WSK: 60GHz WiGig Frequency Synthesizer Using Injection Locked Oscillator

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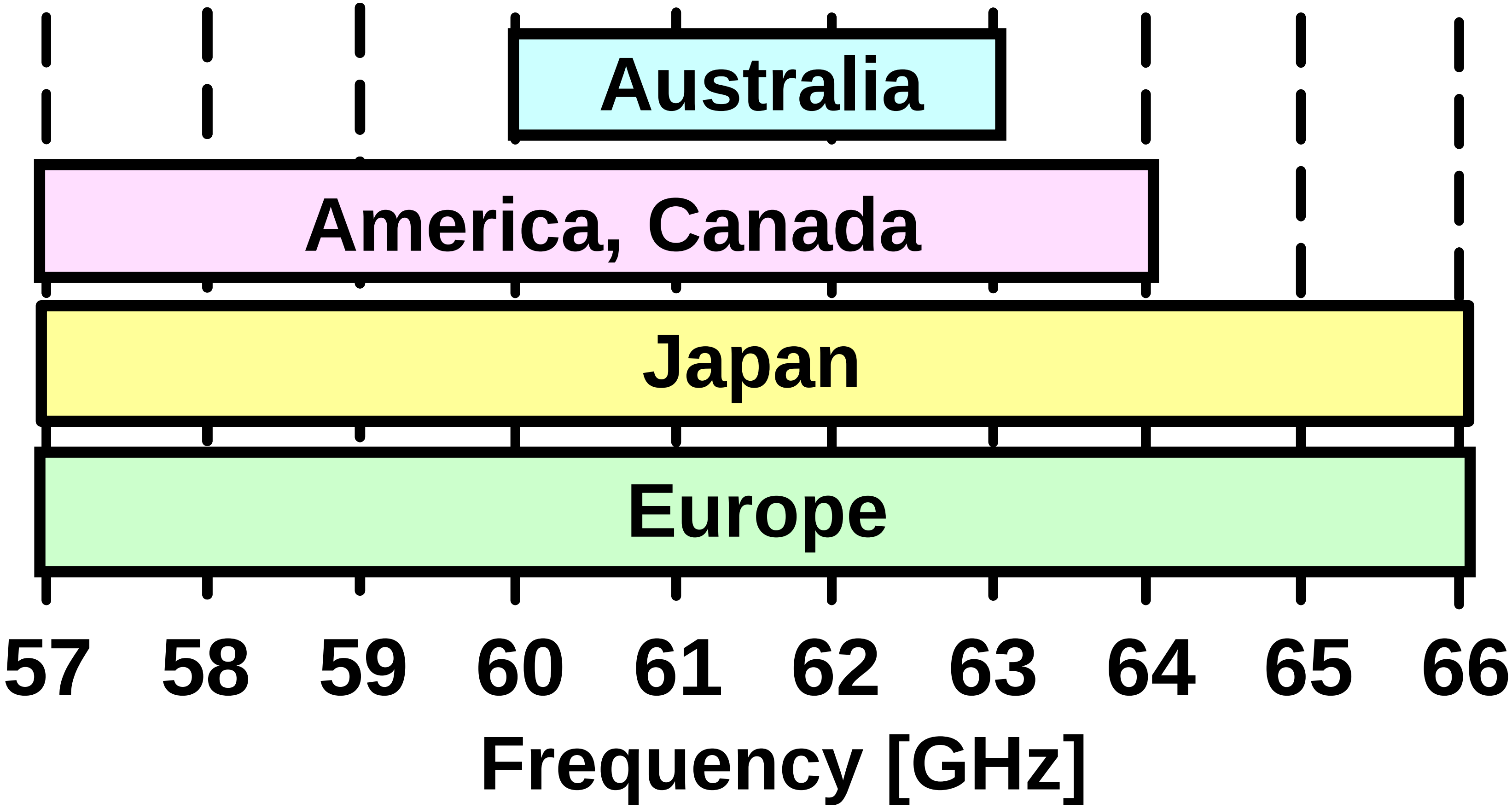
Outline

- Motivation
- Phase Noise Requirement for IEEE802.11ad/WiGig
- 60GHz Synthesizer Design
- 60GHz Transceiver
- Conclusion

Worldwide Frequency Allocation

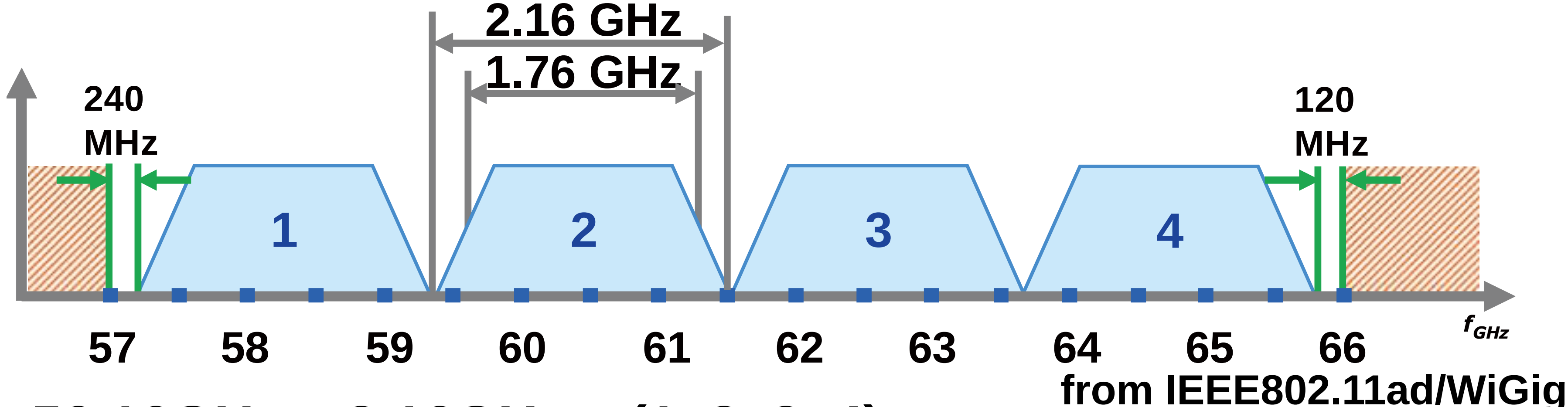
60GHz unlicensed band



9GHz-BW for IEEE802.11ad/WiGig

60GHz-Band Capability

- QPSK ➔ 3.52Gbps/ch
- 16QAM ➔ 7.04Gbps/ch
- 64QAM ➔ 10.56Gbps/ch



56.16GHz + 2.16GHz x (1, 2, 3, 4)

from Clause 21.3.1 (p.443) & Annex E (p.539) in 802.11ad-2012.pdf

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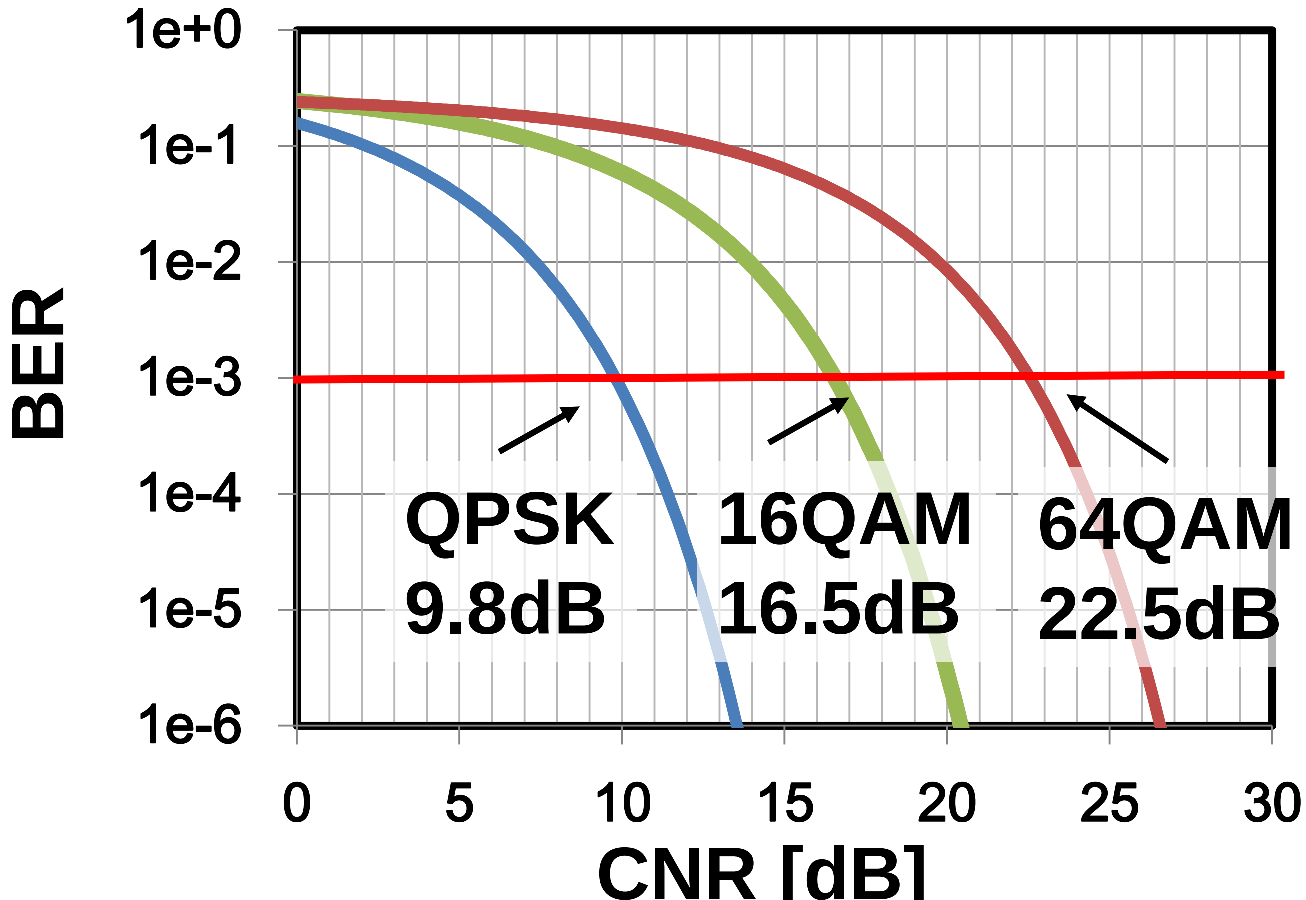
Required CNR for BER < 10^{-3}

$$\text{System SNR} = \sqrt{(\text{TX SNR})^2 + (\text{RX SNR})^2}$$

+3dB is required.



802.11ad TX EVM Requirement

-TX EVM=TX SNR(MER)

MCS	Modulation		Data rate [Mb/s]	TX EVM [dB] (spec)
9	π/2-QPSK	SC	2502.5	-15
12	π/2-16QAM	SC	4620	-21
17	QPSK	OFDM	2079.00	-13
21	16QAM	OFDM	4504.50	-20
24	64QAM	OFDM	6756.75	-26

SC: single carrier

from Table 21-18, 21-21 (p.472, 477) & Table 21-14, 21-16 (p.461, 469) in 802.11ad-2012.pdf

60GHz Transceiver Challenge

EVM degradation (TX EVM <-26dB for 64QAM)

TX

AM-AM, AM-PM:	-30dB (EVM-vs-Pout)
phase noise:	-30dB
I/Q mismatch:	<-40dB
gain/phase flatness:	<-40dB

RX

NF, IIP3:	<-40dB (depending on Pin)
phase noise:	-30dB
I/Q mismatch:	<-40dB
gain/phase flatness:	<-40dB (depending on DBB)

Phase Noise Issue at mmW

- Phase noise degrades EVM.
- Phase noise becomes larger at millimeter-wave for both in-band and out-of-band of PLL.

e.g.

5GHz ➔ 60GHz

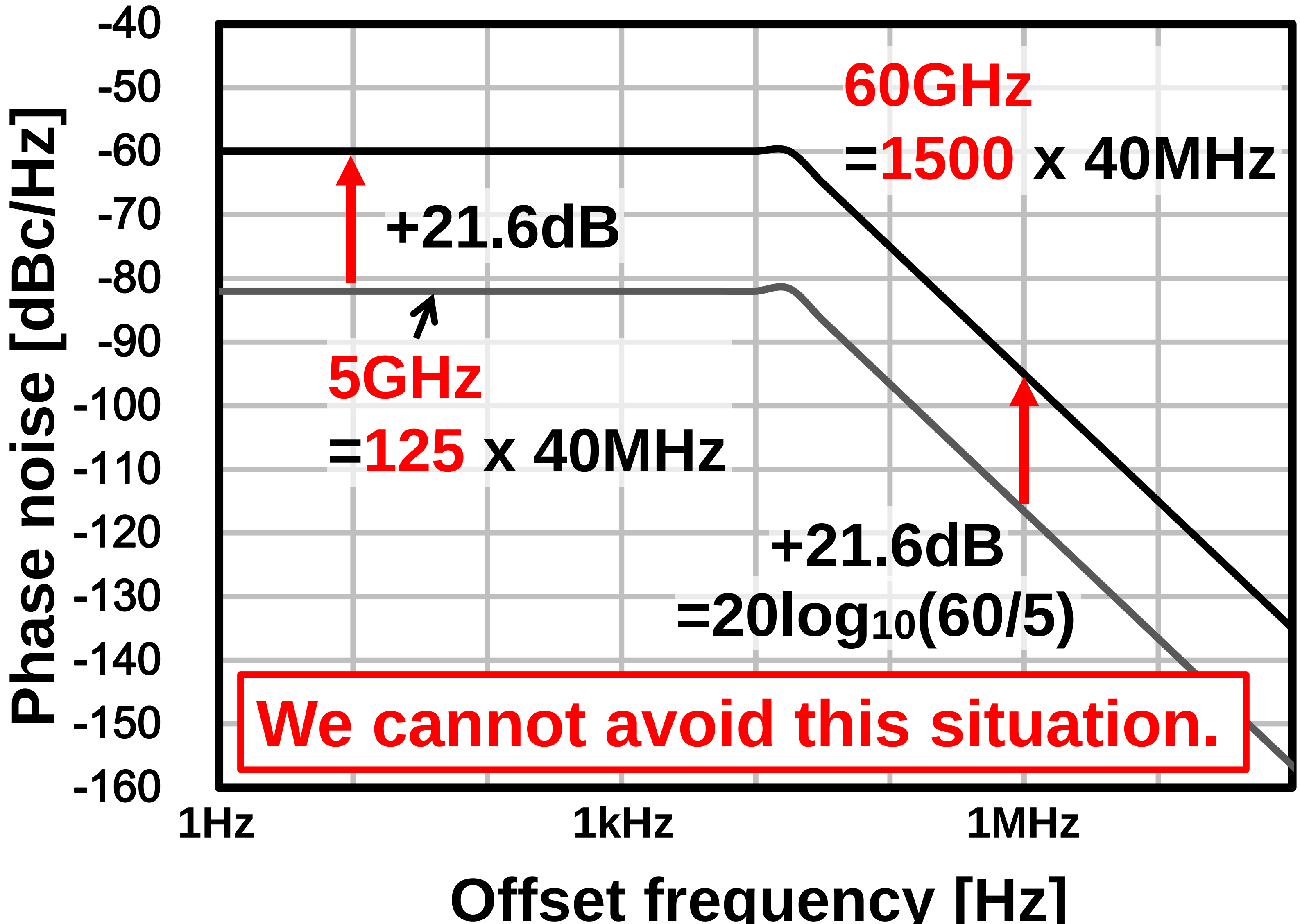
+21.6dB increase

=20log$_{10}$(60GHz/5GHz)

$$\mathcal{L}_{\mathrm{out-of-band}} \propto \left(\frac{f_{\mathrm{osc}}}{f_{\mathrm{offset}}}\right)^2$$

$$\mathcal{L}_{\mathrm{in-band}} \propto \left(\frac{f_{\mathrm{osc}}}{f_{\mathrm{ref}}}\right)^2$$

Phase Noise Degradation



We cannot avoid this situation.

