm distance**
- **Less than 1.5 dB degradation in 16QAM EVM from sum of QPSKs**

EVM Measurement (cont'd)





- **Better gain and phase matching at lower data rates**
- **Lower EVM degradation from QPSK to 16QAM**

Performance Comparison

Reference	[1]	[2]	[3]	[4]	This Work
D/A Interface	External AWG	External AWG	External AWG	Integrated / Multi-bit digital in	Integrated / Raw bits in
Level of Integration	Mixer/ LO Chain	IQ IF/Mixer/PA/ LO Chain	IF/Mixer/PA/ LO Chain	RF-DAC/Antenna	LO Chain/Modulator/PA
Freq (GHz)	289-311	57-66	70-105	130-142	100-120
Modulation	32QAM	64QAM	16QAM	16QAM	16QAM
Single Channel Data Rate	105 Gb/s	21.12Gb/s	60 Gb/s	7 Gb/s	20 Gb/s
$EVM_{rms,avg}$ (dB)	-21	-24.1	-16.9	-13.8	-15.8
Estimated BER	10^{-3}	10^{-3}	10^{-3}	10^{-2}	10^{-3}
Peak Pout (dBm)	-5.5	10.4	-1.9	13.2 (EIRP)	3
Power (mW)	1400	544	120	1255	520
Tech	40nm CMOS	65nm CMOS	65nm CMOS	45nm CMOS SOI	180nm SiGe BiCMOS

Acknowledgements

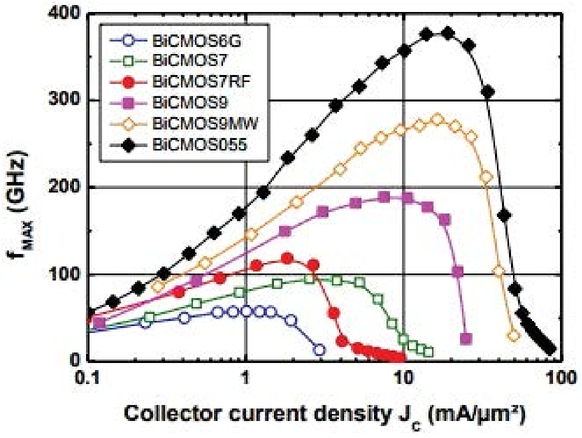
- NCIC Labs Ph.D. students especially Hossein Mohammadnezhad and Huan Wang
- National Science Foundation
- Samsung Advanced Institute of Technology
- Keysight Technologies, especially, Dave Hu and Neema Shafigh
- STMicroelectronics and TowerJazz Semiconductors for Chip Fabrications

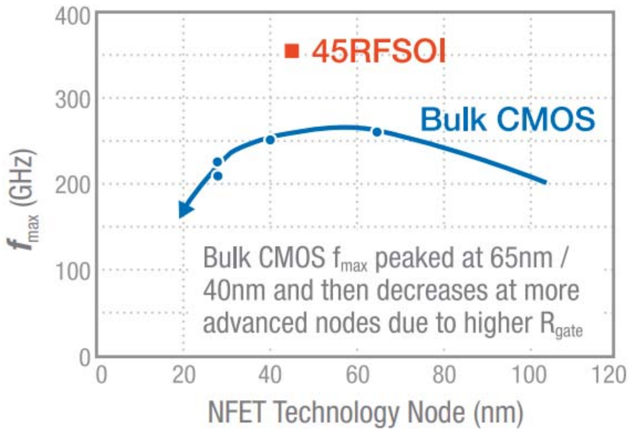
Backup Slides

Justification for Silicon Implementation

Bandwidth – Active Device Technologies

- Si-based technologies offer high level system integration with low cost
- Device speed sufficient for operation in 100-200GHz band
- Best Commercially available SiGe processes:
  - STMicroelectronics 55nm SiGe BiCMOS[24]: 320/370GHz f_T/f_{max}
  - GlobalFoundries 90nm SiGe BiCMOS[23]: 310/370GHz f_T/f_{max}
- Best Commercially available CMOS processes:
  - STMicroelectronics 28nm FDSOI[28]: 275/250GHz f_T/f_{max}
  - GlobalFoundries 45nm RFSOI[29]: 305/355GHz f_T/f_{max}





Bulk CMOS f_{max} peaked at 65nm / 40nm and then decreases at more advanced nodes due to higher R_{gate}

Examples of Higher-Order Direct (De-)Modulation in RF/Analog Domain

Example 2

mm-Wave RF-to-Bits Multi-Phase RF-Correlation-Based Direct-Demodulation 8PSK Receiver

Ph.D. Researchers: Hossein Mohammadnezhad, Huan Wang

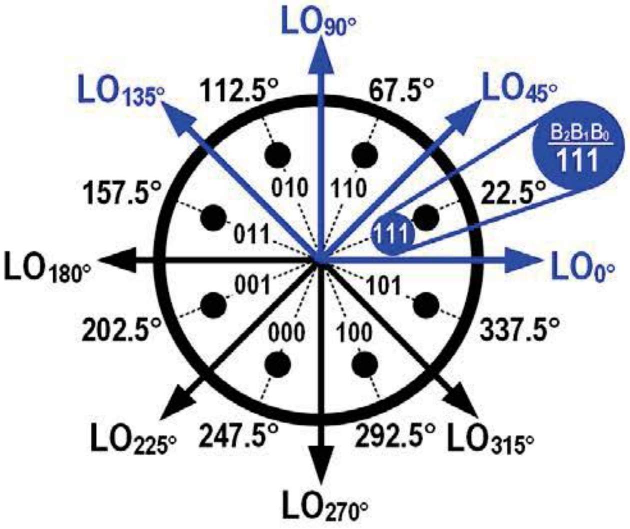
- H. Mohammadnezhad, H. Wang, A. Cathelin and P. Heydari, “A Single-Channel RF-to-Bits 36Gbps 8PSK RX with Direct Demodulation in RF Domain,” *IEEE Custom Integrated Circuits Conference (CICC)*, Austin, TX, 2019

