ICTイノベーションフォーラム
2019/10/9

課題番号：175003017

CMOSミリ波帯フェーズドアレイ無線機の研究開発

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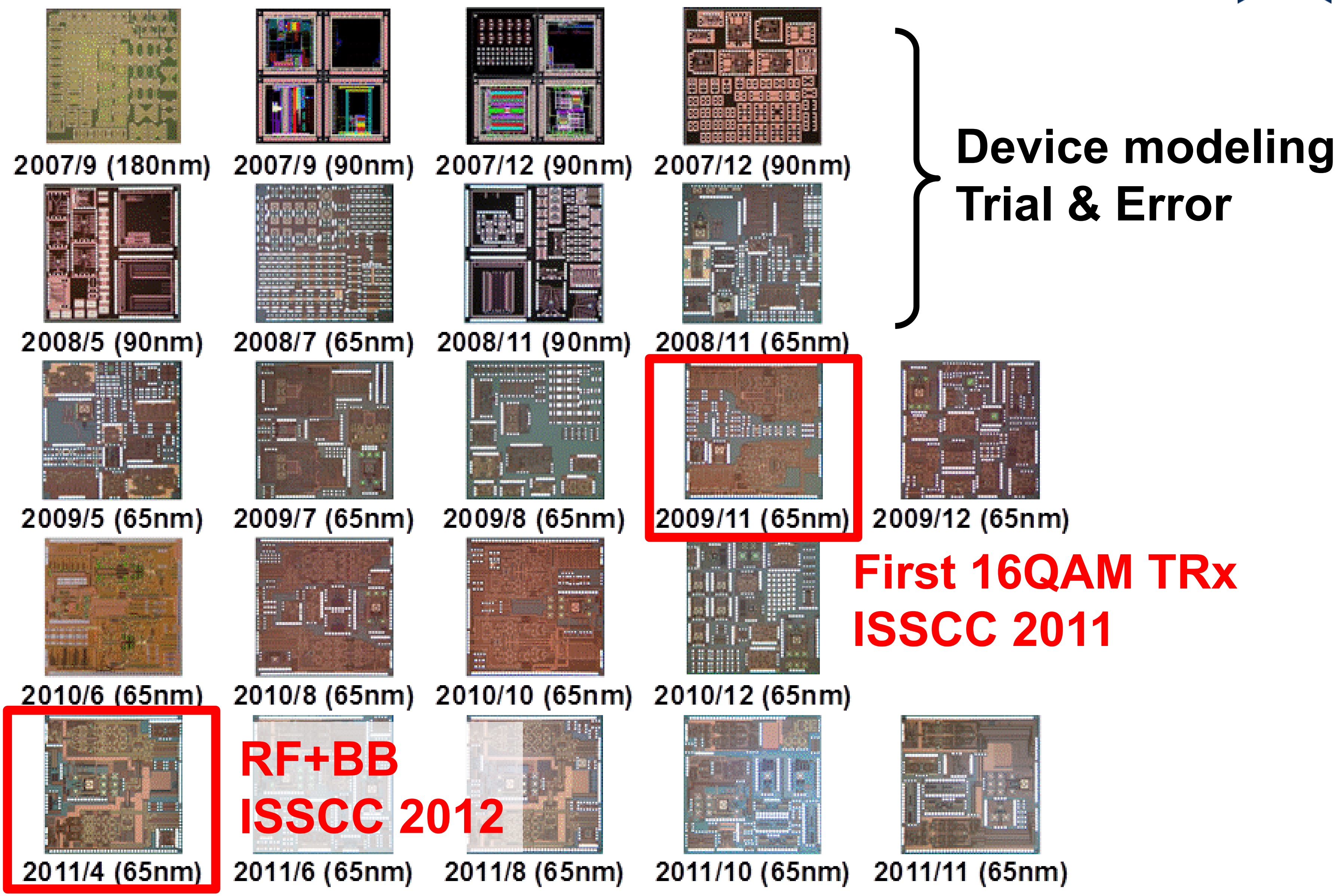
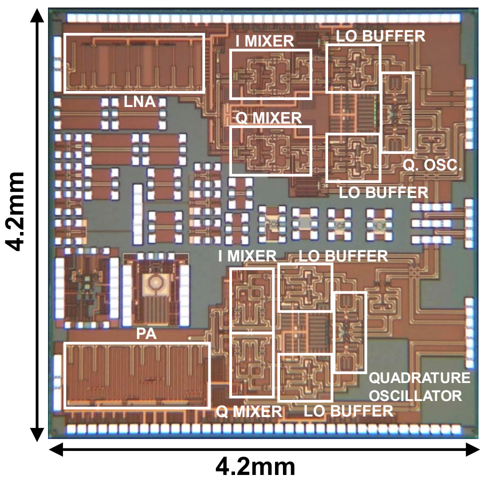
筒井 弘 (北海道大学)