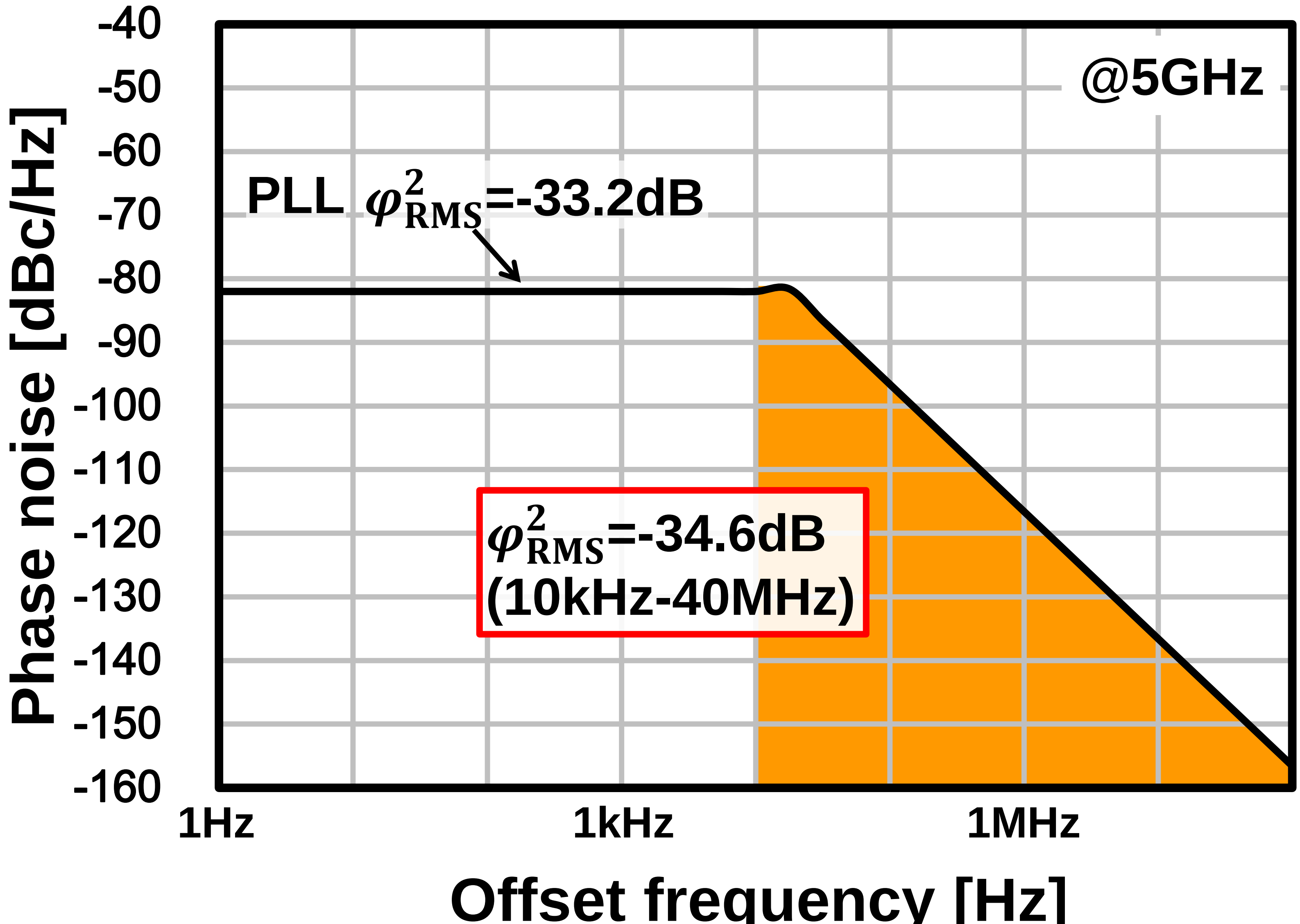
Influence on EVM

- **Phase noise influence on EVM can be estimated by the following equations.**
- **Integrated DSB phase noise φ^2_{RMS} is sometimes integrated from 10kHz to 40MHz due to measurement issue. ➔ correct?**

$$\varphi^2_{\mathrm{RMS}} = 2\int_0^{B/2} \mathcal{L}(f)df \cong 2\int_0^{\infty} \mathcal{L}(f)df$$

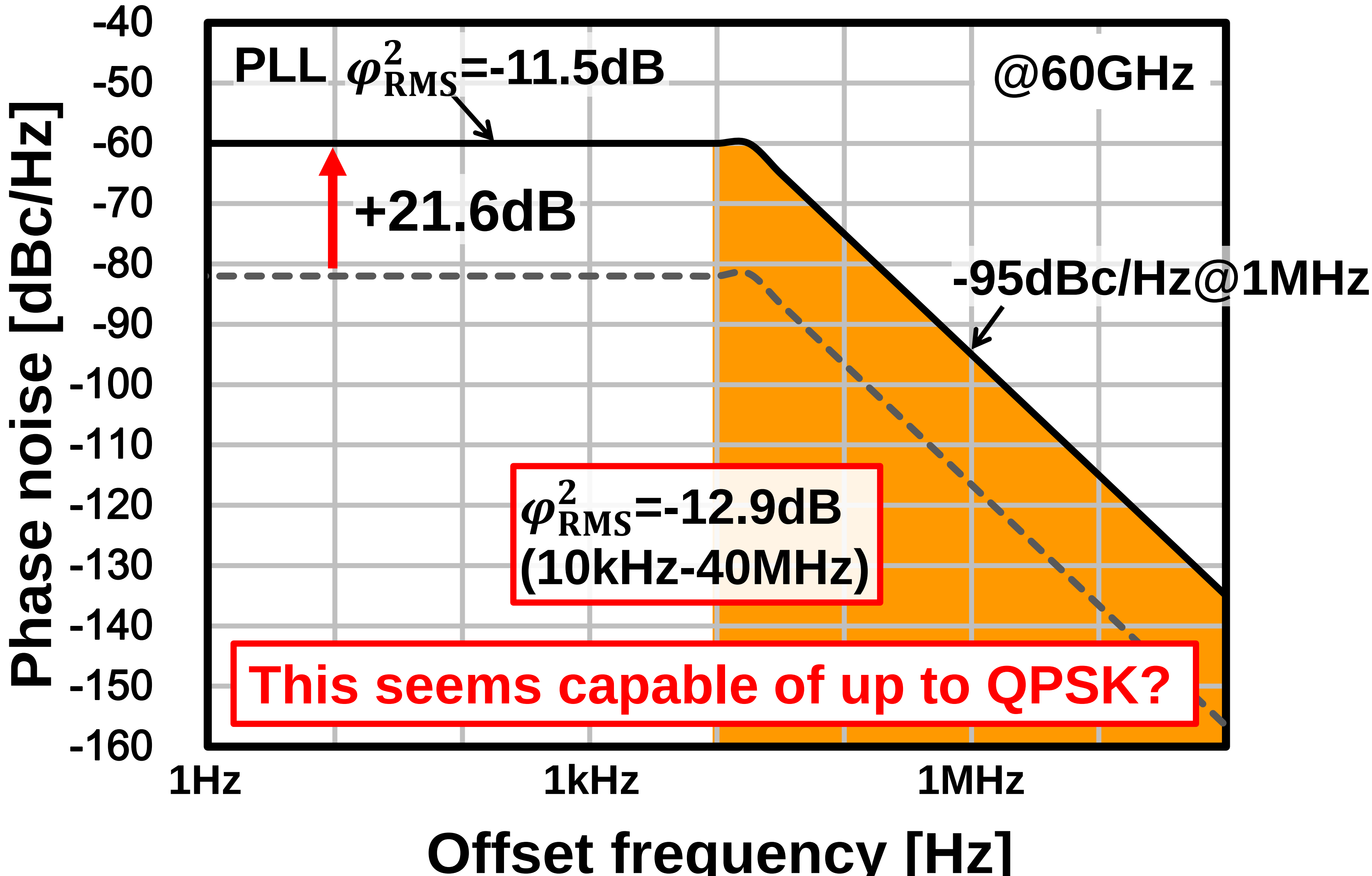
$$TX\ EVM = \sqrt{\frac{1}{SNR^2} + \varphi^2_{\mathrm{RMS}}}$$

Phase Noise for 802.11ac

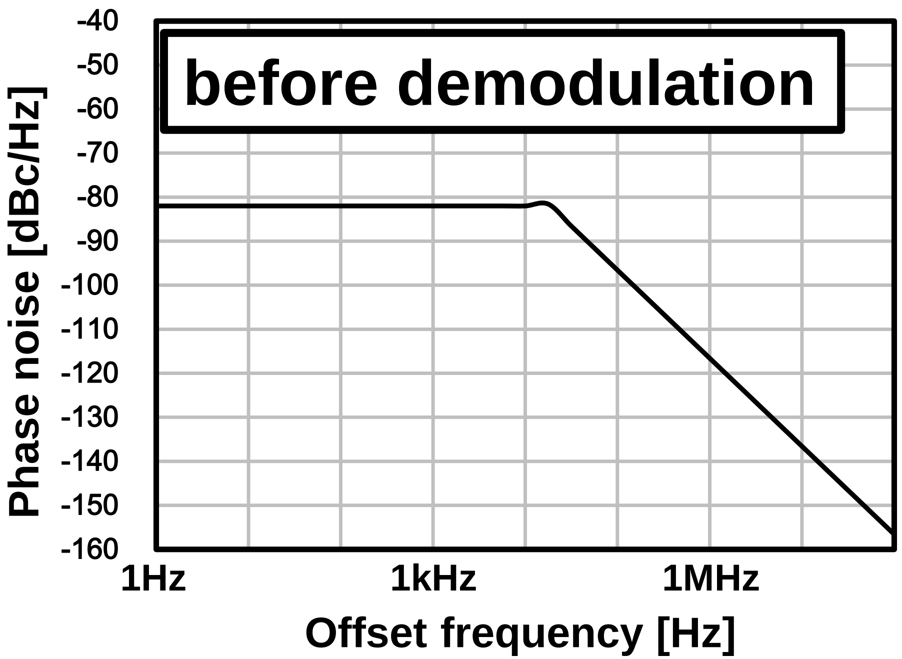


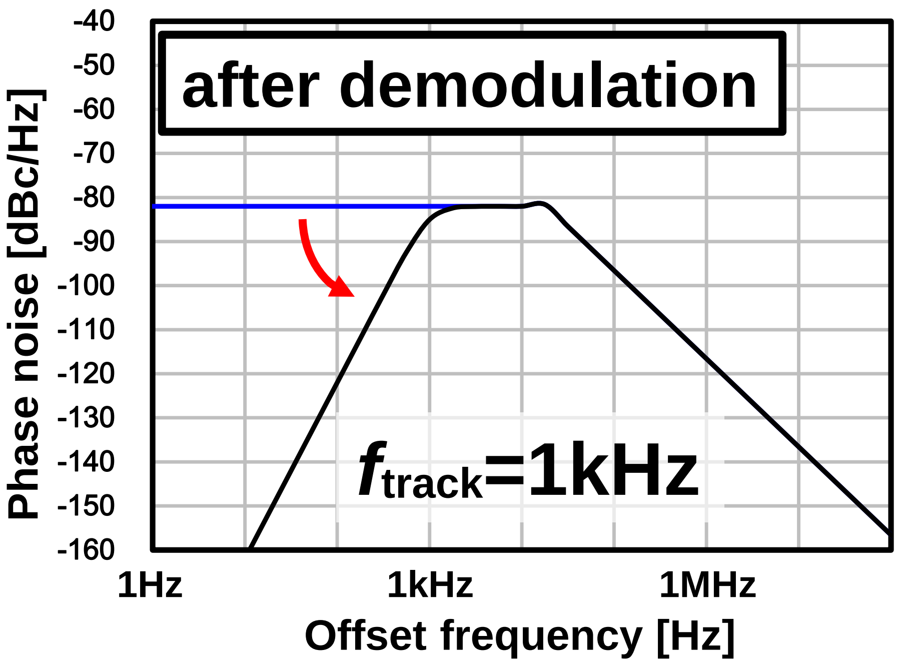
Phase Noise for 802.11ad

RFIC 2014



Carrier Tracking at Digital Baseband





A decision-directed PLL used for symbol-timing recovery can cancel low-offset phase noise, which is 2nd-order LPF at f_{track}.

IEEE802.11ac standard (OFDM)

Modulation	Code rate	N_{BPSC}	N_{CBPS}	N_{DBPS}	Data rate [Mbps]
QPSK	3/4	2	936	702	195
16-QAM	3/4	4	1872	1404	390
64-QAM	5/6	6	2808	2340	650
256-QAM	5/6	8	3744	3120	866.67

Subcarrier frequency spacing: 0.3125MHz (=160MHz/512)

# of data subcarriers=468 (in 501 with 156.5625MHz-BW)

T_{DFT}: OFDM IDFT/DFT period (=3.2us)

T_{GI}: Guard Interval duration (=0.4us = T_{DFT}/8)

R: code rate

N_{BPSC}:# coded bits per single carrier

N_{CBPS}:# coded bits per symbol (=468*N_{BPSC})

N_{DBPS}:# data bits per symbol (=N_{CBPS}*R)

Data rate = $N_{DBPS}/(T_{DFT}+T_{GI})$ = 0.3125MHz*N_{DBPS}*$T_{DFT}/(T_{DFT}+T_{GI})$

IEEE802.11ad standard (OFDM)

MCS	Modulation	Code rate	N_{BPSC}	N_{CBPS}	N_{DBPS}	Data rate [Mbps]
17	QPSK	3/4	2	672	504	2079.00
21	16-QAM	13/16	4	1344	1092	4504.50
24	64-QAM	13/16	6	2016	1638	6756.75

Subcarrier frequency spacing: 5.15625MHz

# of data subcarriers=336 (in 355 with 1830.5MHz-BW)

T_{DFT}: OFDM IDFT/DFT period (=0.194us)

T_{GI}: Guard Interval duration (=48.4ns = T_{DFT}/4)

R: code rate

N_{BPSC}:# coded bits per single carrier

N_{CBPS}:# coded bits per symbol (=336*N_{BPSC})

N_{DBPS}:# data bits per symbol (=N_{CBPS}*R)

Data rate = $N_{DBPS}/(T_{DFT}+T_{GI})$ = 5.15625MHz*N_{DBPS}*$T_{DFT}/(T_{DFT}+T_{GI})$

from Table 21-4 (p.446) & Table 21-14 (p.462) in 802.11ad-2012.pdf

Maximum f_{track}?