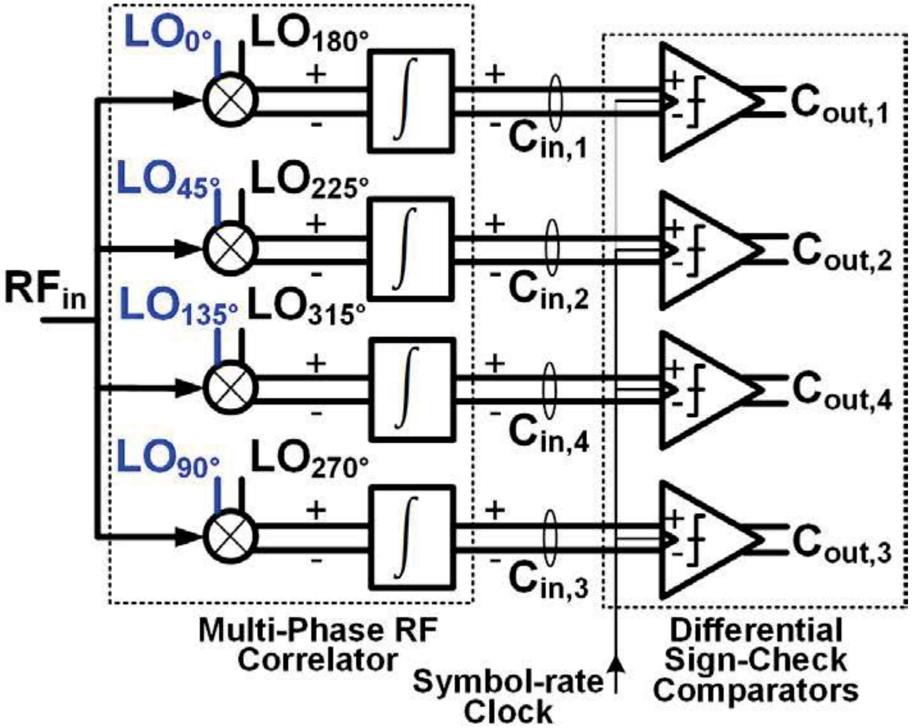
Proposed Direct Demodulation 8PSK Technique

☺ 8PSK modulation, high spectral-efficiency

☺ ADC-less multi-phase RF-correlation demodulation technique

- **22.5° phase offset:** between LO and RF
- **4 differential LO phases:** partition IQ signal space to 8 subsections
- **Simple sign-check comparators:** extract three demodulated bits