研究期間　平成29年度～平成30年度

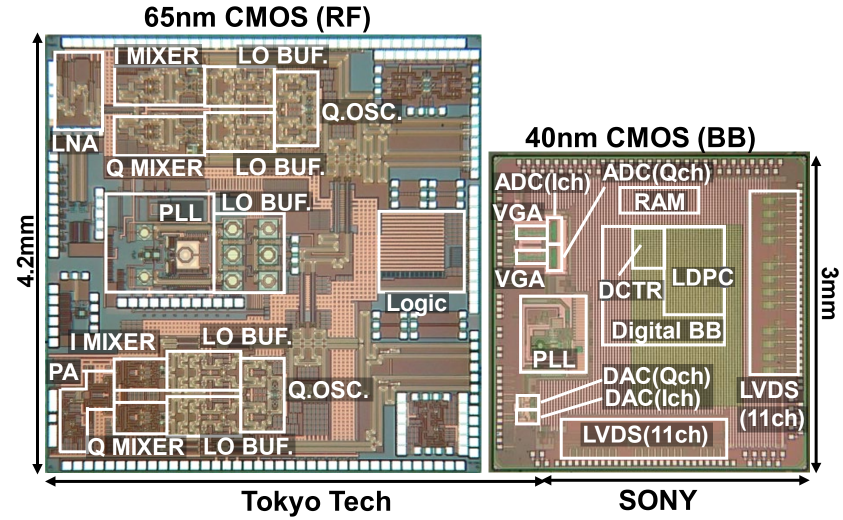
60GHz CMOS R&D in Tokyo Tech since 2007



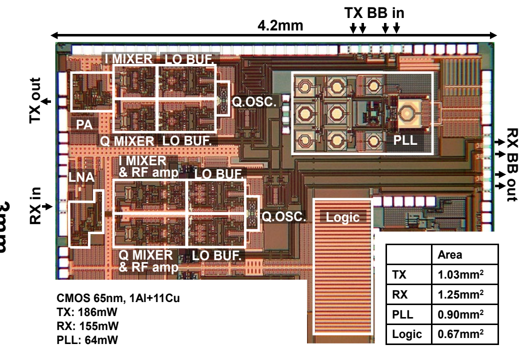
60GHz帯CMOS無線機の開発の歴史



ISSCC 2011
11Gbps by 16QAM
Direct-conversion

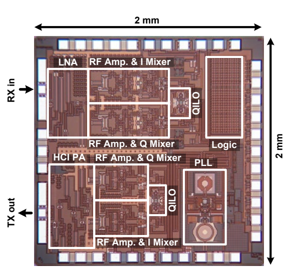


ISSCC 2012
RF+ABB+DBB

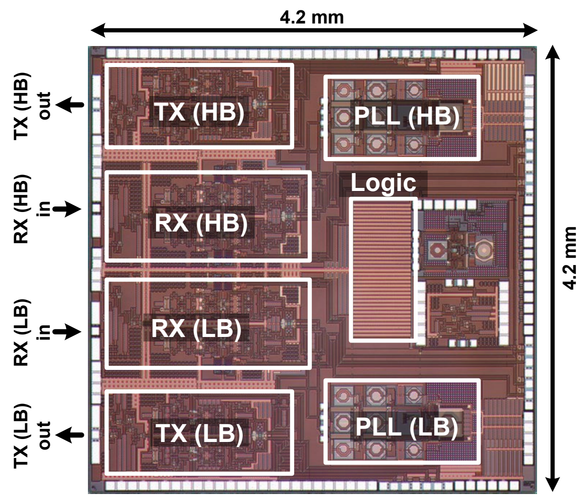


	Area
TX	1.03mm²
RX	1.25mm²
PLL	0.90mm²
Logic	0.67mm²

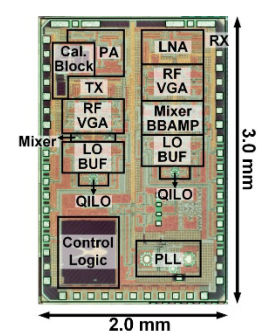
ISSCC 2014
28Gbps by 16QAM



ISSCC 2015
HCI-recovery

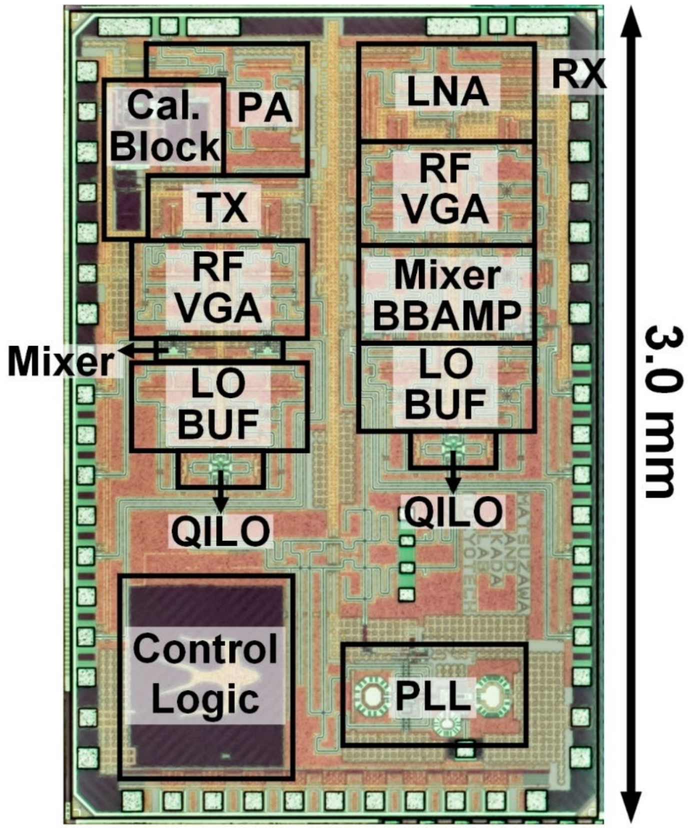


ISSCC 2016
42Gbps by 64QAM



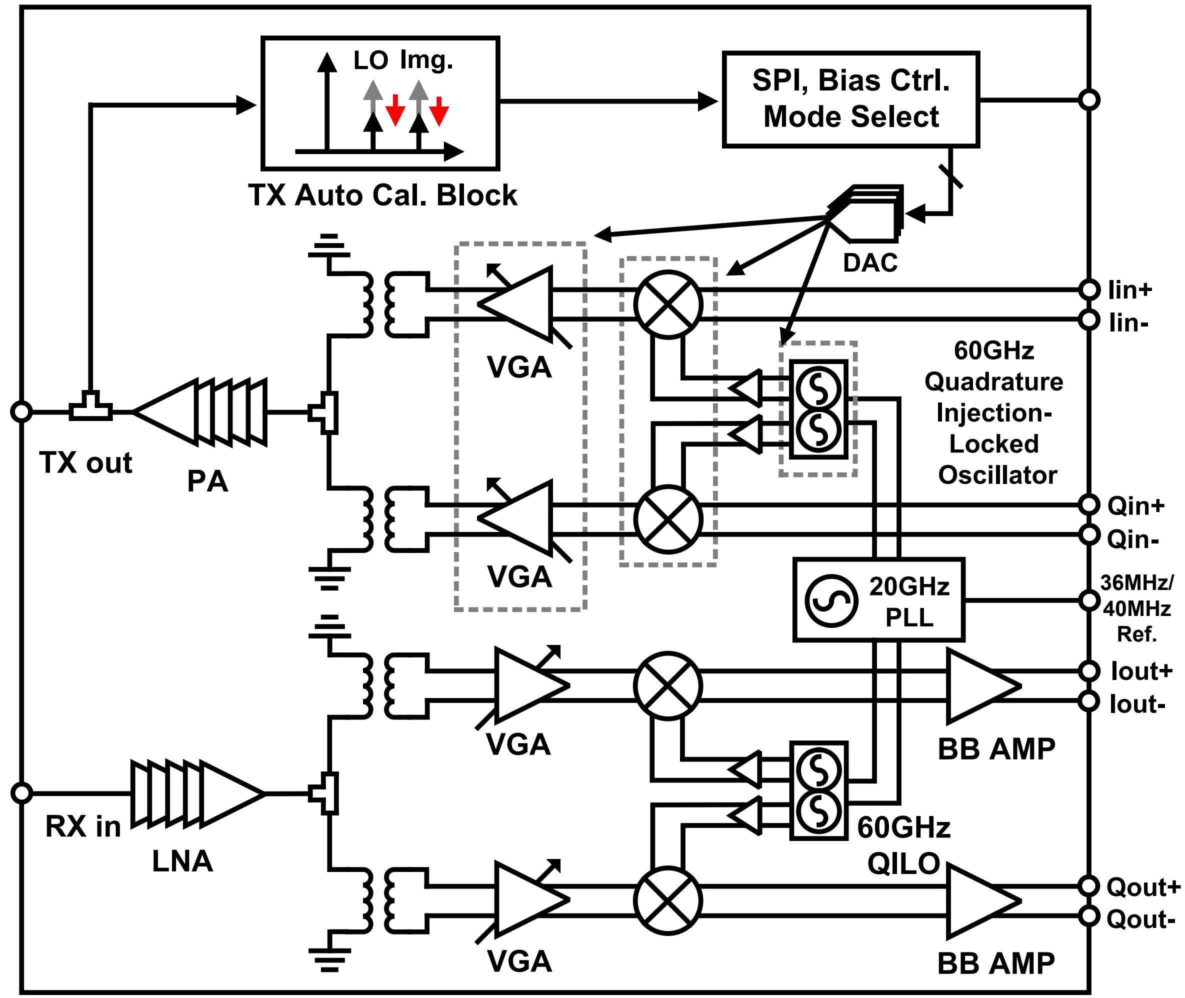
ISSCC 2017
50Gbps, 128QAM
Self-calibration