J. R. Pelliccio, *et al*., APPLIED MICROWAVE & WIRELESS, 2001

$$S_{track}(f) = \frac{1}{1 + \left(\frac{f}{f_{track}}\right)^4}$$

$$f_{track} = \frac{f}{\left(\frac{1}{S_{track}(f)} - 1\right)^{\frac{1}{4}}}$$

For a rough estimation, assume

f = 1/2 x subcarrier spacing

$S_{track}(f) = 10^{-3}$ (=-30dB)

802.11ac

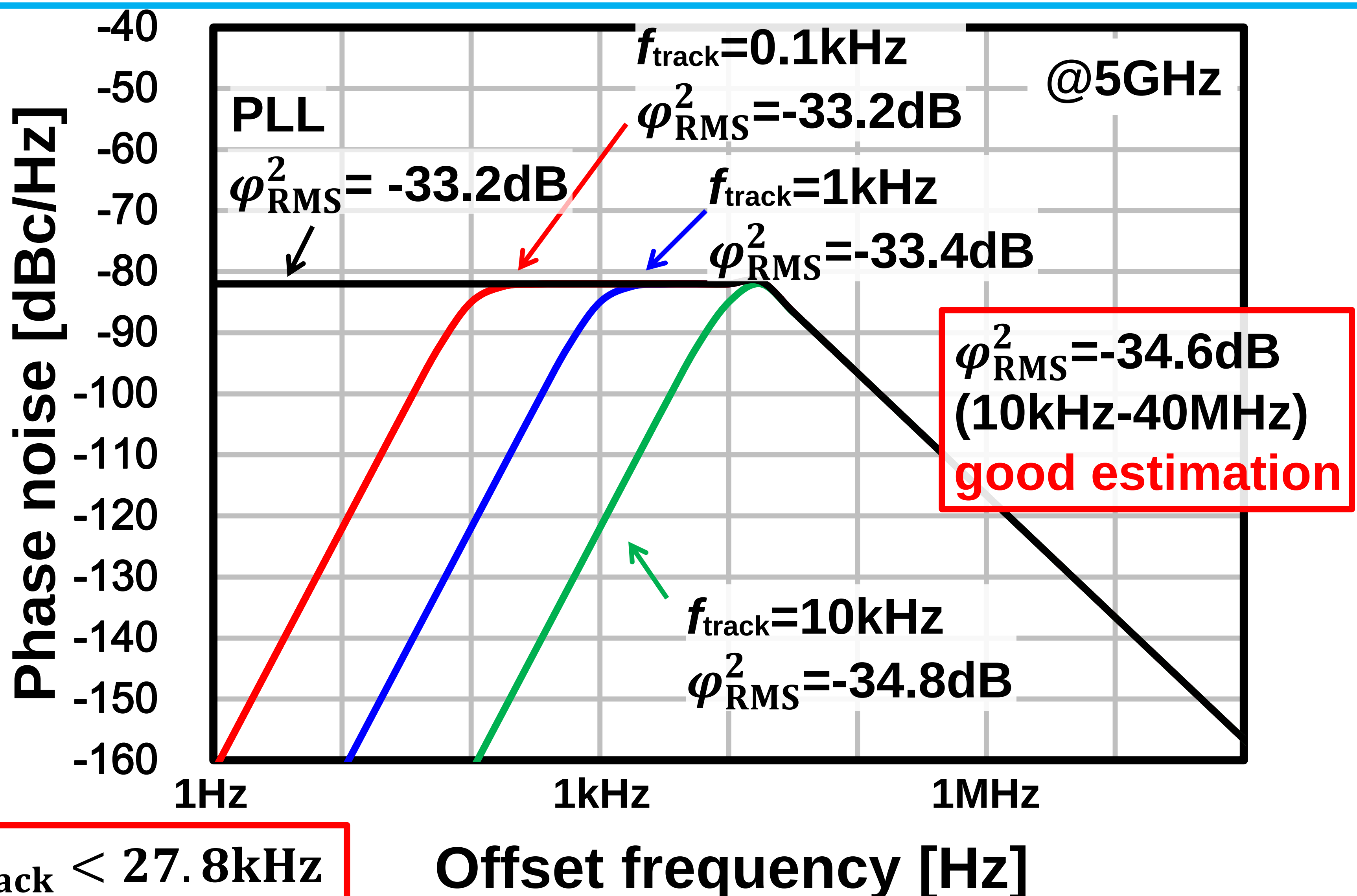
$$f_{track} < 312.5\text{kHz} \times 0.089 = 27.8\text{kHz}$$

802.11ad

$$f_{track} < 5156.25\text{kHz} \times 0.089 = 458.6\text{kHz}$$

Phase Noise for 802.11ac

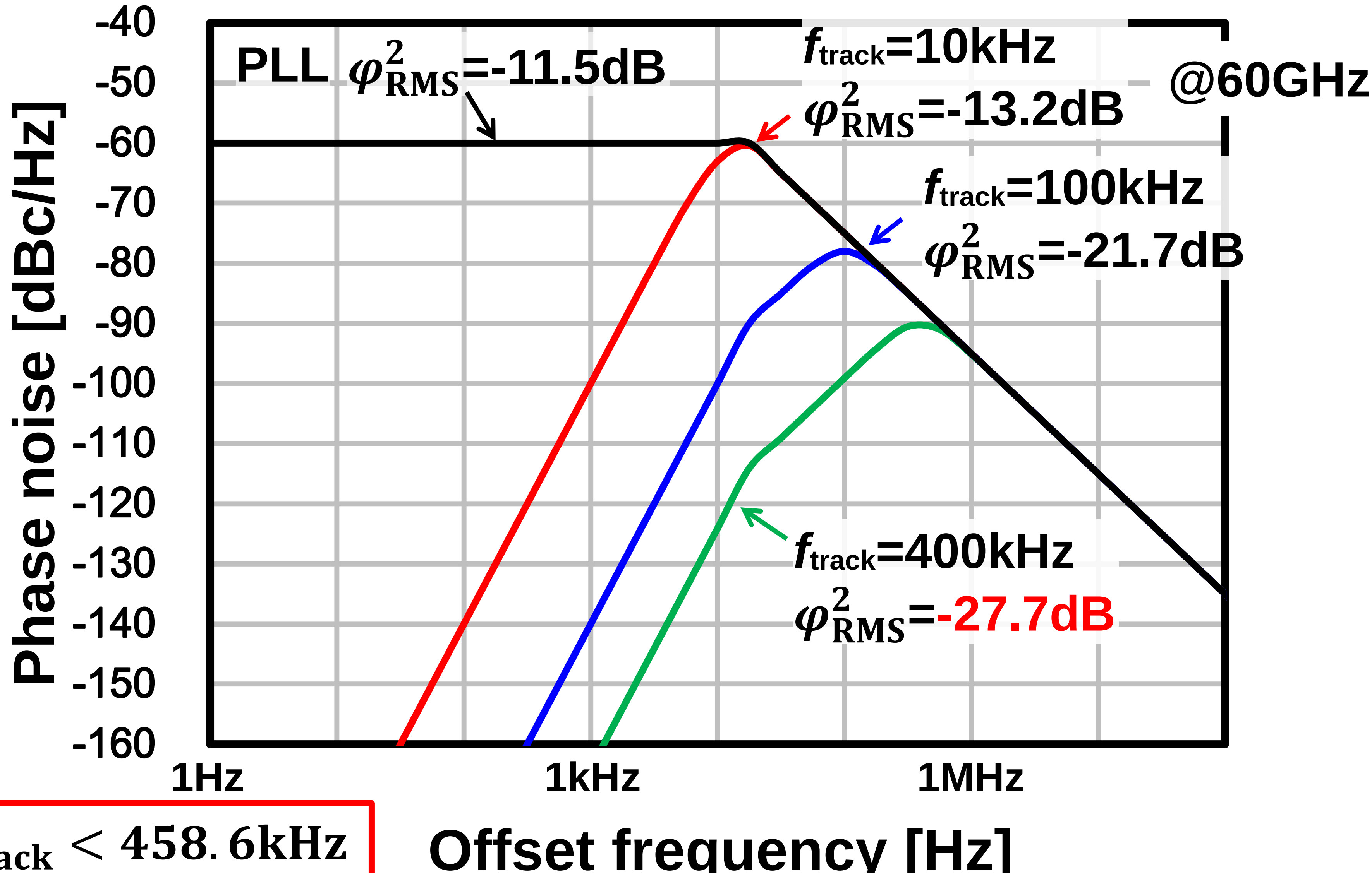
RFIC 2014



$f_{track} < 27.8\text{kHz}$

Phase Noise for 802.11ad

RFIC 2014



$f_{track} < 458.6\text{kHz}$

Effective Integrated Phase Noise

$$\varphi^2_{\mathrm{RMS,eff}} = 2\int_0^{B/2} \mathcal{L}(f)\left(1 - \frac{1}{1+\left(\frac{f}{f_{\mathrm{track}}}\right)^4}\right)df$$

$$TX\ EVM = \sqrt{\frac{1}{SNR^2} + \varphi^2_{\mathrm{RMS,eff}}}$$

B : bandwidth of modulated signal

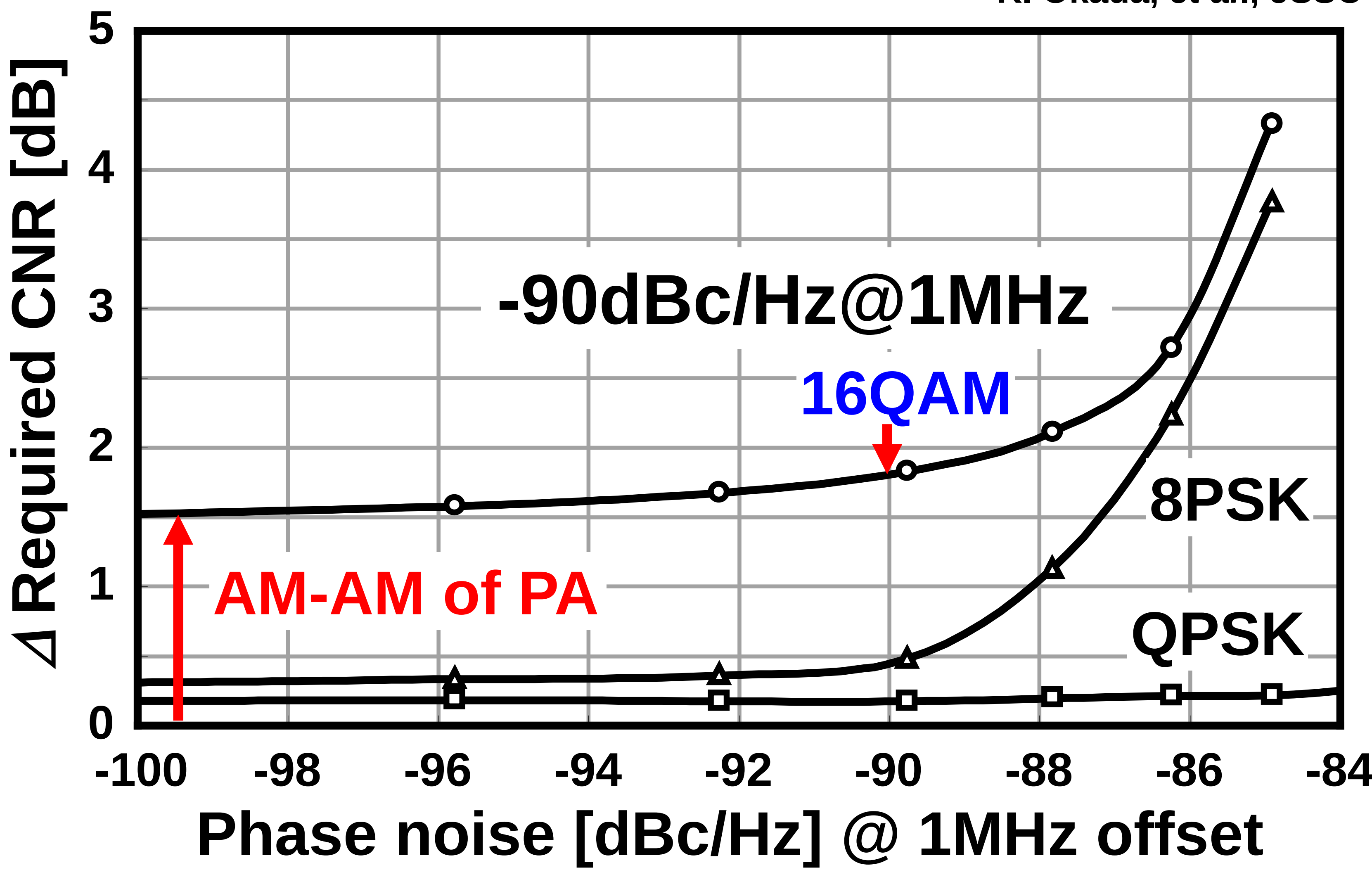
(B can be infinity for approximation)

f_{track}: tracking bandwidth of symbol timing recovery

($f_{\mathrm{track}} < 456.8\mathrm{kHz}$ for IEEE802.11ad OFDM)

Cross Effect

*K. Okada, *et al*., JSSC 2011



Phase Noise Requirement

Requirement for IEEE802.11ad/WiGig

- **QPSK: -83dBc/Hz@1MHz (-15.7dB)**
- **16QAM: -90dBc/Hz@1MHz (-22.7dB)**
- **64QAM: -96dBc/Hz@1MHz (-28.7dB)**

with f_{track}=400kHz & 2.7dB margin

In-band phase noise is not important, but the supply-pushing has to be cared for a TDD operation.