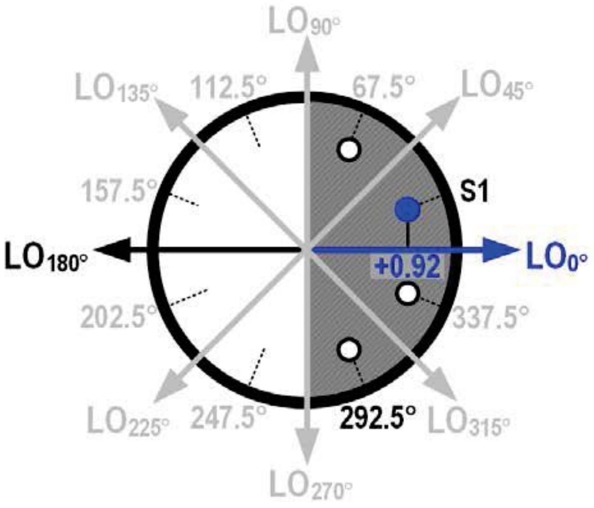




Multi-Phase RF-Correlation Demodulation

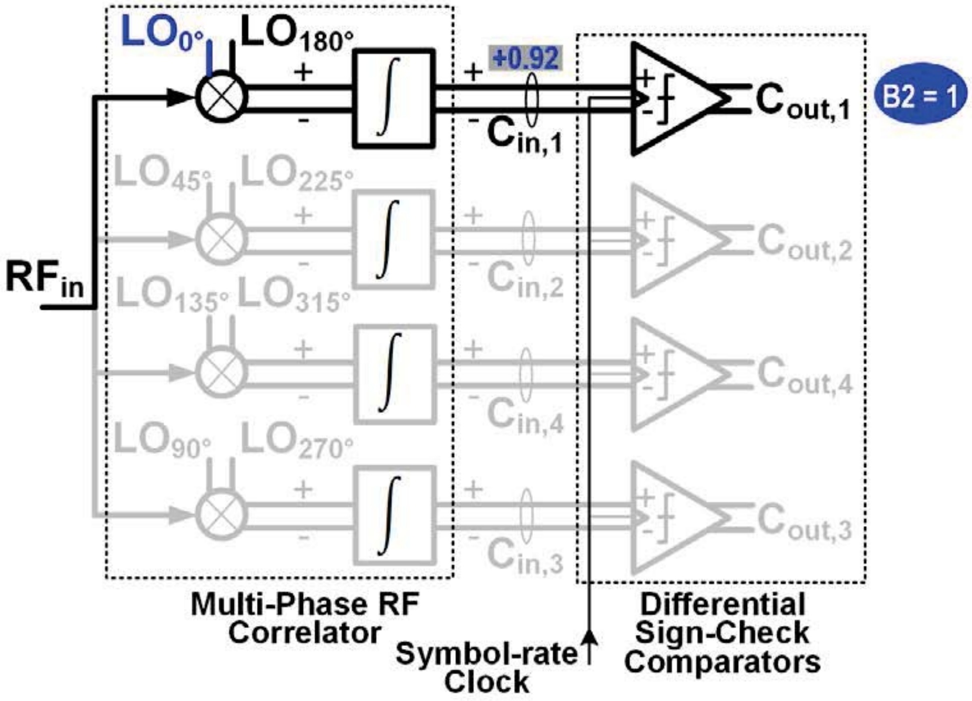
RF-correlation

($LO_{0°}$, $LO_{180°}$)



Bit B2

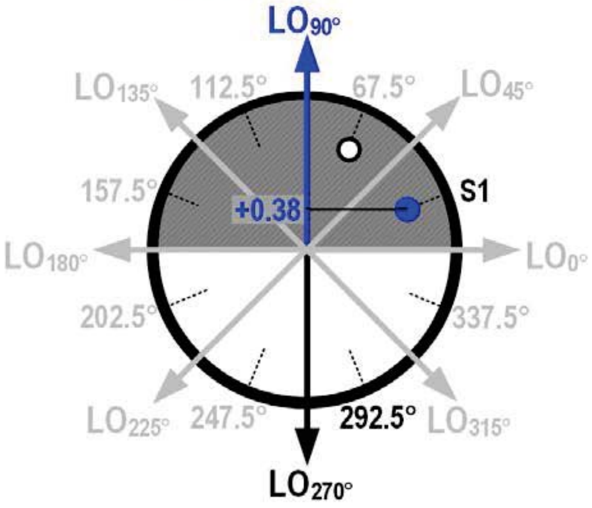
Right- or Left-Half Circle



Multi-Phase RF-Correlation Demodulation

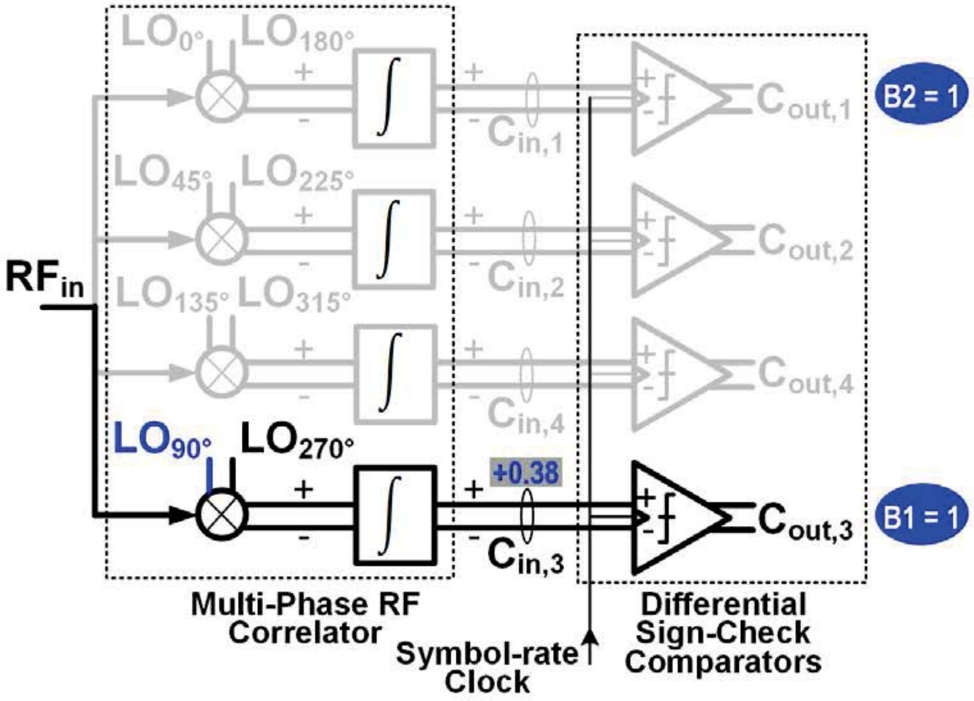
RF-correlation

($LO_{90°}$, $LO_{270°}$)