60GHz帯CMOS無線機



65nm CMOS

自動校正機能を内蔵

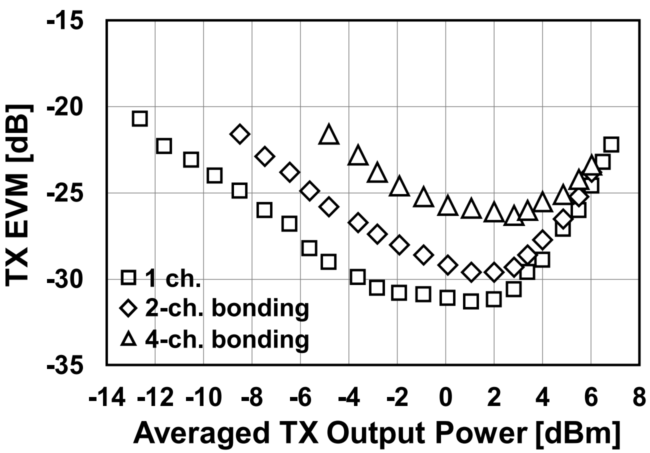


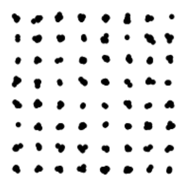
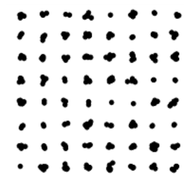
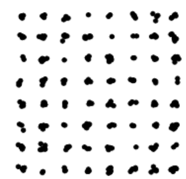
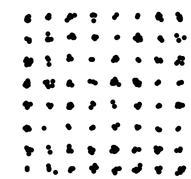
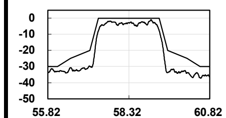
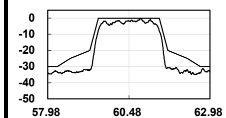
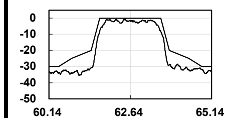
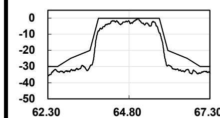
J. Pang *et. al.*, ISSCC 2017

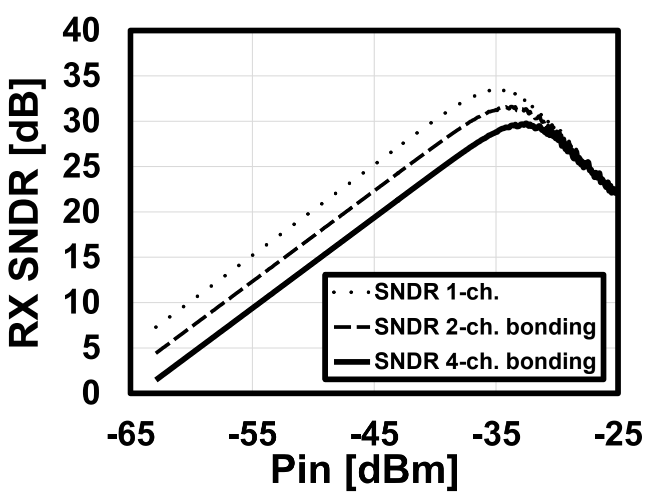
Tokyo Tech

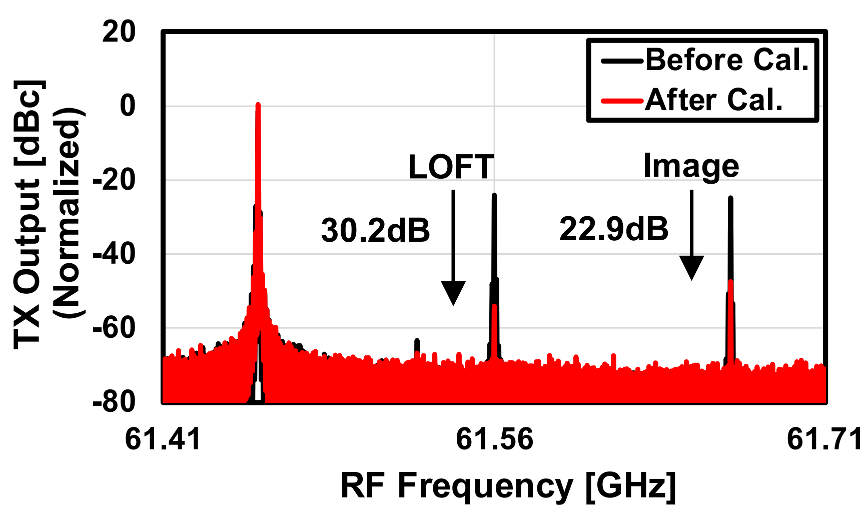
実測評価

Up to 50.1Gbps



Channel/ Carrier freq.	ch.1 58.32GHz	ch.2 60.48GHz	ch.3 62.64GHz	ch.4 64.80GHz
Modulation	64QAM			
Data rate*	10.56Gb/s	10.56Gb/s	10.56Gb/s	10.56Gb/s
Constellation**				
Spectrum**				
TX EVM**	-30.3dB	-30.0dB	-29.3dB	-28.4dB
TX-to-RX EVM***	-28.2dB	-27.0dB	-25.2dB	-27.1dB