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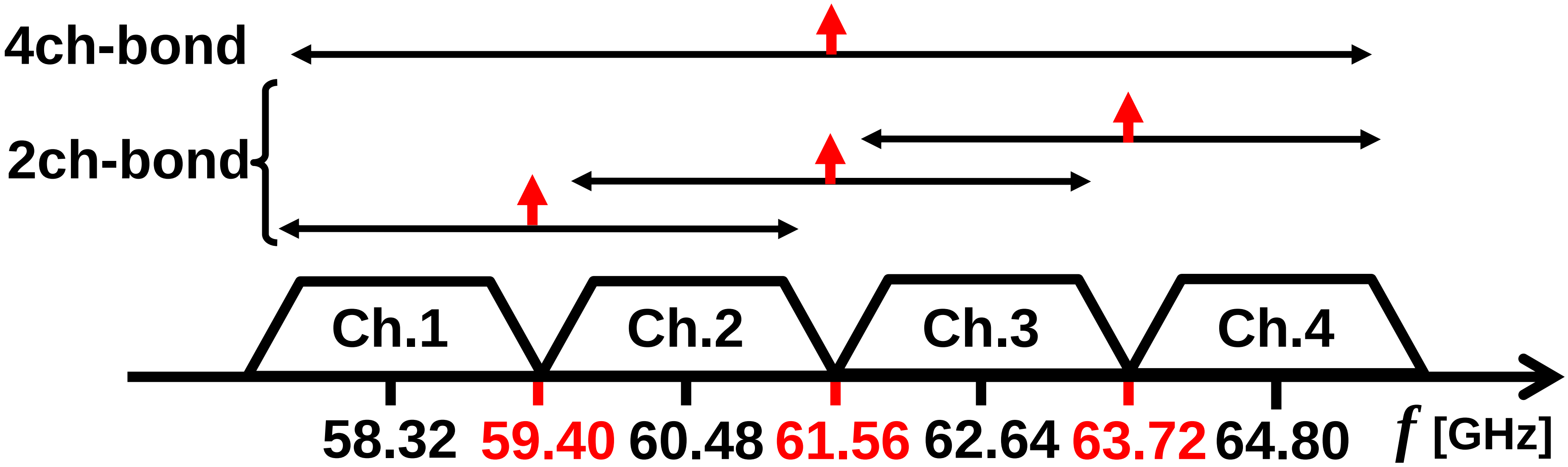
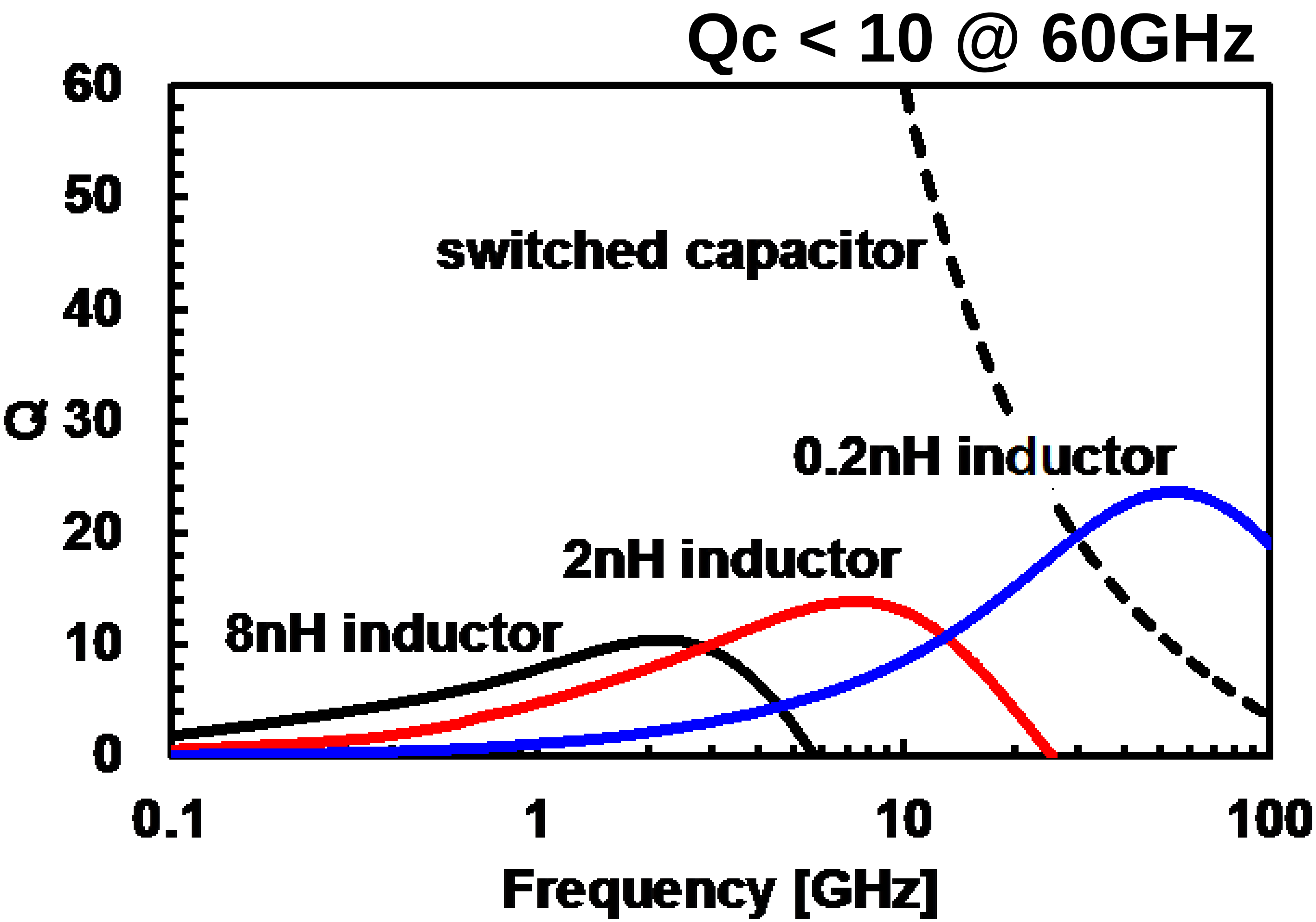
60GHz LO Considerations

- -96dBc/Hz@1MHz for 64QAM
- 7 carrier frequencies for channel bonding from 58.32GHz to 64.80GHz (10.5%)
- 40-MHz reference clock for sharing other WiFi



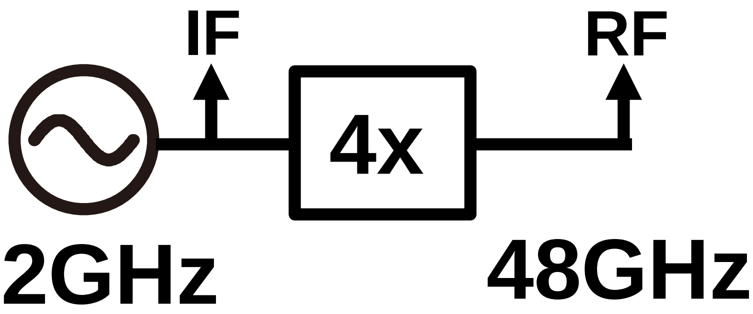
Oscillation Frequency

60-GHz fundamental oscillation is not a good idea.



Frequency Multiplier

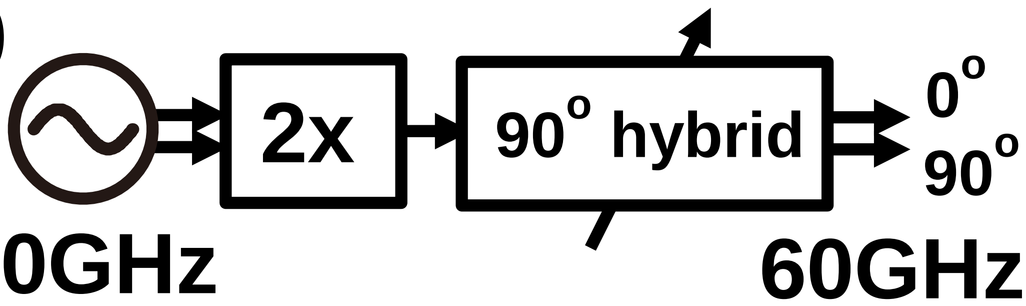
(1)



- for hetero-dyne TRX
- reasonable for PN and FTR

*S. Emami, *et al*., ISSCC 2011

(2)

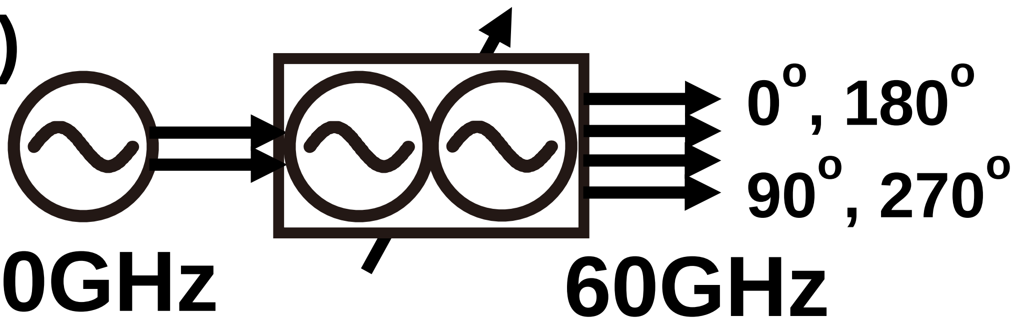


(20GHz x3, 15GHz x4 are OK.)

- 30GHz is a bit high for PN and FTR
- I/Q phase calibration is required.

**C. Marcu, *et al*., ISSCC 2009

(3)