Bit B1

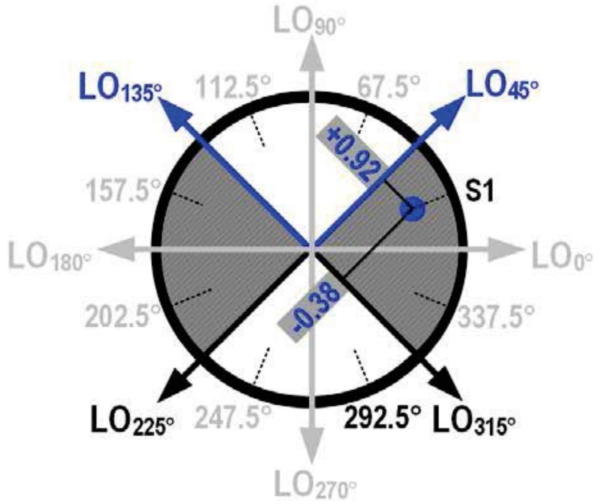
Top- or Bottom-Half Circle



Multi-Phase RF-Correlation Demodulation

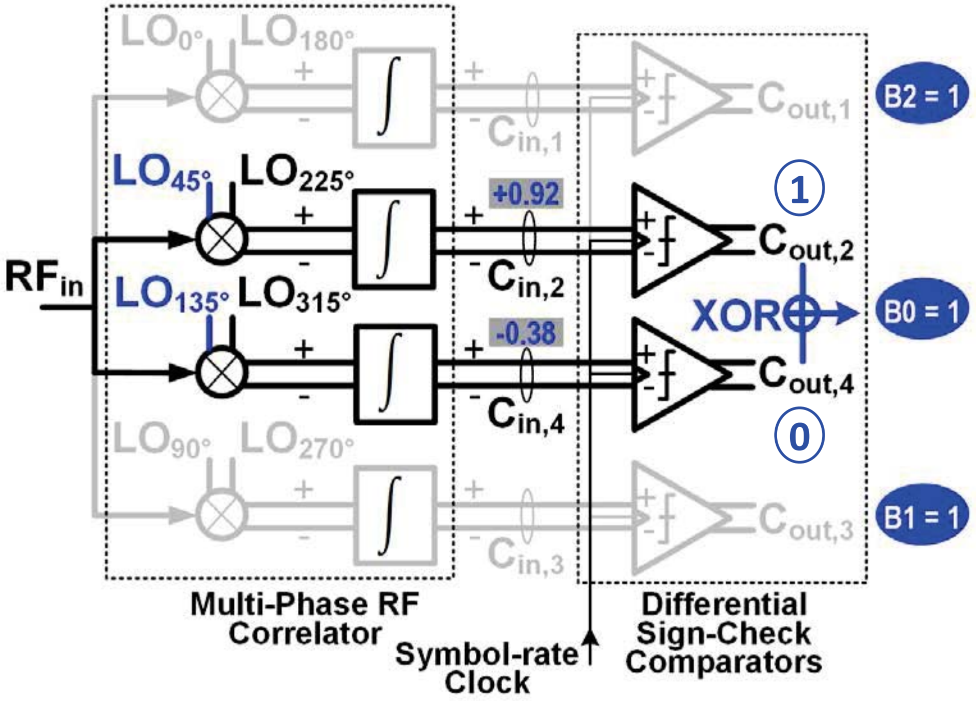
RF-correlation

$(LO_{45°}, LO_{225°})$ & $(LO_{135°}, LO_{315°})$



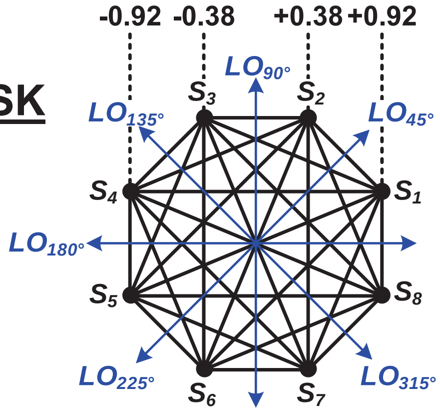
Bit B0

XOR Quadrants



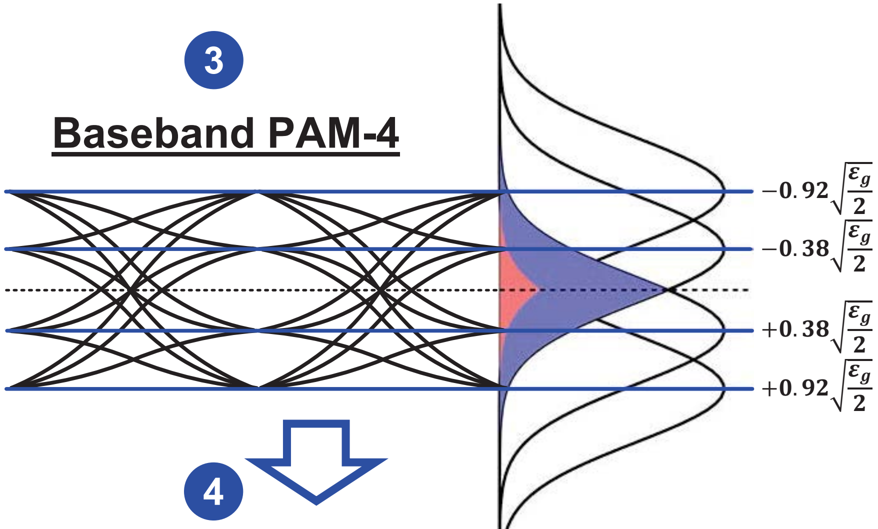
RF-Correlation Direct Demodulation: Flow-Chart