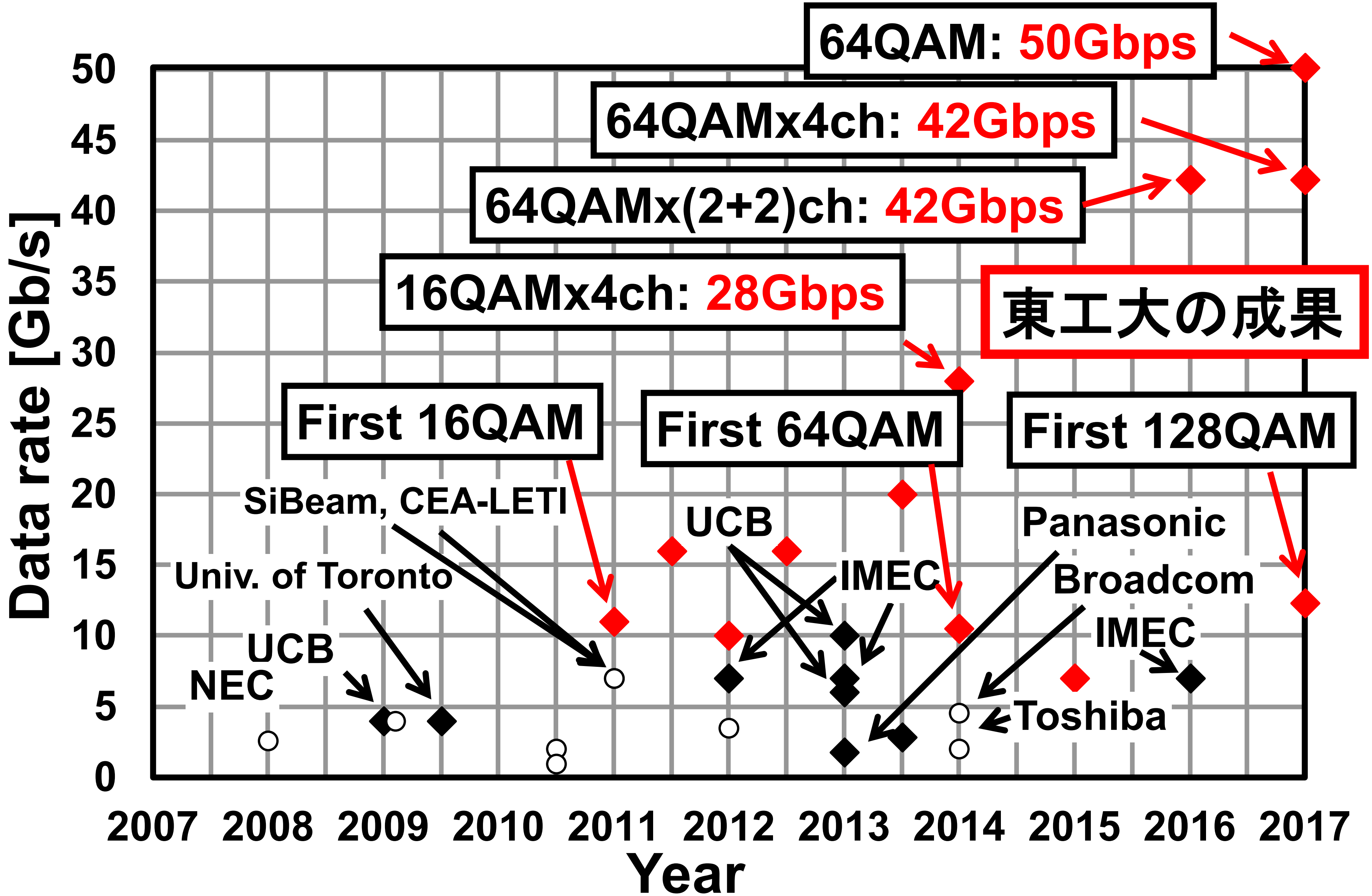




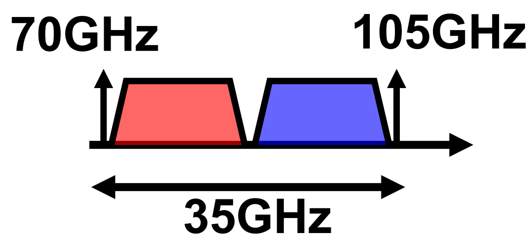
IMRR: <-50dB

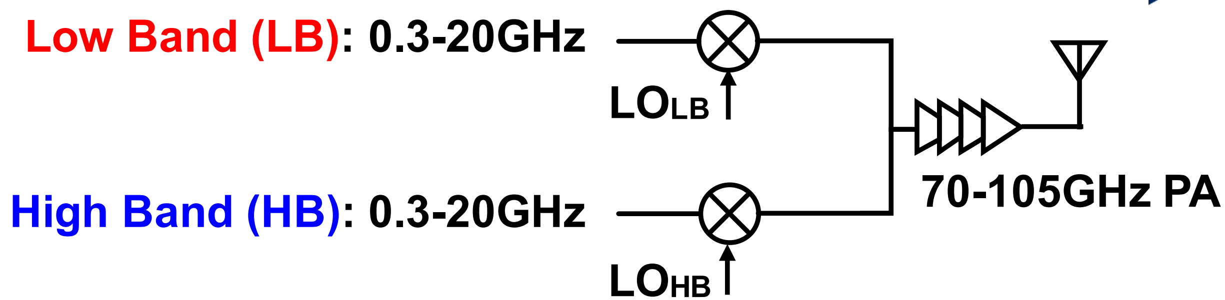
LOFT: <-50dBc

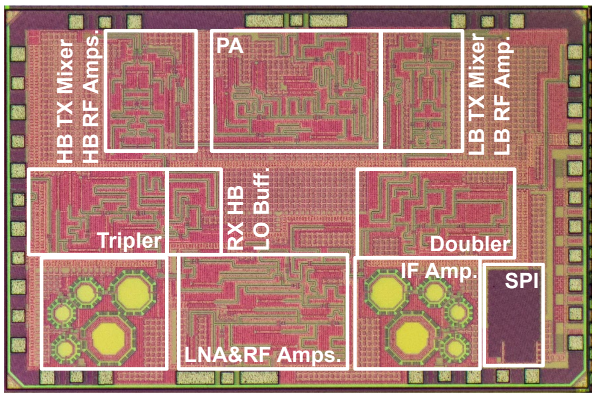
60GHz帯無線機の性能比較



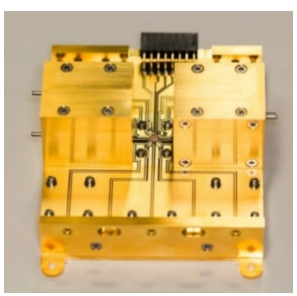
120Gbps 100GHz帯CMOS無線機



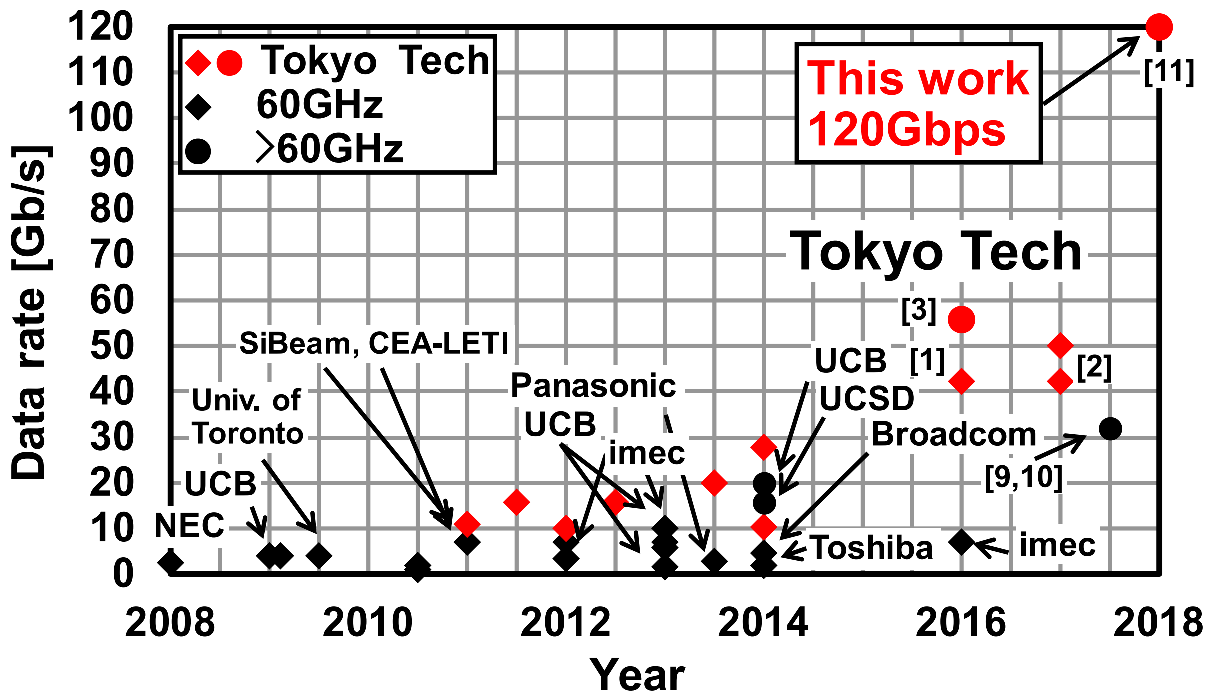




65nm CMOS, 2mm x 3mm
TX: 110mW, RX: 177mW



waveguide module

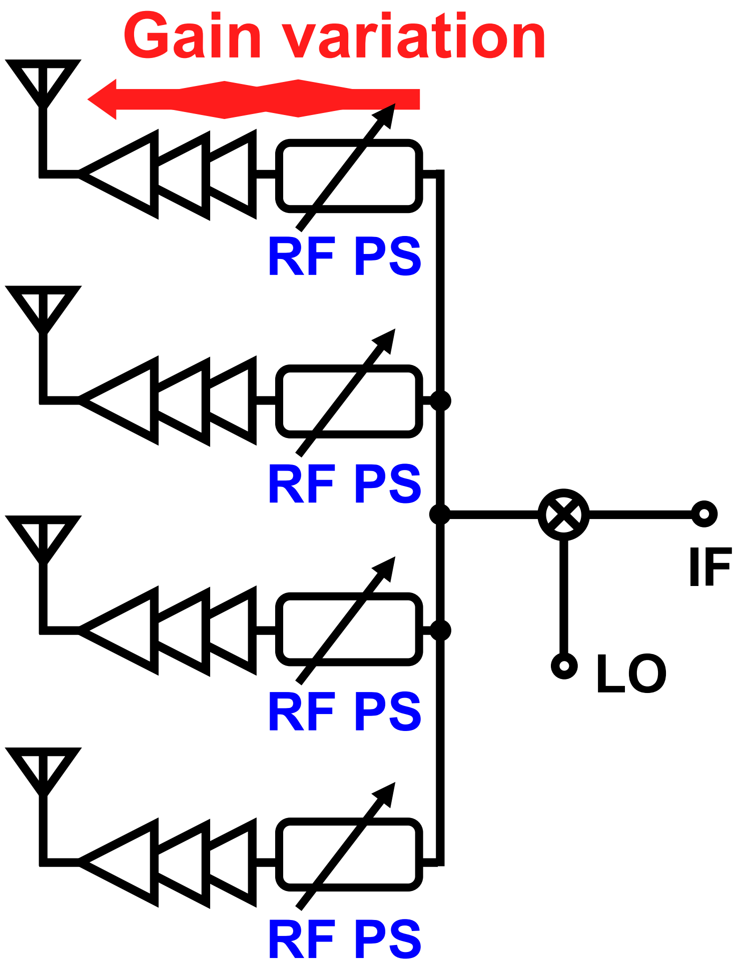


16QAM, 23dBi horn 120Gb/s @ 0.2m
(with 56dBi antenna 120Gb/s @ 400m is possible)