- 60GHz QILO***
- good for PN and FTR

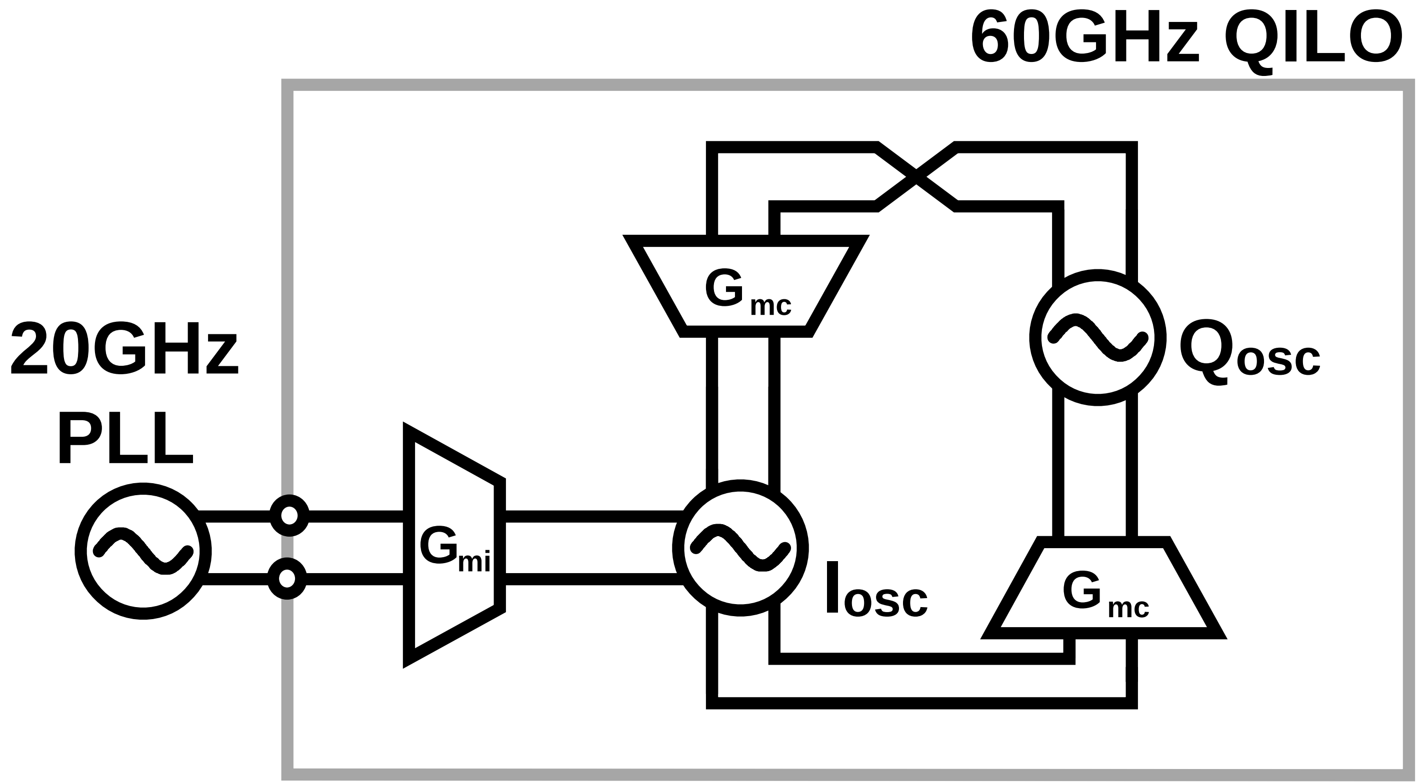
***W. Chan, *et al*., ISSCC 2008

Quadrature ILO

QILO: Quadrature Injection-Locked Oscillator*

working as a frequency tripler

*W. Chan, *et al*., ISSCC 2008

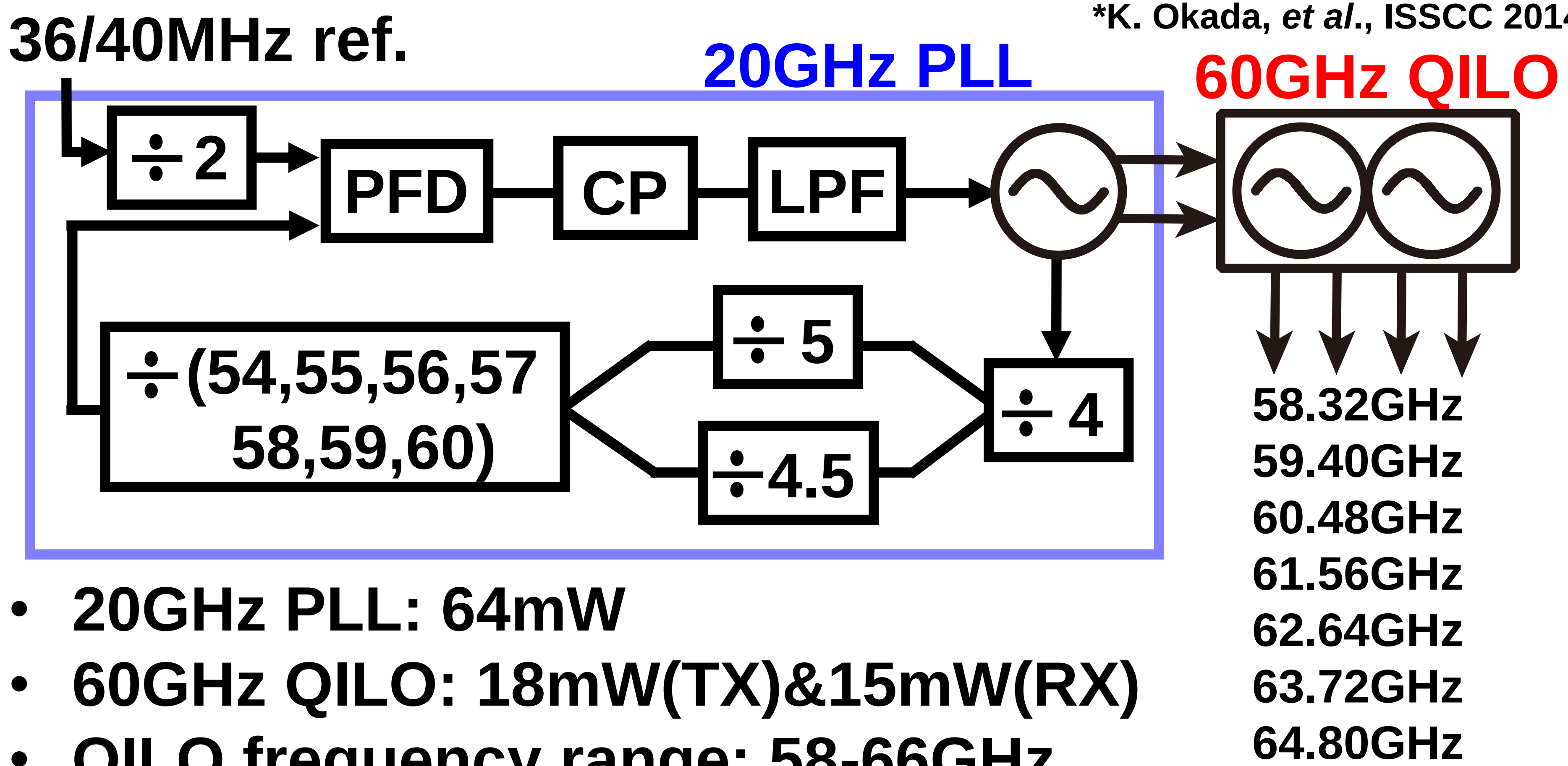


Single-side injection**

**K. Okada, *et al*., ISSCC 2011

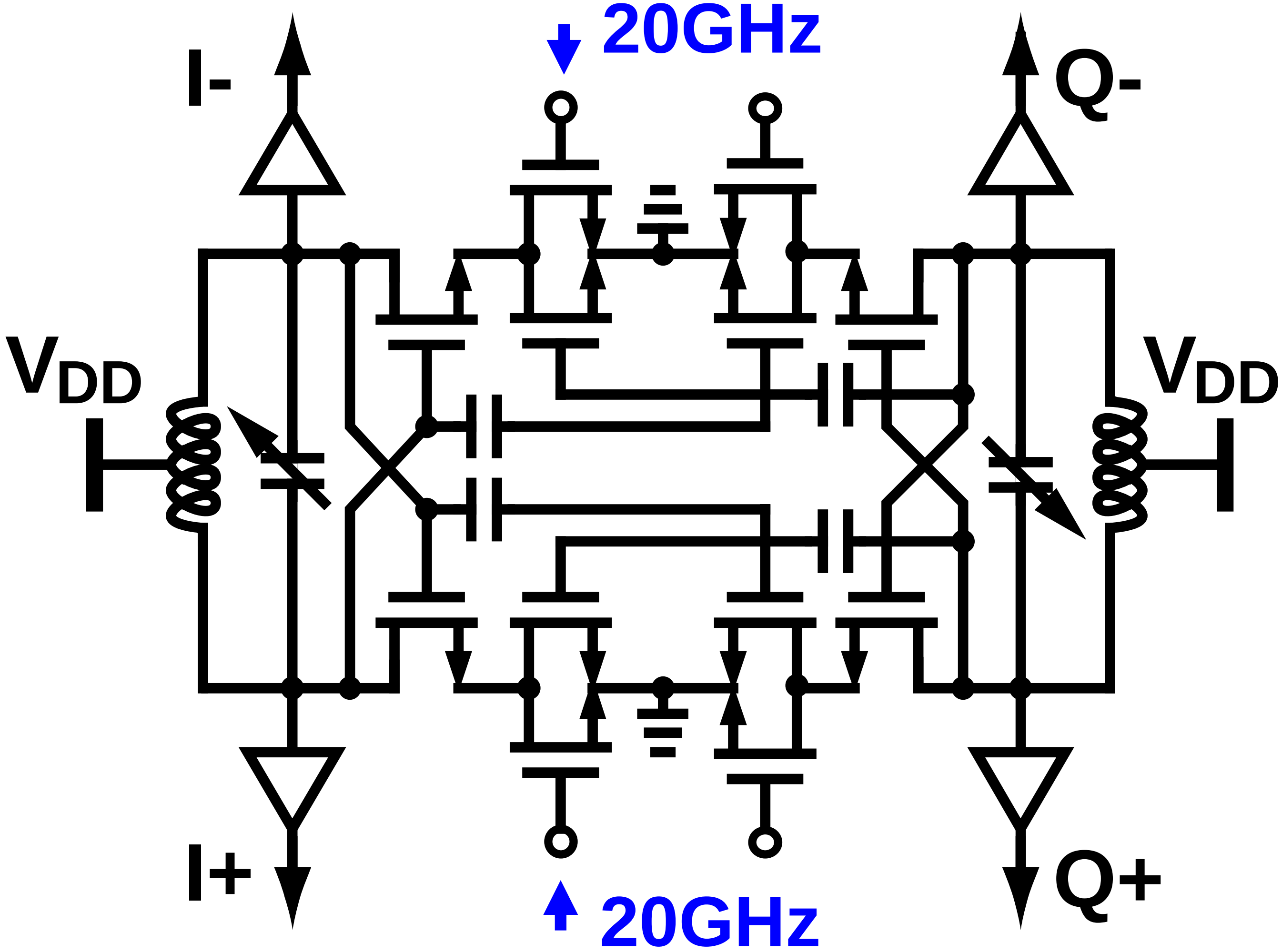
60GHz Quadrature LO Design

*K. Okada, *et al*., ISSCC 2014



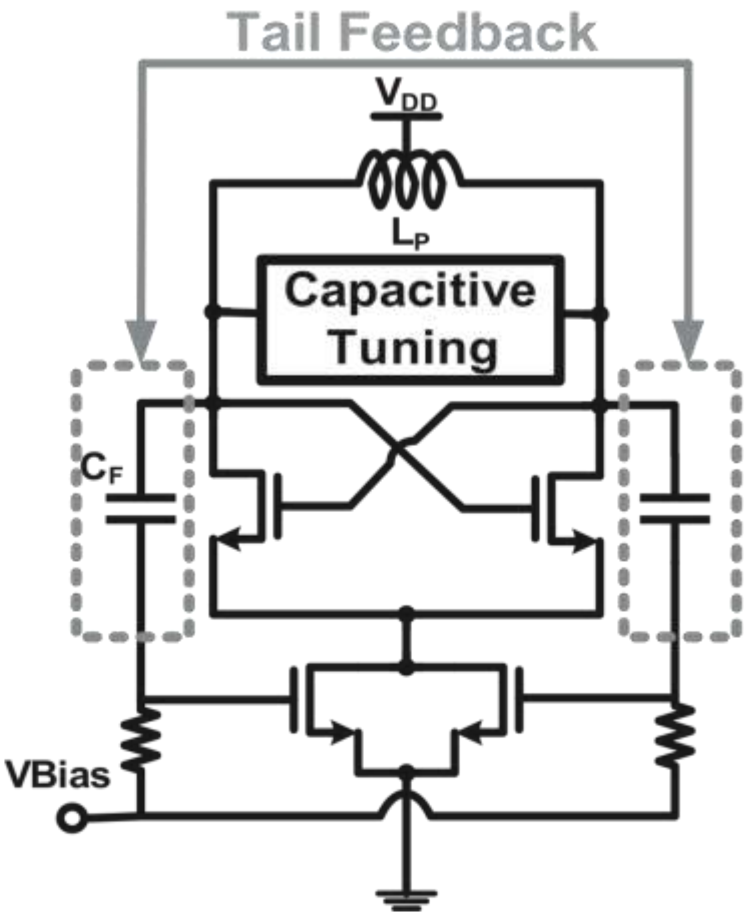
- 20GHz PLL: 64mW
- 60GHz QILO: 18mW(TX)&15mW(RX)
- QILO frequency range: 58-66GHz
- Phase noise improvement by injection locking
- -96.5dBc/Hz @ 1MHz at 61.56GHz

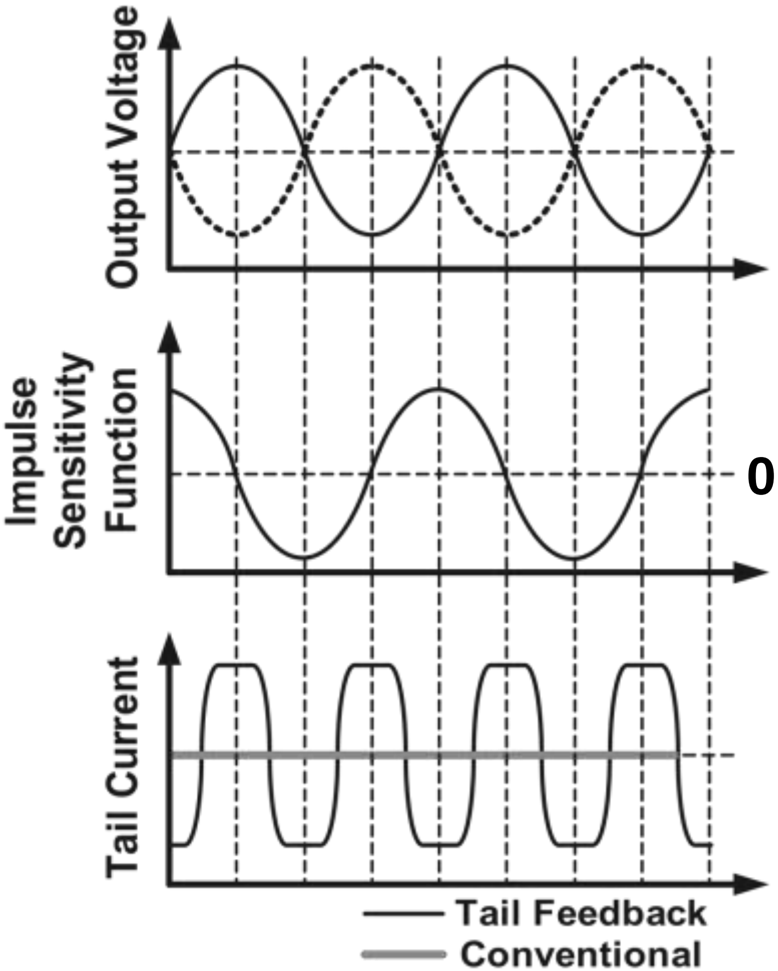
Quadrature ILO



*W. Chan, *et al*., ISSCC 2008 **A. Musa, *et al*., JSSC 2011 ***K. Okada, *et al*., ISSCC 2011, 2012

20GHz VCO





Tail feedback TEG VCO achieves -107dBc/Hz@1MHz

***K. Okada, *et al*., JSSC 2011**

Comparison of 60GHz LO

Ref.	REF Freq. (MHz)	Frequency (GHz)	Phase Noise @1MHz	Features	Power (mW)
[1]	100	57.0-66.0	-75dBc/Hz	Direct 60GHz QPLL	78
[2]	203.2	59.6-64.0	-92dBc/Hz	30GHz PLL + hybrid	76
[3]	100	56.4-63.4	-90dBc/Hz	60GHz AD-PLL	48
[4]	36	58.1-65.0	-96dBc/Hz	Sub-harmonic Injection 20GHz PLL + 60GHz QILO	72
[5]	36/40	58-66	-97dBc/Hz	Sub-harmonic Injection 20GHz PLL + 60GHz QILO	79
[6]	36/40	58.3-65.4	-95dBc/Hz	Sub-harmonic Injection 20GHz PLL + 60GHz QILO	33

[1] K. Scheir, *et al*., ISSCC 2009 [2] C. Marcu, *et al*., JSSC 2009 [3] W. Wu, *et al*., ISSCC 2013 [4] W. Deng, *et al*., JSSC 2013 [5] K. Okada, *et al*., ISSCC 2014 [6] T. Siriburanon, *et al*., RFIC 2014

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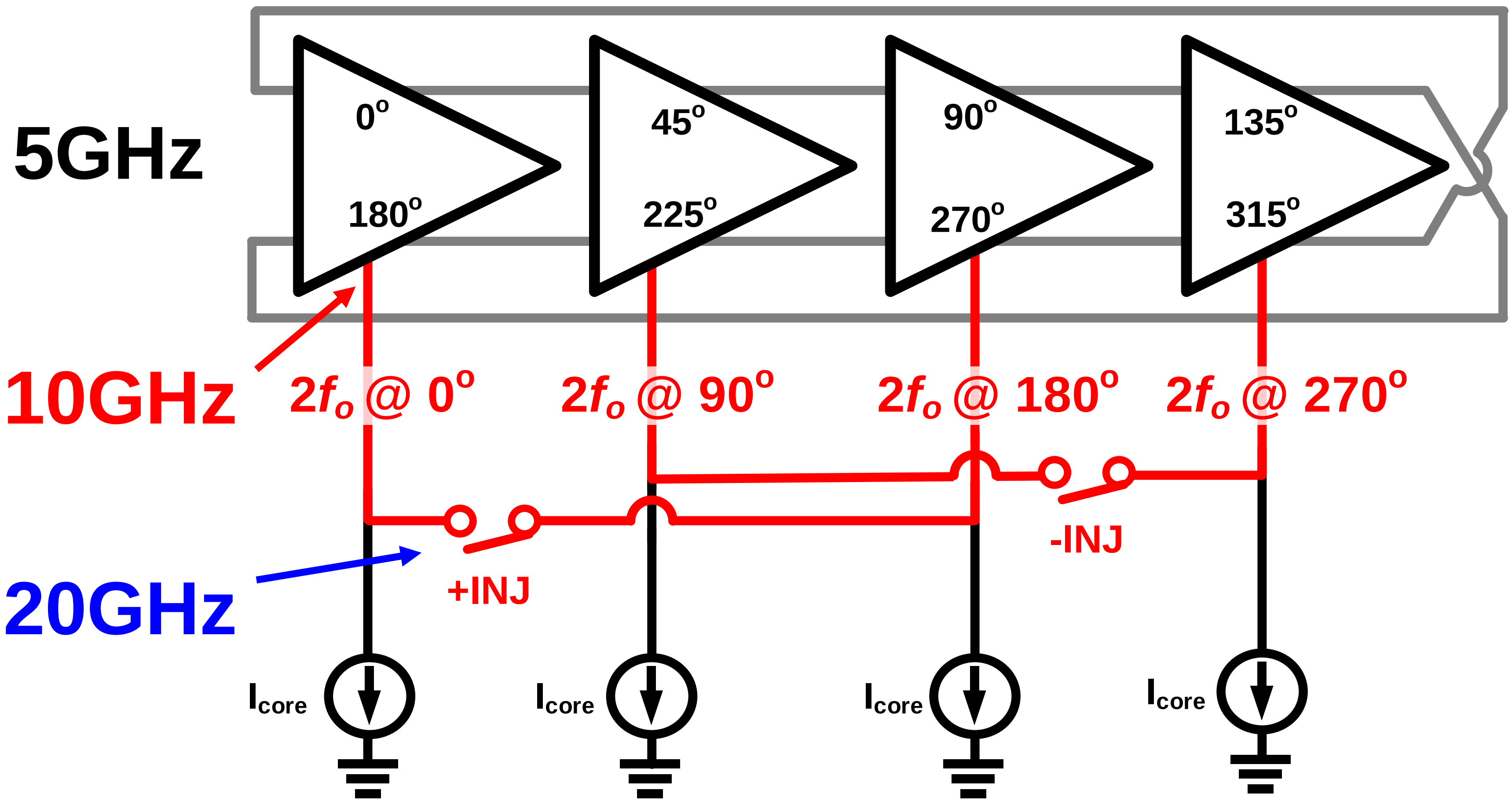
- 60GHz Synthesizer Design
  - 20GHz-to-5GHz ILFD
  - QILO as a phase shifter
  - Sub-sampling PLL