① **RF 8PSK**



② *Multi-phase RF-Correlation*

③ **Baseband PAM-4**



④ **Correlation Values**

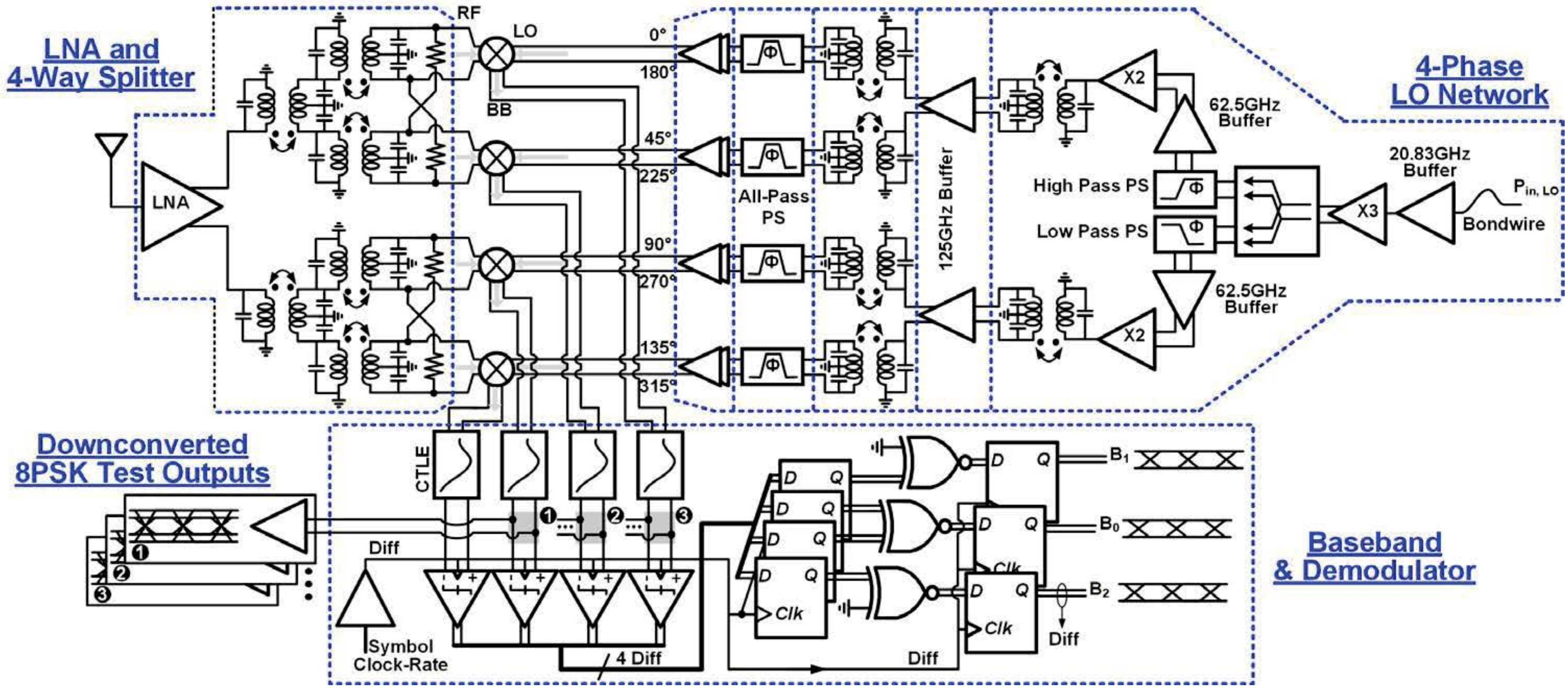
	S1	S2	S3	S4	S5	S6	S7	S8
LO 0°	+0.92	+0.38	-0.38	-0.92	-0.92	-0.38	+0.38	+0.92
LO 45°	+0.92	+0.92	+0.38	-0.38	-0.92	-0.92	-0.38	+0.38
LO 135°	-0.38	+0.38	+0.92	+0.92	+0.38	-0.38	-0.92	-0.92
LO 90°	+0.38	+0.92	+0.92	+0.38	-0.38	-0.92	-0.92	-0.38