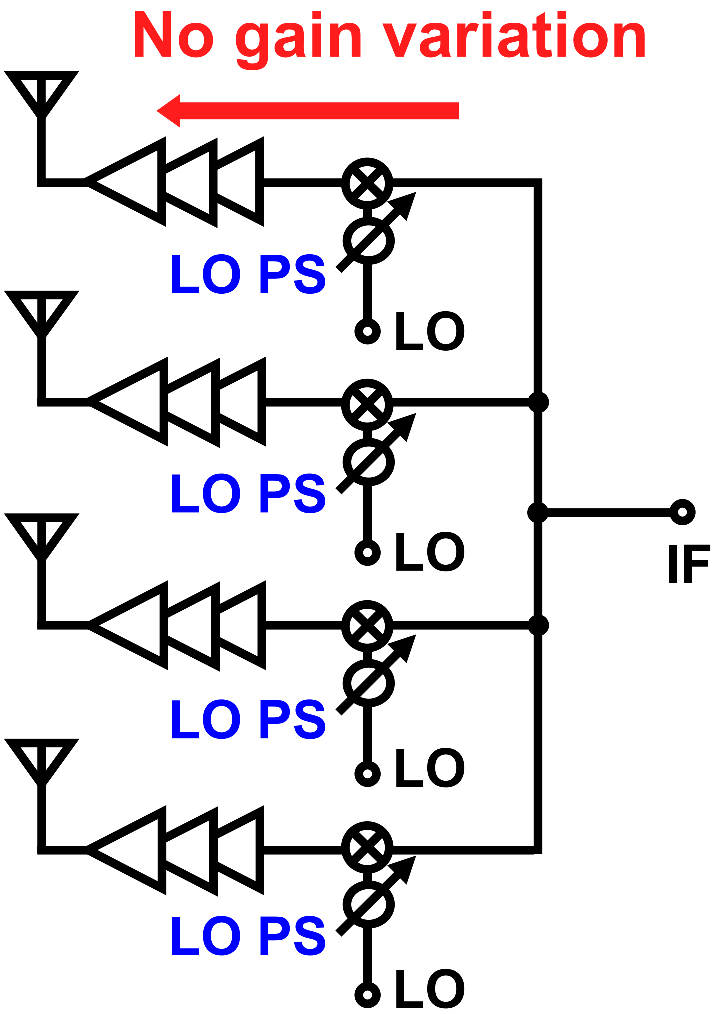
K.K.Tokgoz, ISSCC 2018

フェーズドアレイ方式

RF Phase Shifter

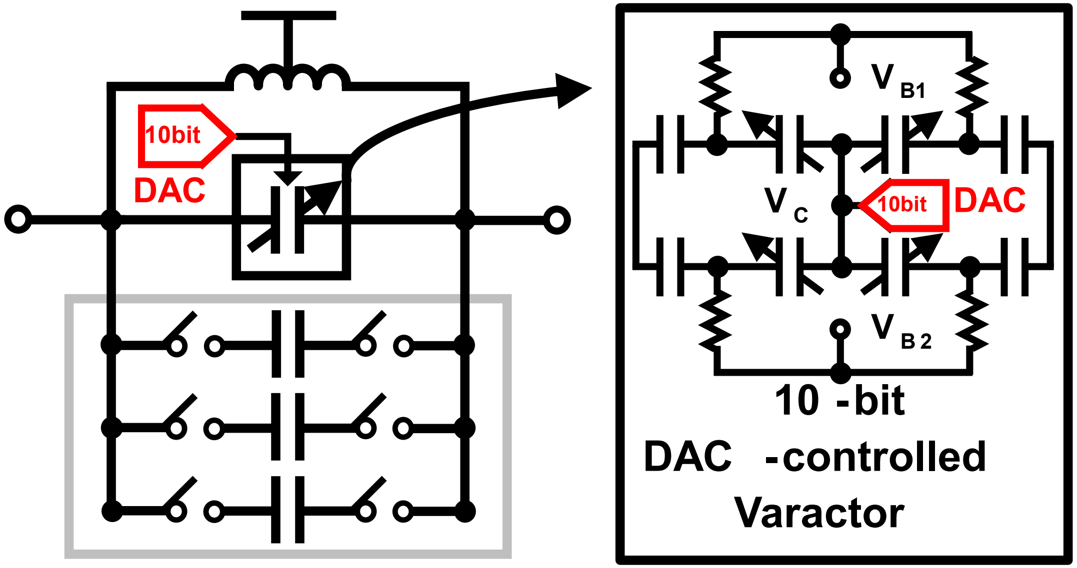


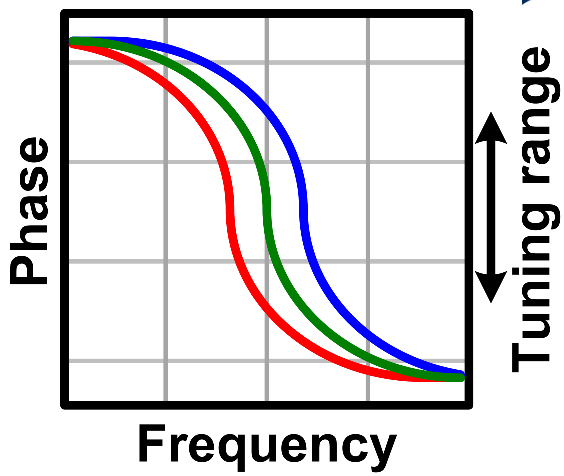
LO Phase Shifter (This work)