20GHz-to-5GHz ILFD (/4)

Progressive-mixing ILFD*,**



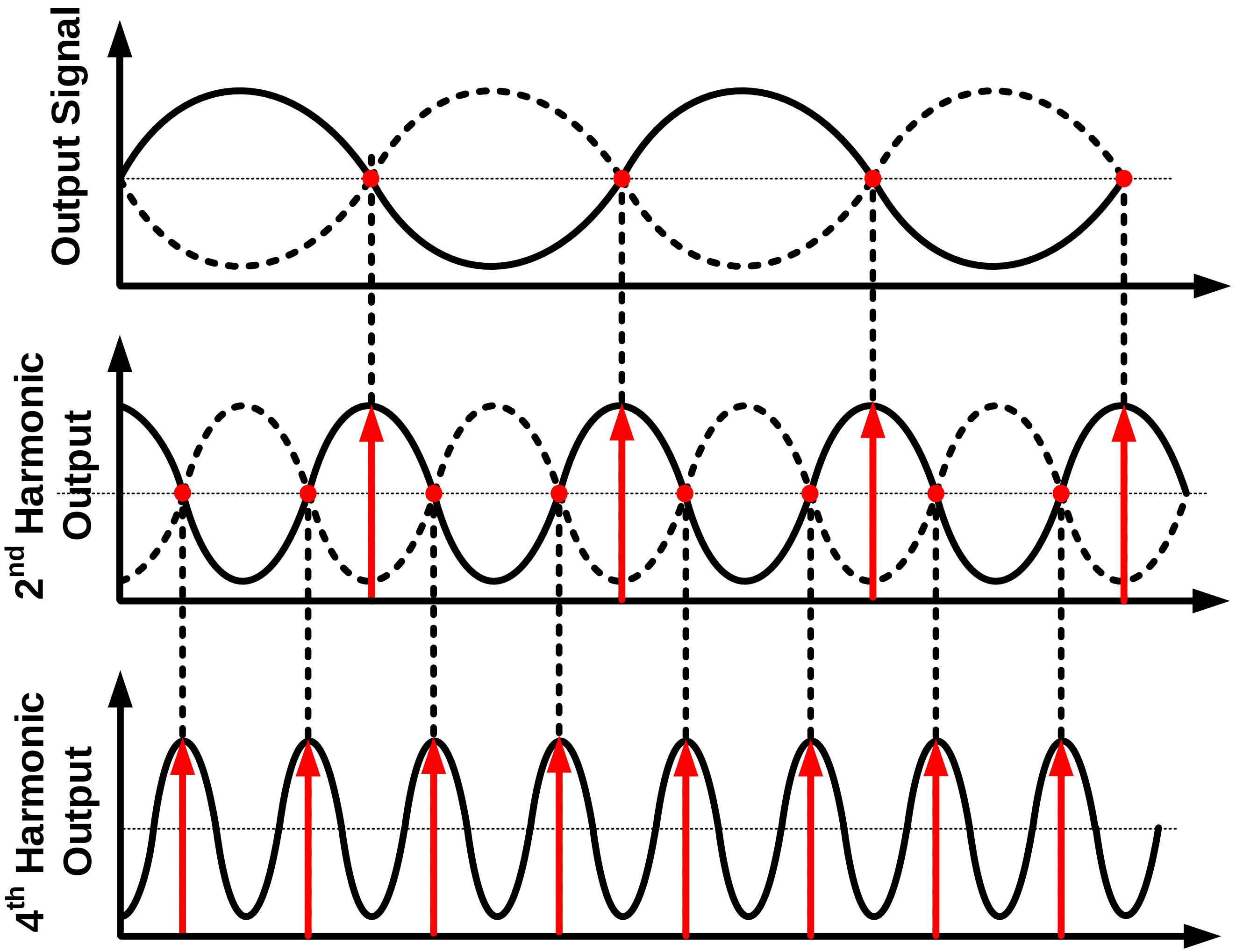
*A. Musa, *et al*., A-SSCC 2011 **T. Siriburanon, *et al*., ESSCIRC 2013

Divide-by-4 Operation

5GHz

10GHz

20GHz



Locked State of Divide-by-4 operation

Divide-by-4 Dividers

	Features	Locking Range (GHz)	Power (mW)	Area (mm^2)
[1]	Direct mixing	22.6-28 (21%)	8.3	0.140
[2]	Direct mixing	31.0-41.0 (27%)	3.3	0.002
[3]	LC Direct mixing	58.5-72.9 (22%)	2.2	0.032
[4]	CML + LC ILFD	13.5-30.5 (77%)	7.3	0.33
[5]	Progressive mixing	13.4-21.3 (31%)	3.9	0.003
[6]	Progressive mixing	15.2-20.4 (24%)	3.1	0.002

[1] A-SSCC 2007 [2] ISSCC 2006 [3] CICC 2012 [4] T-MTT 2011

[5] A. Musa, *et al*., A-SSCC 2011 [6] T. Siriburanon, *et al*., ESSCIRC 2013

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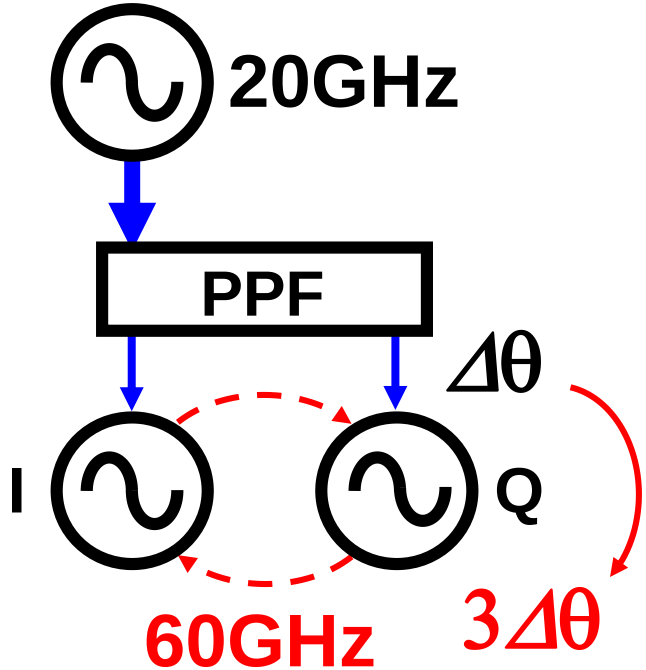
  - **Sub-sampling PLL**

Quadrature ILO

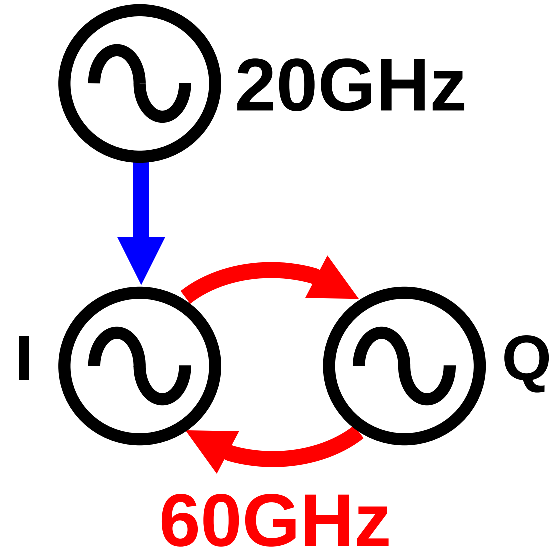
Previous work*



I/Q mismatch

PPF:polyphase filter

This work**

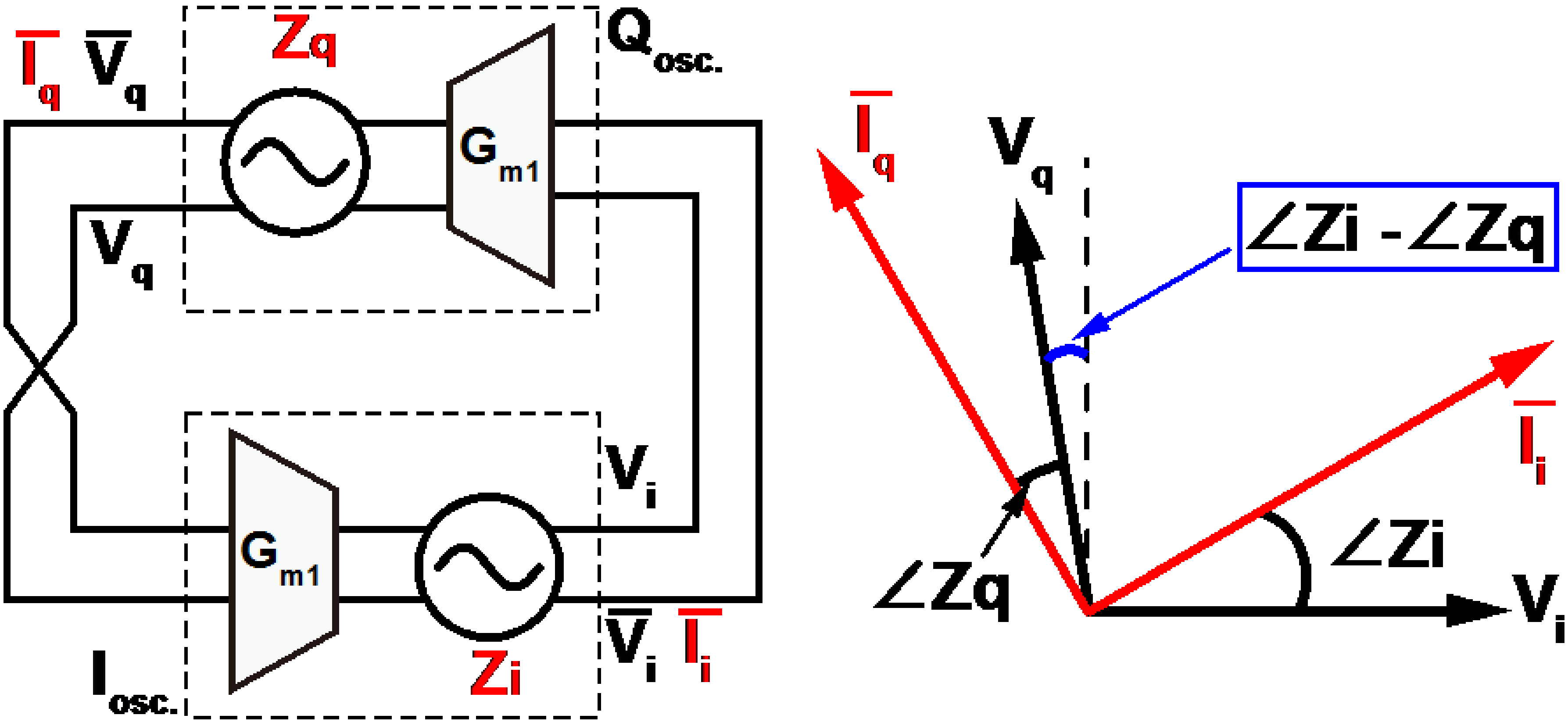


Single-side injection
- This can be used as a very fine <u>phase shifter</u>.

*W. Chan, *et al*., ISSCC 2008

**K. Okada, *et al*., ISSCC 2012

Phasor Analysis



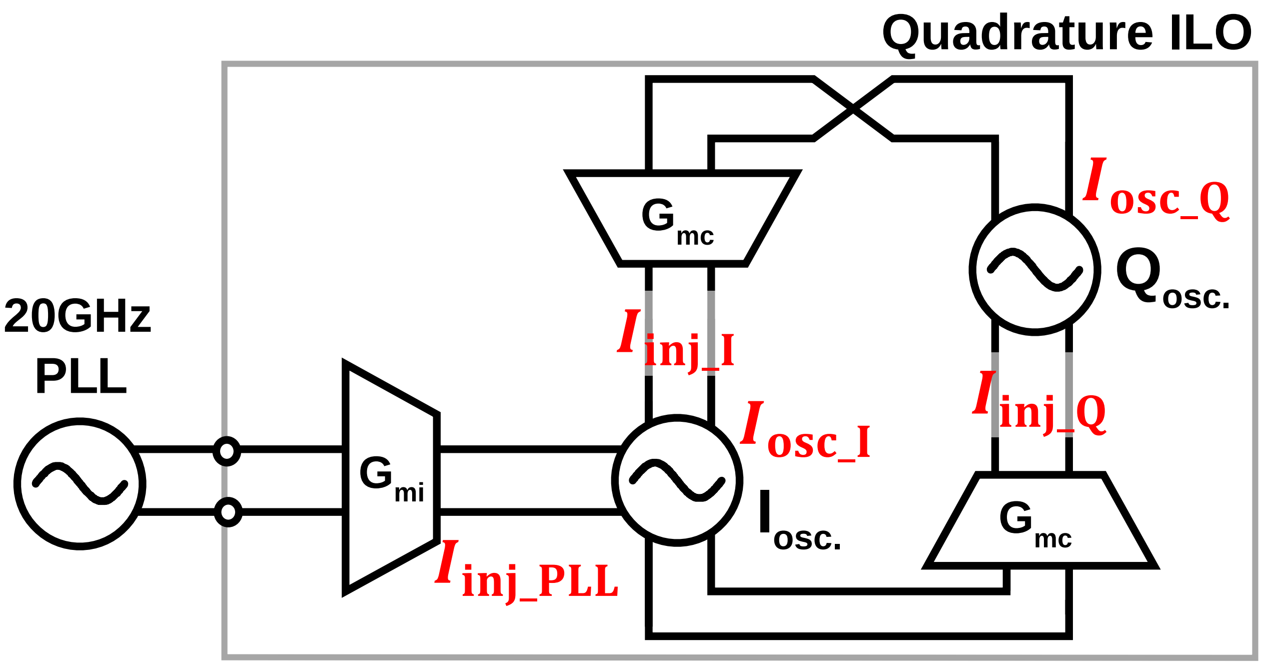
(Zi, Zq : tank impedance)

I/Q phase difference can be controlled by Zi and Zq.