⑤ *Simple BPSK Decisions*

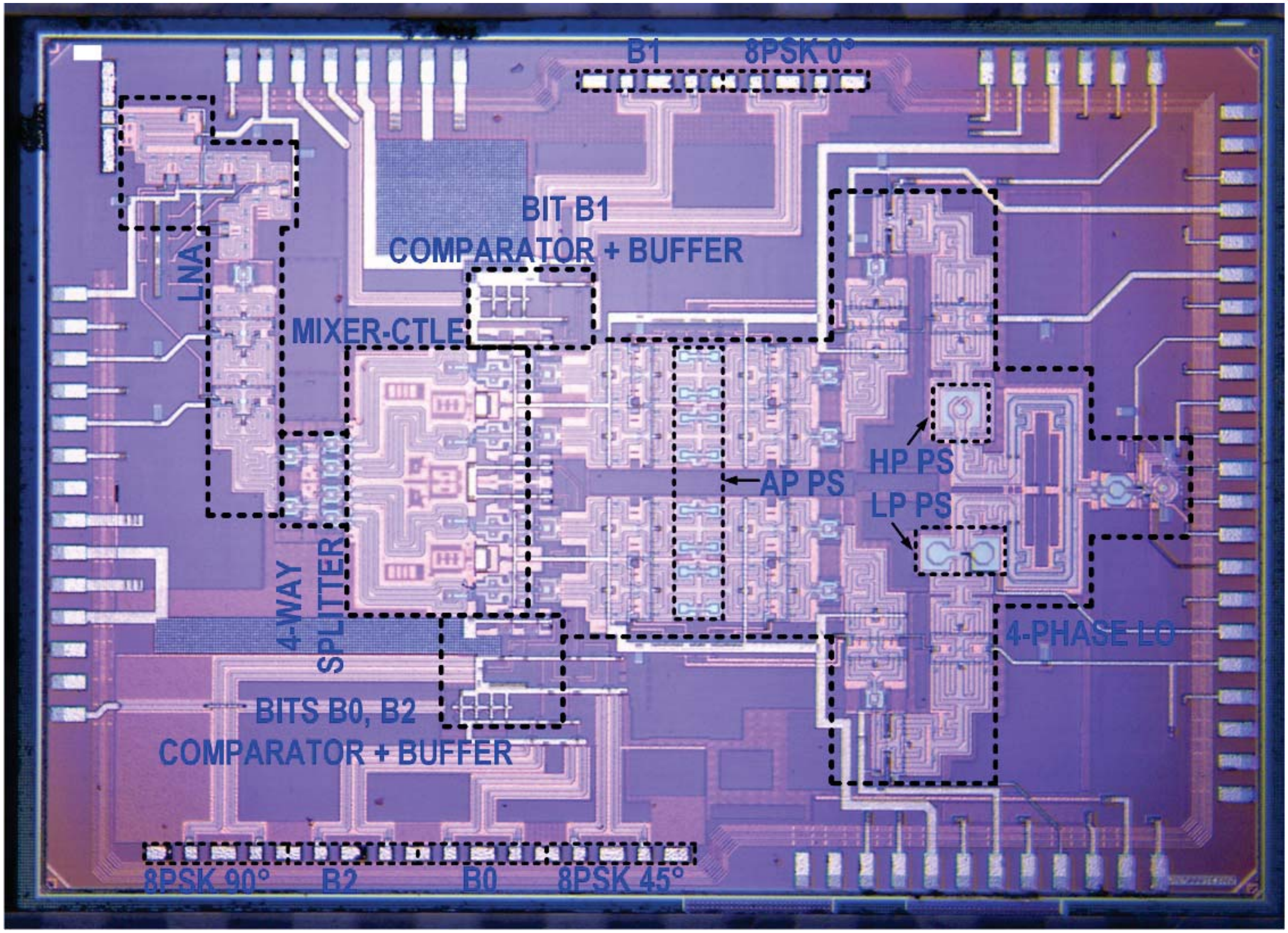
⑥ **Demodulated 3 Bits Per Symbol**

	S1	S2	S3	S4	S5	S6	S7	S8
B2	1	1	0	0	0	0	1	1
B0	1	0	0	1	1	0	0	2
B1	1	1	1	1	0	0	0	0

Proposed Direct Demodulation 8PSK RX



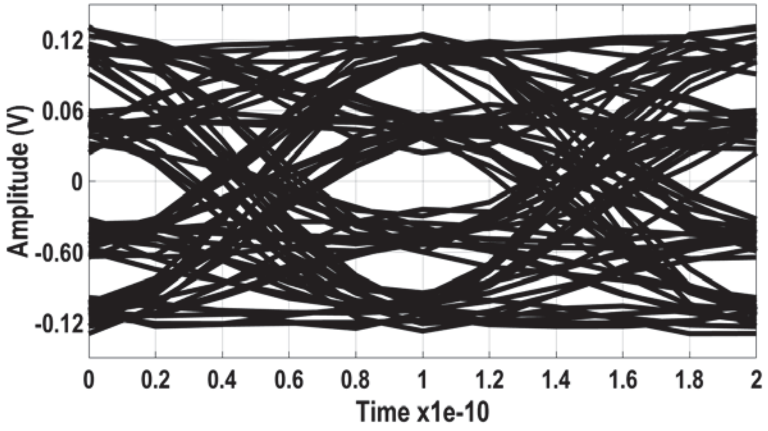
Die Micrograph

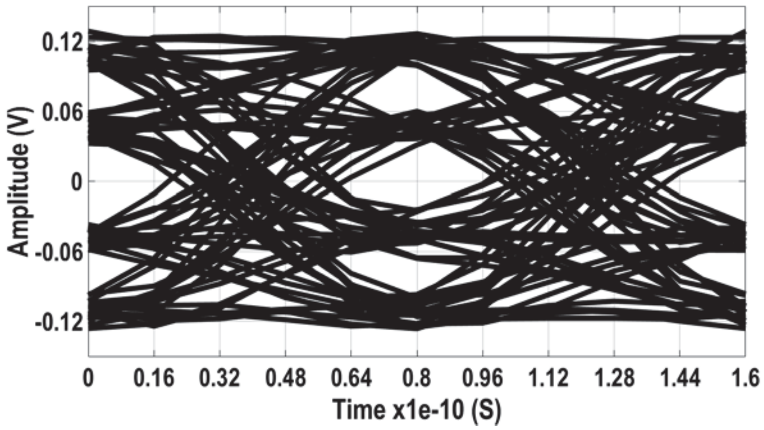


- 55nm SiGe BiCMOS process (occupies 2.5mm^2 active area)