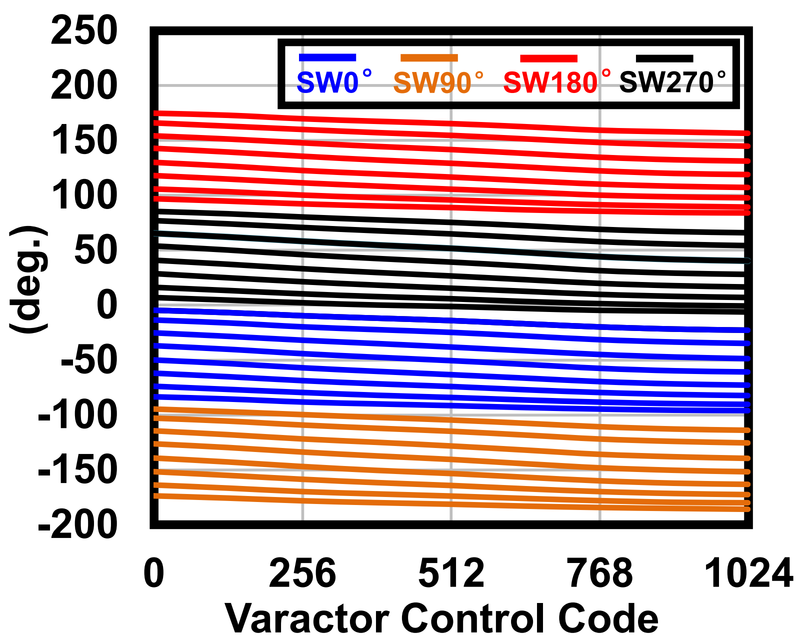


J. Pang, et al., RFIC2018, JSSC2019

共振器型位相器





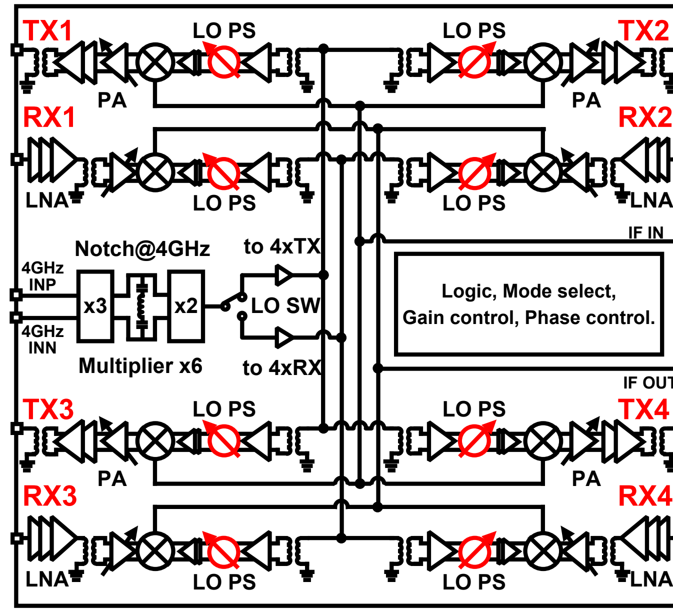


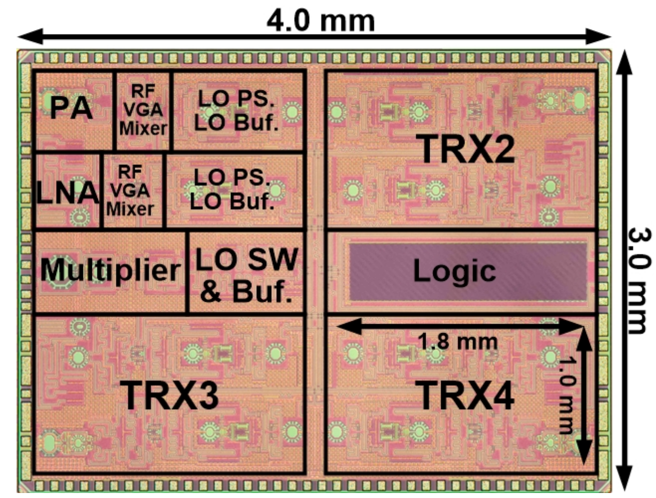
- DC-to-phase conversion
- 0.04degree resolution by 10-bit DAC

J. Pang, et al., RFIC2018, JSSC2019

28GHz帯フェーズドアレイ無線機

- **28GHz 4-element TRX**
- **65nm CMOS**
- **LO phase shifting**
  - Gain-invariant tuning
  - Small phase error
- **Heterodyne**
  - 4-GHz IF in / out
- **Symmetric & differential IF signal distribution**
- **Symmetric & single-ended LO distribution**

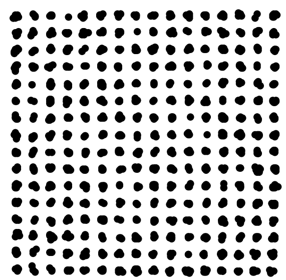
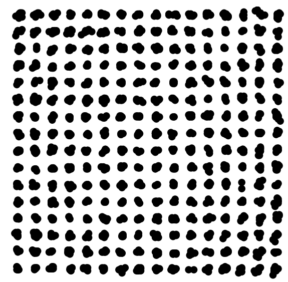
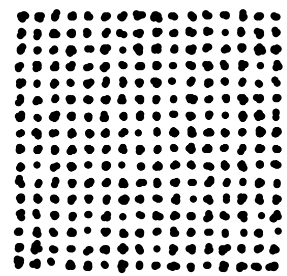
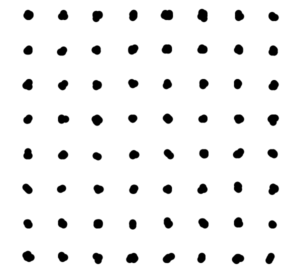