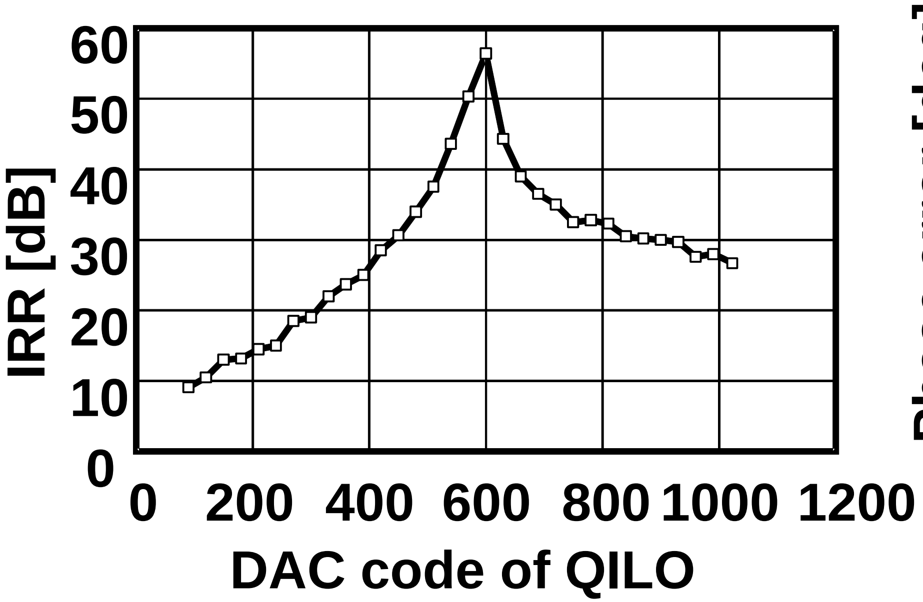
I/Q Phase Shift

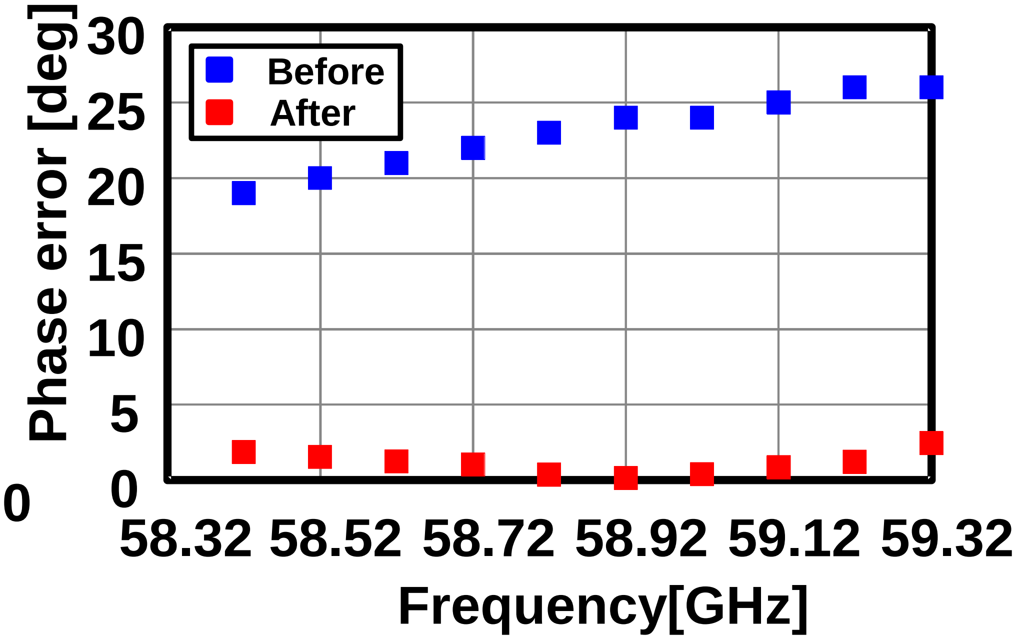
QILO can be used as a very-fine phase shifter.

$$\Delta\phi = \sin^{-1}\left(2Q_{\mathrm{I}}\frac{\omega_{0\mathrm{I}}-\omega_{\mathrm{inj\_PLL(20GHz)}}}{\omega_{0\mathrm{I}}}\frac{I_{\mathrm{osc\_I}}}{I_{\mathrm{inj\_I(60GHz\ Q)}}+\alpha I_{\mathrm{inj\_PLL(20GHz)}}}\right) - \sin^{-1}\left(2Q_{\mathrm{Q}}\frac{\omega_{0\mathrm{Q}}-\omega_{\mathrm{inj\_PLL(20GHz)}}}{\omega_{0\mathrm{Q}}}\frac{I_{\mathrm{osc\_Q}}}{I_{\mathrm{inj\_Q(60GHz\ I)}}}\right)$$



Phase Resolution





I/Q gain cal.: RF VGA

I/Q phase cal. : QILO with 10-bit DAC

0.1 degree/code (estimated) can be realized.

***S. Kawai, *et al*., RFIC 2013**

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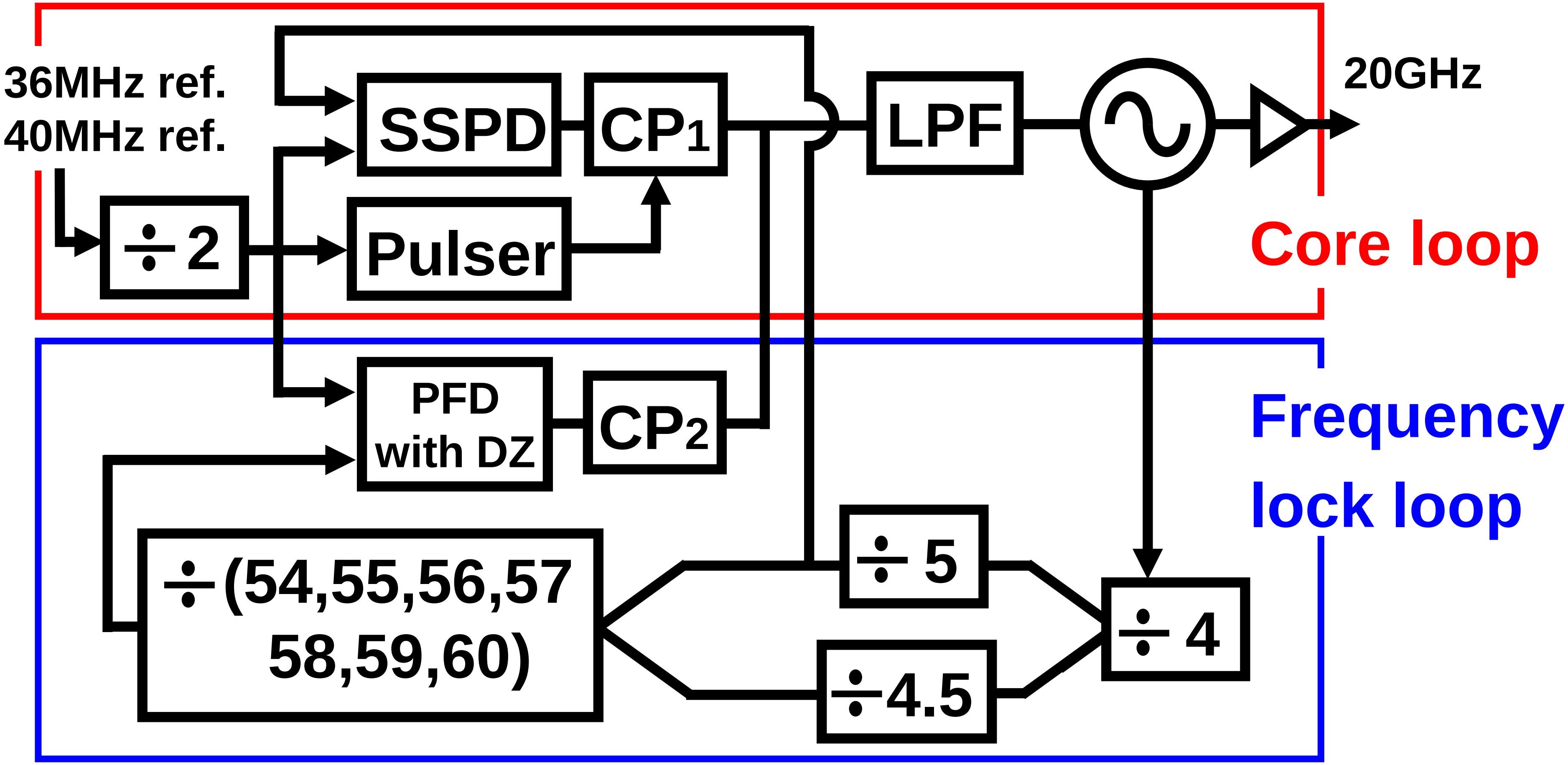
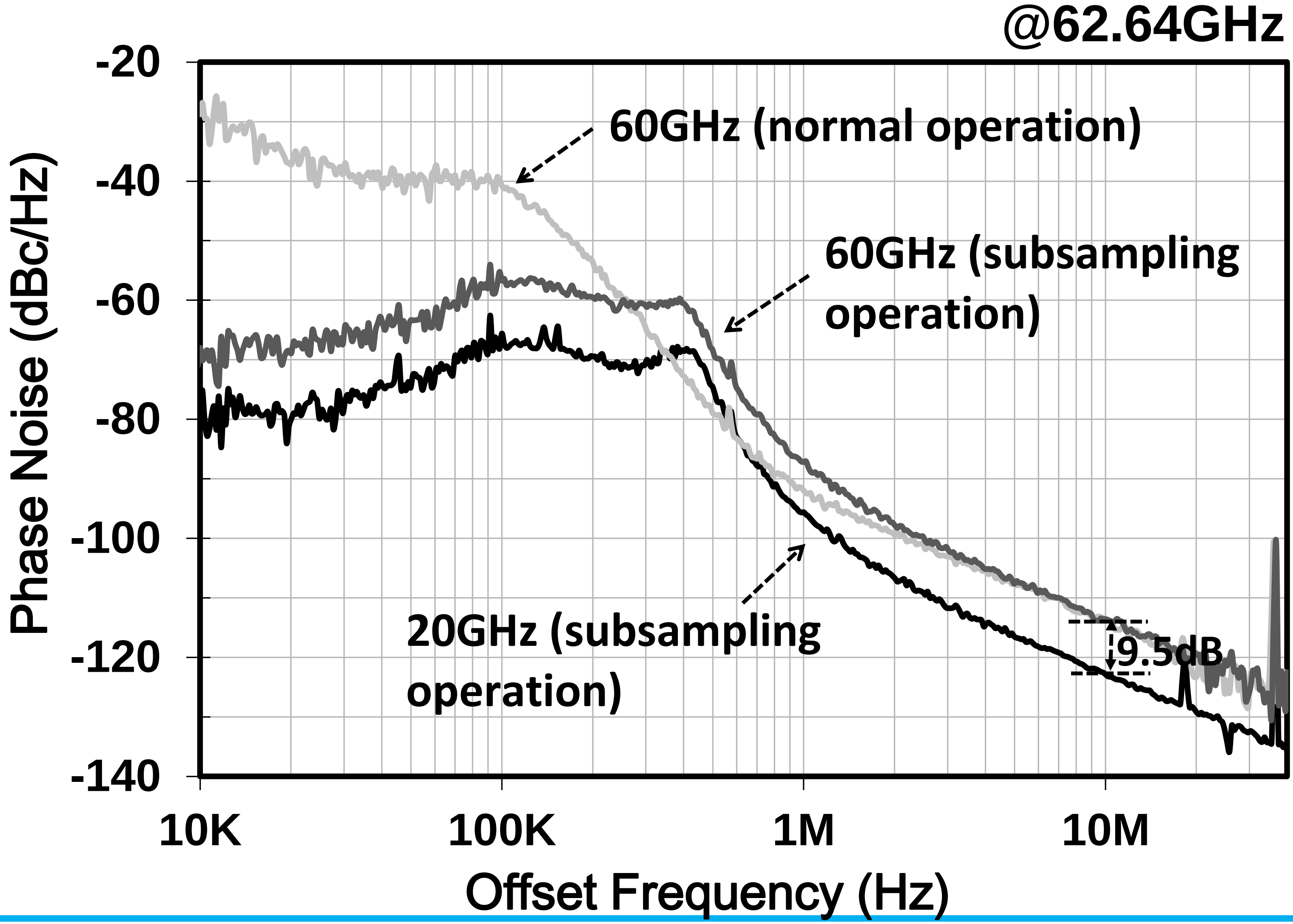
mmW Sub-Sampling PLL

Improvement of in-band phase noise



*T. Siriburanon, *et al*., RFIC 2014 **V. Szortyka, *et al*., ISSCC 2014

Phase Noise of SS-PLL



Phase Noise Comparison

Ref.	REF Freq. (MHz)	Frequency (GHz)	Integrated Jitter (ps)	Phase Noise @10kHz offset	Phase Noise @10MHz offset	Features	Power (mW)
[1]	100	57.0-66.0	1.5	-66 dBc/Hz	-108 dBc/Hz	Direct 60GHz QPLL	78
[2]	203.2	59.6-64.0	2.3	-65 dBc/Hz	-112 dBc/Hz	30GHz PLL + Coupler	76
[3]	100	56.0-62.0	0.94	-71 dBc/Hz	-109 dBc/Hz	60GHz AD-PLL	48
This [6] (normal)	36/40	58.3-65.4	12.0	-40 dBc/Hz	-115 dBc/Hz	Sub-harmonic Injection 20GHz PLL + 60GHz QILO	32.8
This [6] (SS)	36	58.3-65.4	2.1	-69 dBc/Hz	-115 dBc/Hz	Sub-harmonic Injection 20GHz SS-PLL + 60GHz QILO	34.2

[1] K. Scheir, *et al*., ISSCC 2009 [2] C. Marcu, *et al*., JSSC 2009 [3] W. Wu, et al., ISSCC 2013 [4] W. Deng, et al., JSSC 2013 [5] K. Okada, *et al*., ISSCC 2014 [6] T. Siriburanon, *et al*., RFIC 2014