Wireless Measurement: 8PSK Constellations

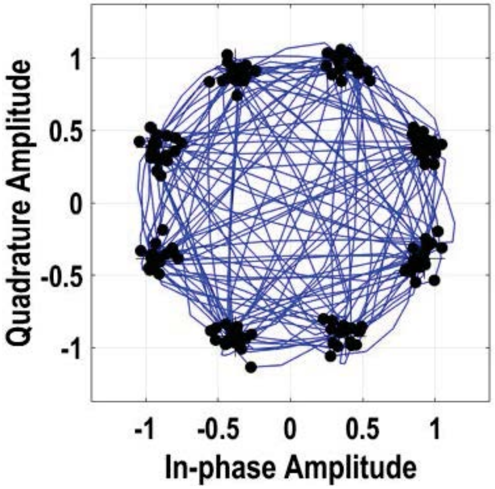
30Gbps 8PSK

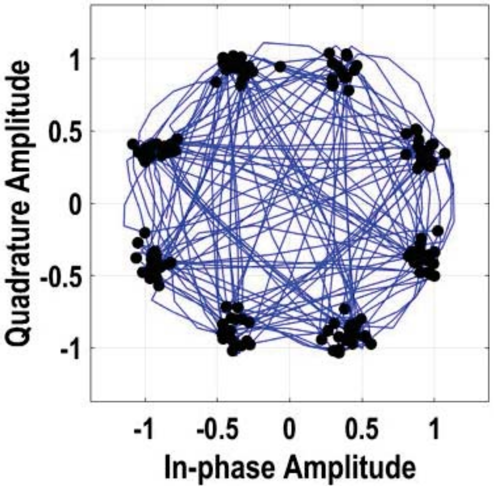




36Gbps 8PSK

30Gbps

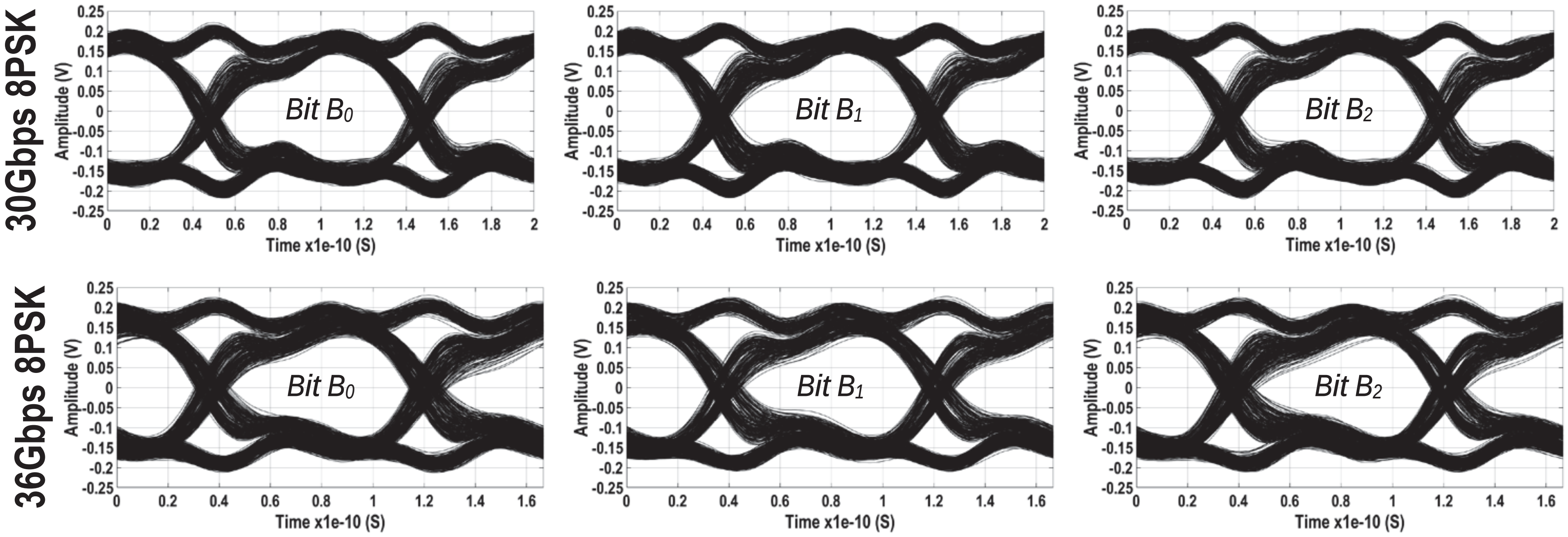




36Gbps

- 8PSK constellations reconstructed from two IQ branches
- 30/36Gbps 8PSK constellations at 30cm wireless distance

Wireless Measurement: Demodulation



- Wireless measurement of 8PSK direct-demodulated bits at 30cm distance
- BER of 1e-6 for PRBS-7 sequence; -41.28dBm sensitivity

Comparison Table & Conclusion

	This Work	ISSCC 2014 Okada	JSSC 2015 Thyagarajan	JSSC 2015 Thyagarajan	ISSCC 2017 Dolatsha
Modulation	8PSK	QPSK	QPSK	BPSK	OOK
Demodulator	Multi-Phase RF-Correlator	Quadrature Zero-IF	Quadrature Zero-IF	Quadrature Zero-IF	Envelope Detector
Frequency (GHz)	125	60	240	240	130
Data-Rate (Gbps)	**36**	14.08	16	9	11.5
BER	**1e-06**	1e-03	1e-04	1e-05	1e-06
Gain (dB)	32	30	25	25	NA
Wireless Distance (cm)	30*	90	2	2	50
Power Dissipation (mW)	**200.25**	220	260	260	24**
Energy Efficiency (pJ/bit)	**5.56**	15.63	16.25	28.9	2.08**
Technology	55nm SiGe BiCMOS	65nm CMOS	65nm CMOS	65nm CMOS	55nm SiGe BiCMOS