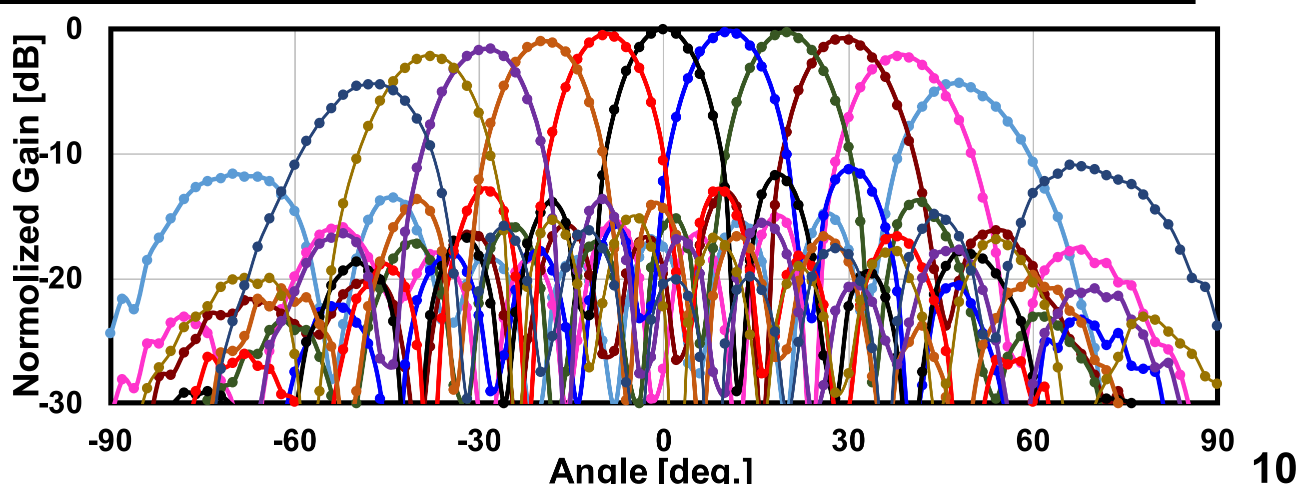
J. Pang, et al., RFIC2018, JSSC2019

OTA評価

With 0°, 20°, 50° beam direction

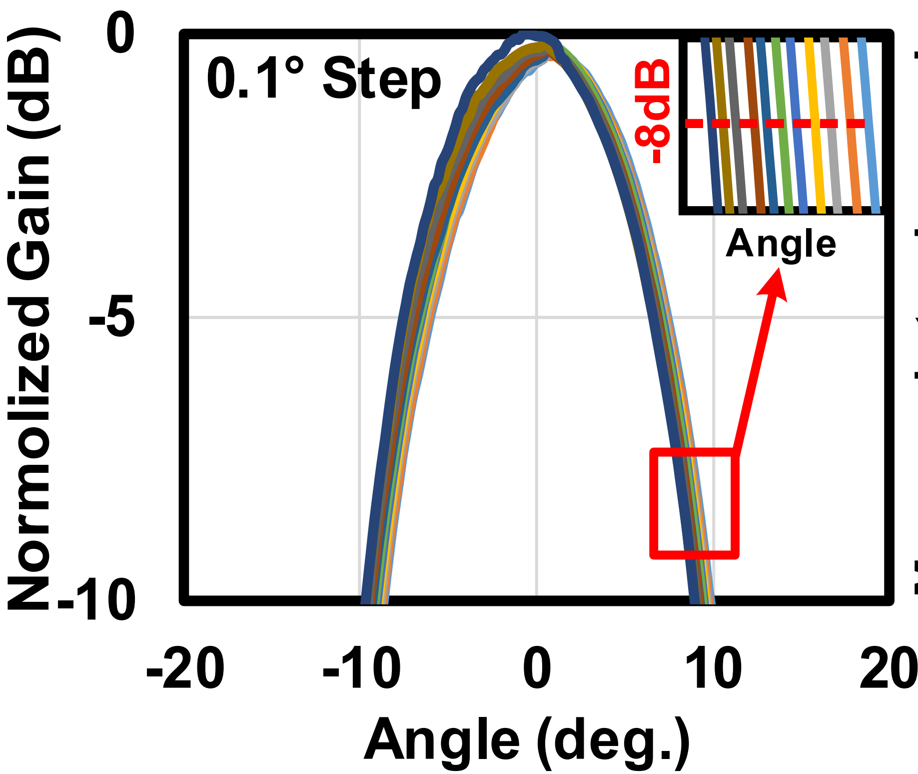
5m OTA Measurement	Modulation	256QAM	256QAM	256QAM	64QAM
	Data rate	6.4Gb/s	6.4Gb/s	6.4Gb/s	4.8Gb/s
	Beam direction	0°	20°	50°	NLOS (20°)
	Constellation*				
	TX EVM (RMS)*	-36.7dB (1.5%)	-36.3dB (1.5%)	-35.9dB (1.6%)	-36.6dB (1.5%)
	TX-to-RX EVM (RMS)**	-34.9dB (1.8%)	-33.4dB (2.1%)	-30.7dB (2.9%)	-22.9dB (7.2%)

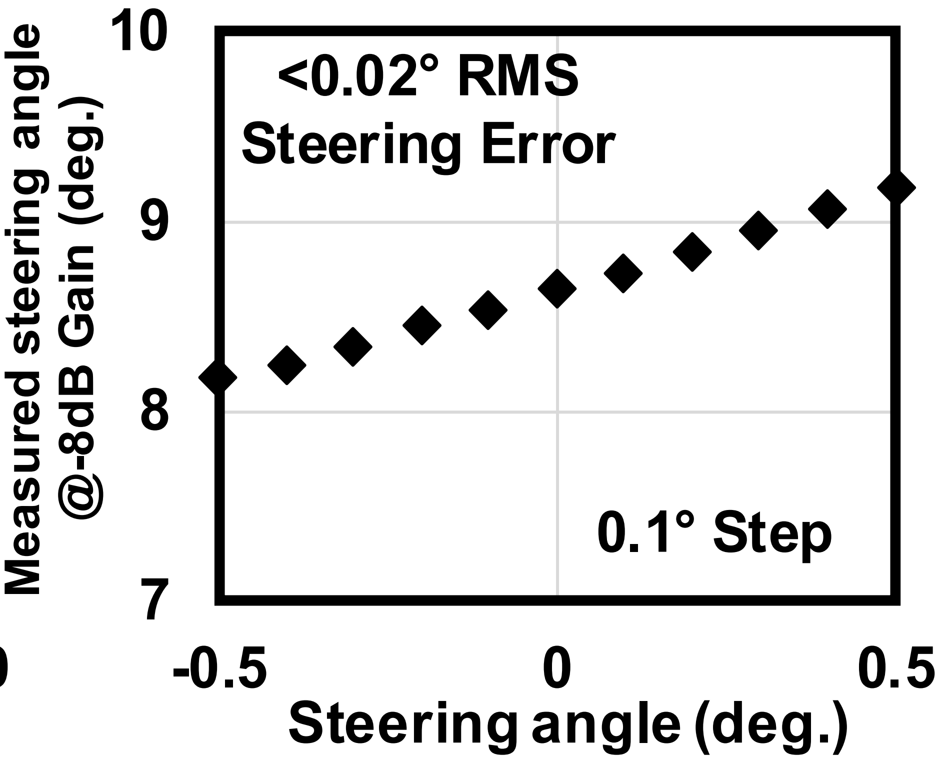
RMS Gain Error	<0.03dB
RMS Phase Error	0.28°
Beam-steering Res.	0.1°



K. Okada

0.1度のビーム制御精度





J. Pang, et al., RFIC2018, JSSC2019

28GHzフェーズドアレイICの比較

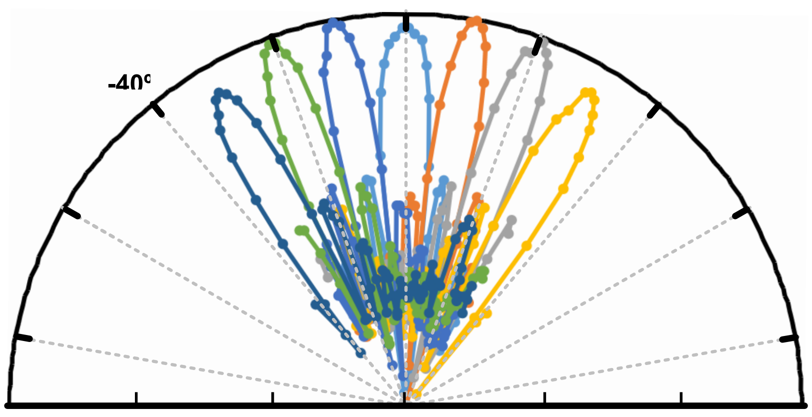
	This work	[2] UCSD	[1] IBM	[3] Qualcomm
Process	65nm CMOS	0.18μm SiGe	0.13μm SiGe	28nm CMOS
PS Architecture	LO PS	RF PS	RF PS	RF PS
Beam-steering Res.	0.1°	1°	1.4°	-
P_{1dB}/path	15.7dBm	10dBm	14dBm	12dBm
Psat/path	18.0dBm	13dBm	16.4dBm	14dBm
Max Data Rate	15Gbps 64QAM, 256QAM	3Gbps 64QAM, 256QAM	3.5Gbps	2.4Gbps 64QAM
Chip Area	$12mm^2$	$11.7mm^2$	$165.9mm^2$	$27.8mm^2$

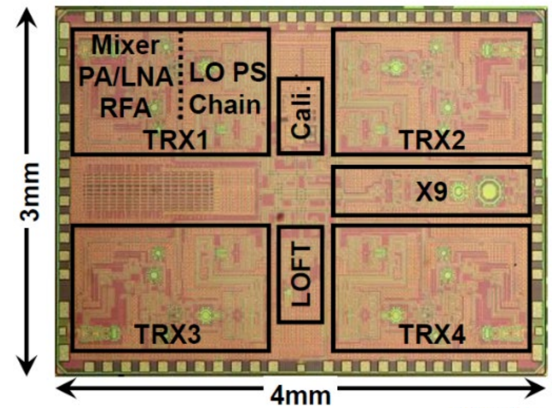
[1] B. Sadhu, et al., IEEE JSSC 2017 [2] K. Kibaroglu, et al., IEEE JSSC 2018
[3] J. Dunworth, et al., ISSCC 2018