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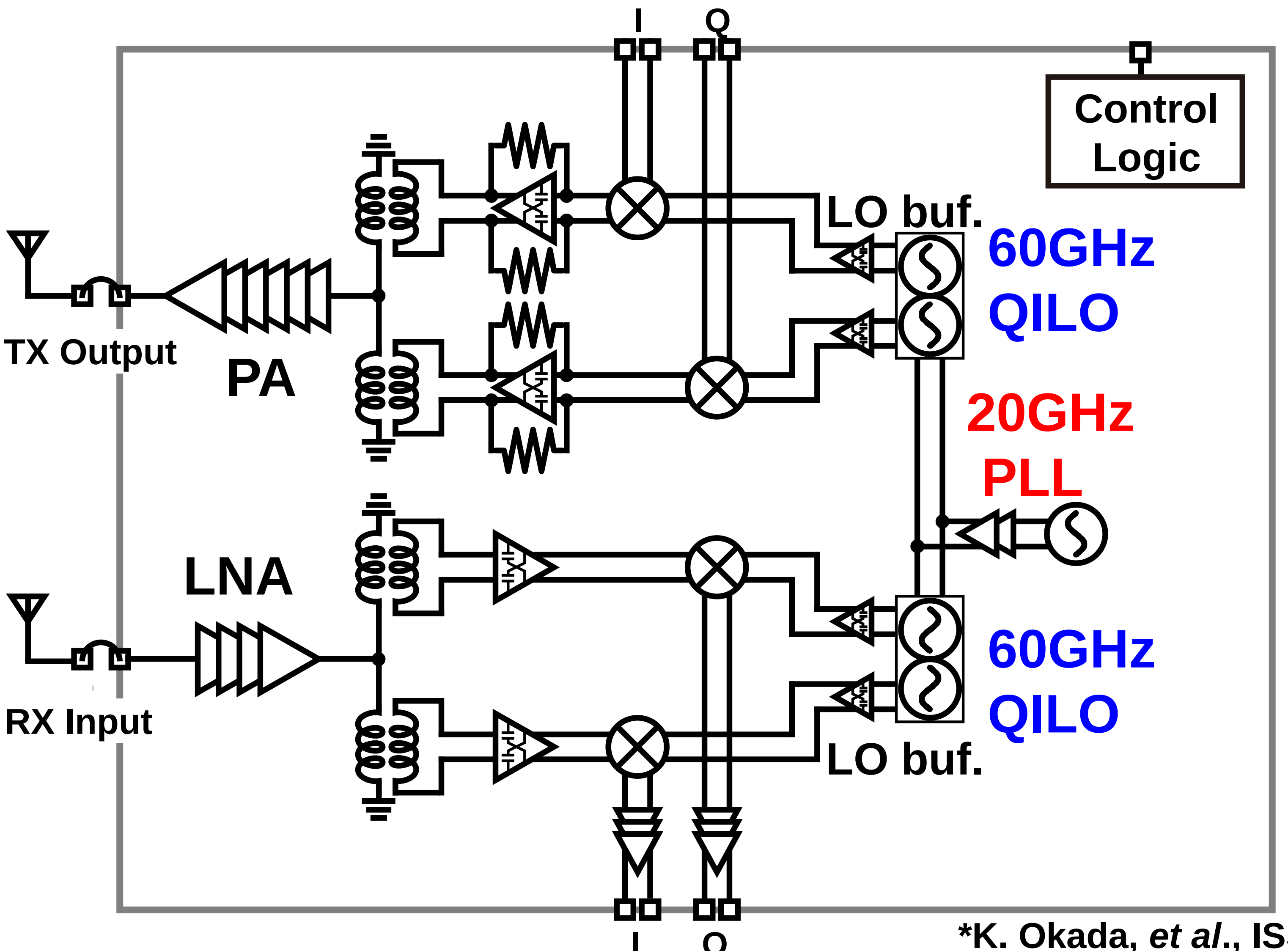
Transceiver Block Diagram

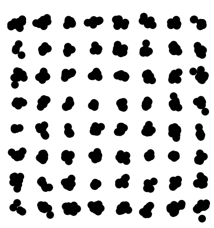
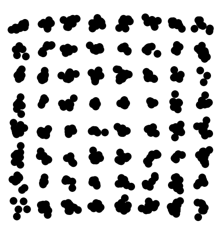
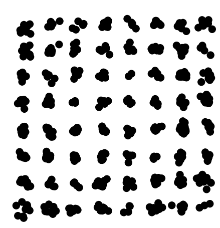
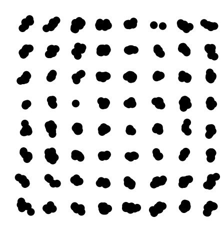
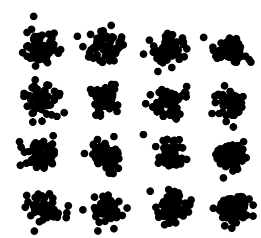
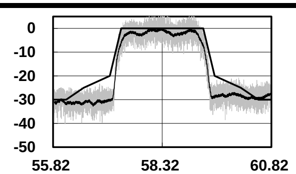
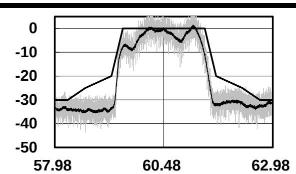
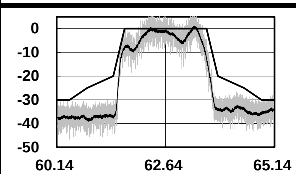
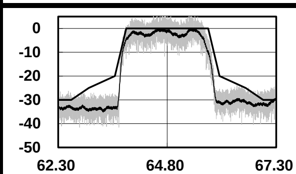
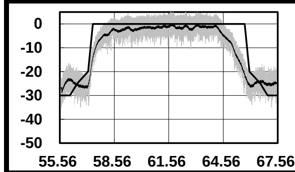


*K. Okada, *et al*., ISSCC 2014

64QAM & 28Gbps 16QAM

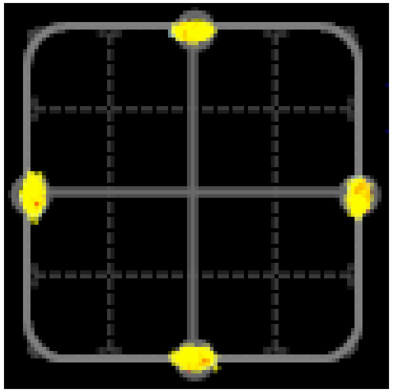
RFIC 2014

64QAM with 10.56Gb/s is achieved for the full 4 channels.

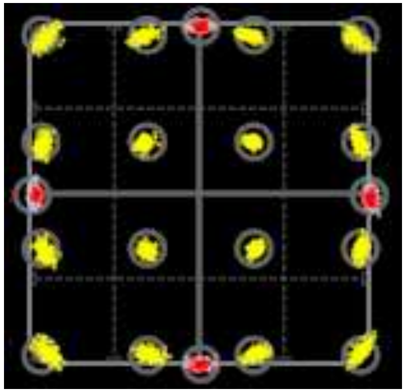
Channel	ch.1 58.32GHz	ch.2 60.48GHz	ch.3 62.64GHz	ch.4 64.80GHz	ch.1-ch.4 bond
Modula-tion	64QAM				16QAM
Data rate	10.56Gb/s	10.56Gb/s	10.56Gb/s	10.56Gb/s	28.16Gb/s
Conste-llation					
Spec-trum					
TX EVM	-27.1dB	-27.5dB	-28.0dB	-28.8dB	-20.0dB
TX-to-RX EVM	-24.6dB	-23.9dB	-24.4dB	-26.3dB	-17.2dB

Measurement for IEEE802.11ad/WiGig

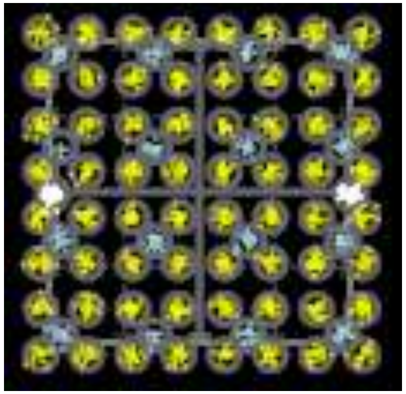
MCS	Modulation		Data rate [Mb/s]	TX EVM [dB]	
				Spec.	Meas.
9	QPSK	SC	2502.5	-15	-27.1
12	16QAM	SC	4620	-21	-27.0
24	64QAM	OFDM	6756.75	-26	-26.5



MCS9



MCS12



MCS24

Measured by Agilent AWG + Osc. + VSA + 81199A in ch.3

Conclusion

- **Phase noise requirement for IEEE802.11ad/WiGig**

  QPSK: -83dBc/Hz@1MHz

  16QAM: -90dBc/Hz@1MHz

  64QAM: -96dBc/Hz@1MHz

- **<20GHz oscillation with a frequency multiplier for good phase noise and wide frequency tuning (58.32-64.80GHz)**
- **The quadrature injection-locked oscillator can be used as a frequency tripler and phase shifter.**
- **A 64QAM transceiver is demonstrated.**

Acknowledgement

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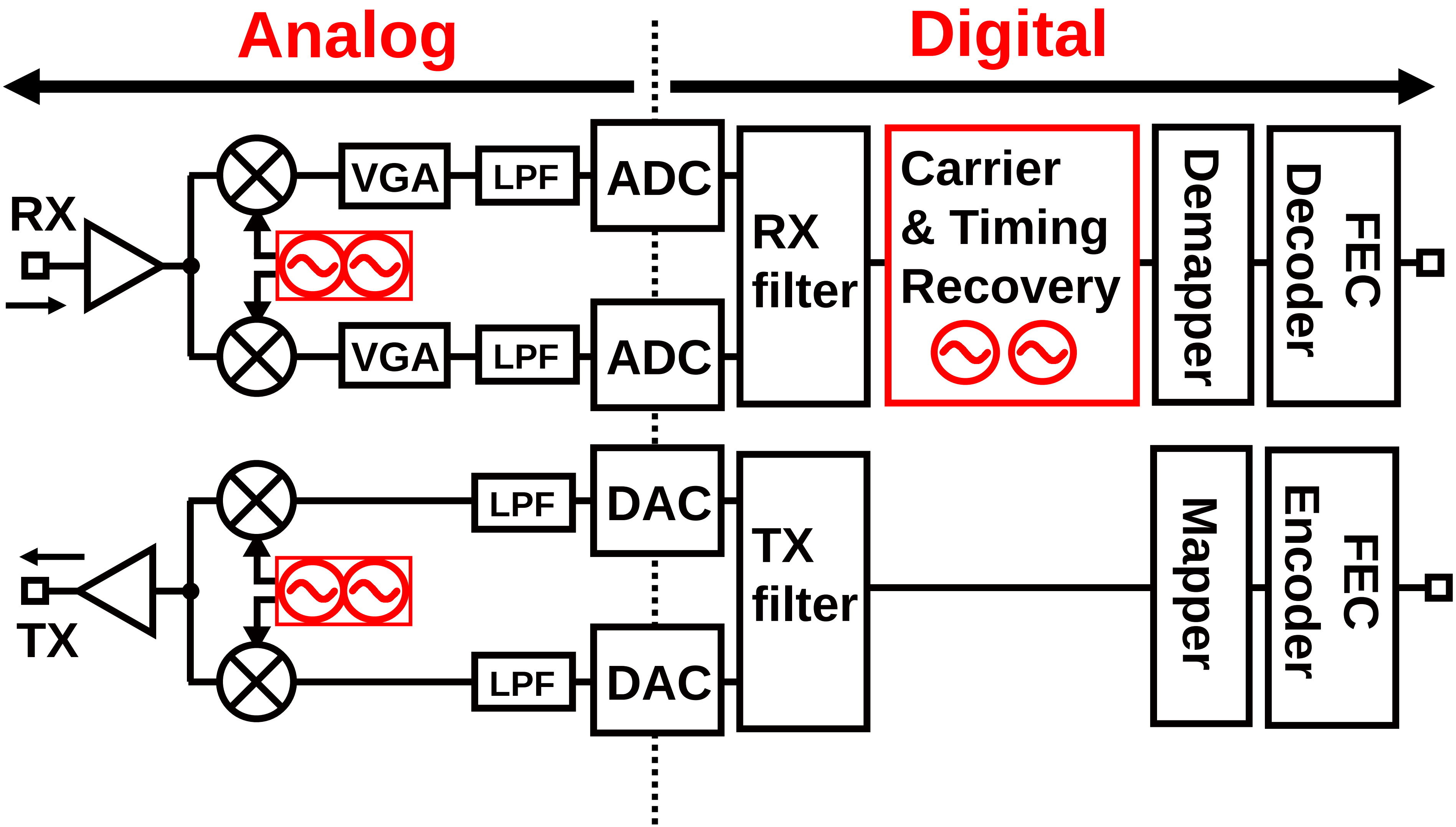
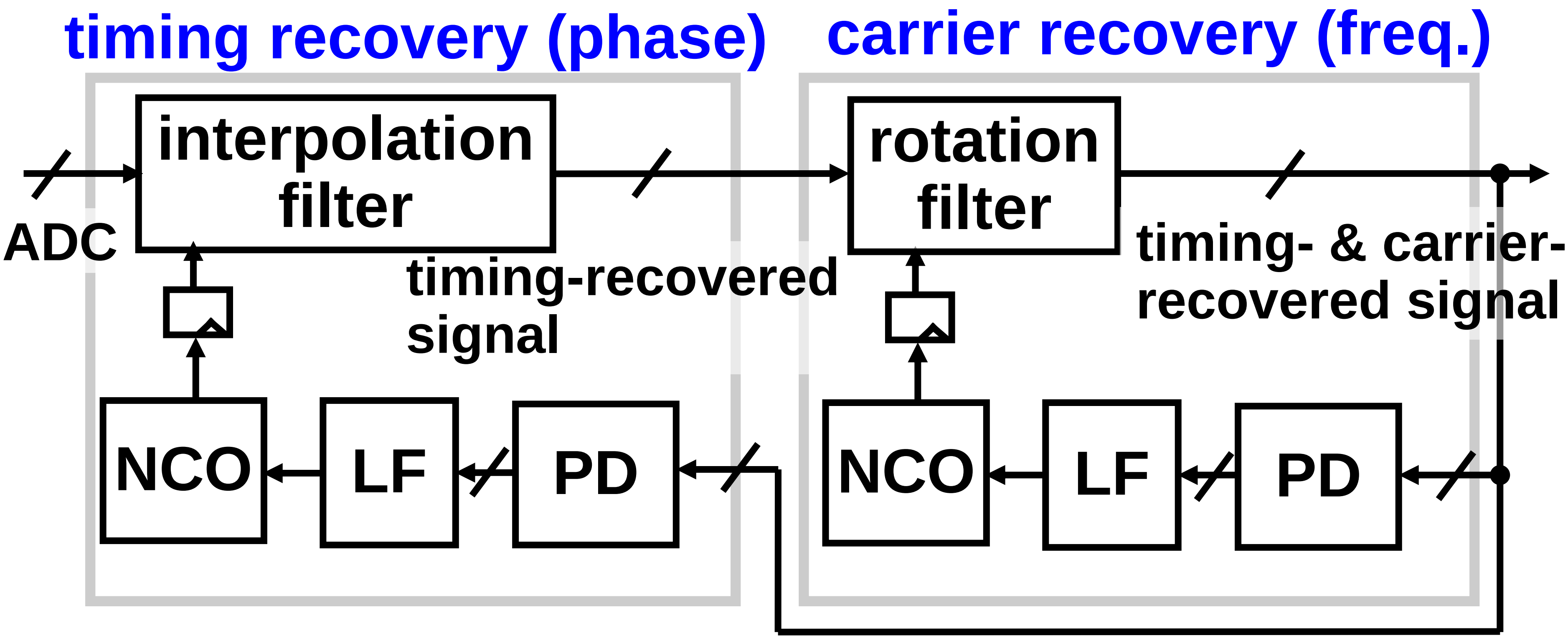
Digital Carrier and Timing Recovery



Digital Carrier and Timing Recovery

RFIC 2014

Cancel in-band phase noise at < f_{track}



NCO: Number-Controlled Oscillator
LF: Loop Filter
PD: Phase Detector