*** Limited by measurement setup**

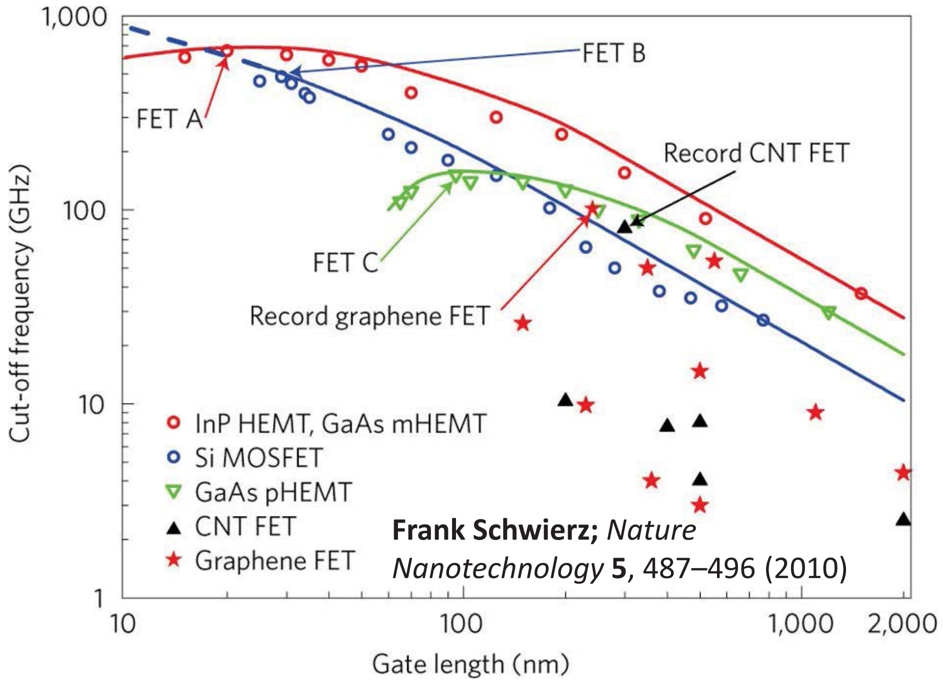
**** Non-coherent reception: excluding power-hungry blocks (synthesizer, LO, quadrature mixer)**

Highest speed, modulation-order, lowest BER and excellent energy efficiency

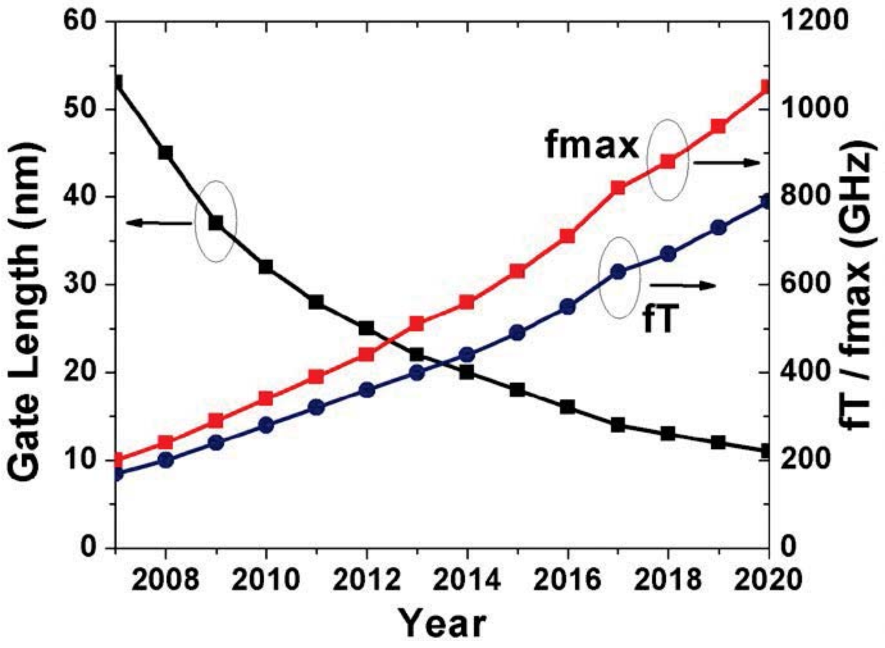
Conclusion

- The current TRX architectures are fundamentally incapable of addressing unresolved challenges to achieve 20+ Gbps data rates
  - Leaving (de-)modulation to the digital back-end, among other tasks, requires high-resolution/high-speed data converters that are impossible to realize in silicon
  - Channel bonding will lead to unacceptable amount of power dissipation
- This talk makes a strong argument in favor of novel TRX architectures incorporating direct-modulation and direct demodulation in RF/analog domain
- Two Examples were presented
  - A new method for ultrahigh-speed direct-modulation 16QAM signal
  - A multi-phase RF-correlation-based direct-demodulation 8PSK RX

Why Silicon?



Frank Schwierz; *Nature Nanotechnology* **5**, 487–496 (2010)



- Cut-off frequency scales up with device scaling
- Use of sophisticated signal processing on a single chip
  - ☞ Dense multiple antenna systems in the form of MIMO or phased-array with many antenna elements
  - ☞ Increasing frequency reuse through the creation of smaller cells, referred to as femto-cells, with ranges on the order of 10–200 m