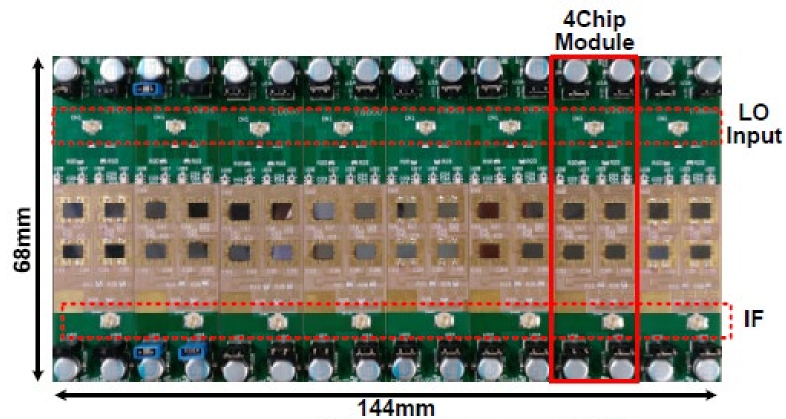
J. Pang, et al., RFIC2018, JSSC2019

39GHzフェーズドアレイ無線機

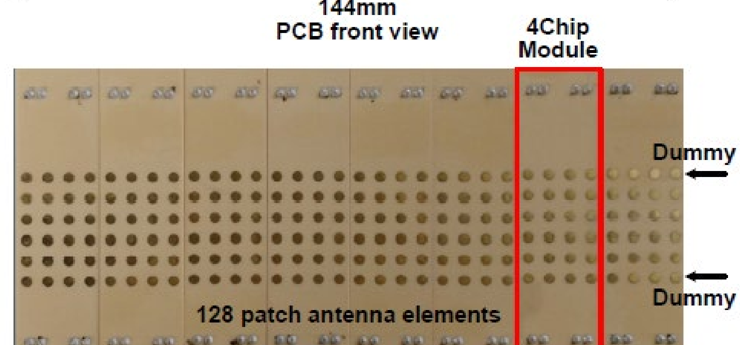
- 64素子構成
- 位相差検出機構を内蔵



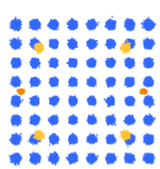
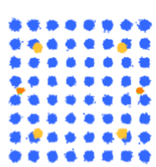
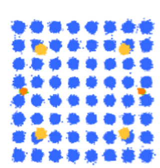




PCB front view



PCB back view

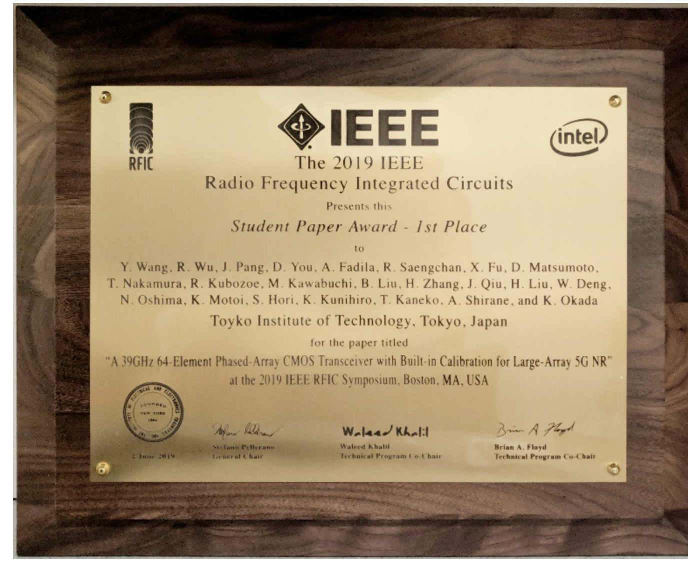
1m OTA Measurement				
	Modulation	64QAM MCS19	64QAM MCS19	64QAM MCS19
	BW	400MHz	400MHz	400MHz
	Beam direction	0°	20°	40°
	TX to RX Constellation			
	TX to RX EVM*	-30.2dB	-30.1dB	-28.6dB

*RMS power normalized EVM, measured with external down-conversion mixer

Y. Wang, et al., RFIC2019

IEEE RFIC Symposium 2019 @ Boston
Best Student Paper Award

Tokyo Tech

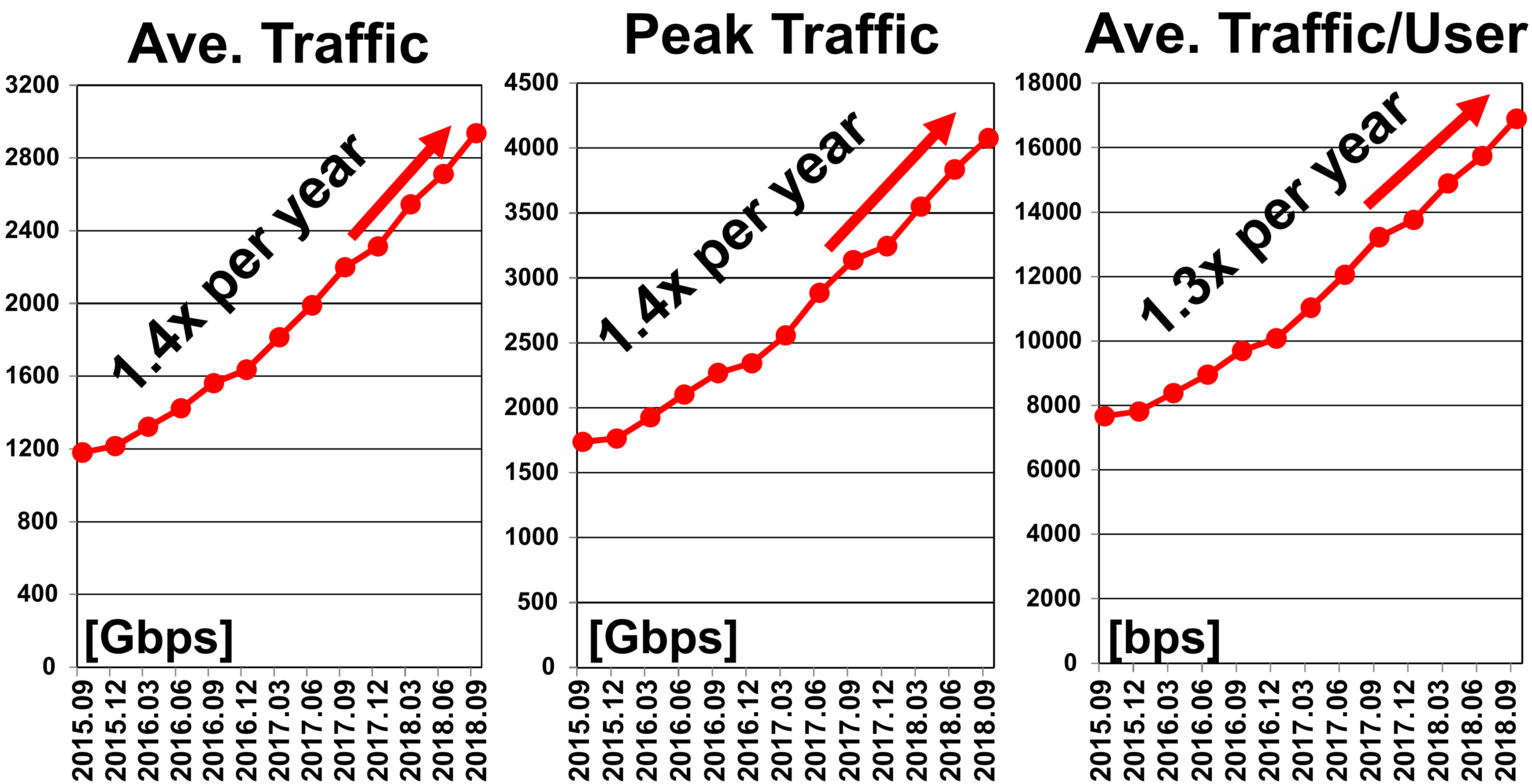


Future Direction & Conclusions

Demand for higher data rate

- Traffic Trend in Japan

$1.4^{20}=900$



http://www.soumu.go.jp/johotsusintokei/field/data/gt010602.pdf

Theoretical Data Rate Limit

$$C = B \log_2(1 + S/N)$$
$$N = \mathrm{kT}\,B$$
$$S = P_\mathrm{r} = P_\mathrm{t} G_\mathrm{t} G_\mathrm{r} \left(\frac{c}{4\pi f_\mathrm{c} d} \right)^2$$
$$B = \alpha\, f_\mathrm{c}$$

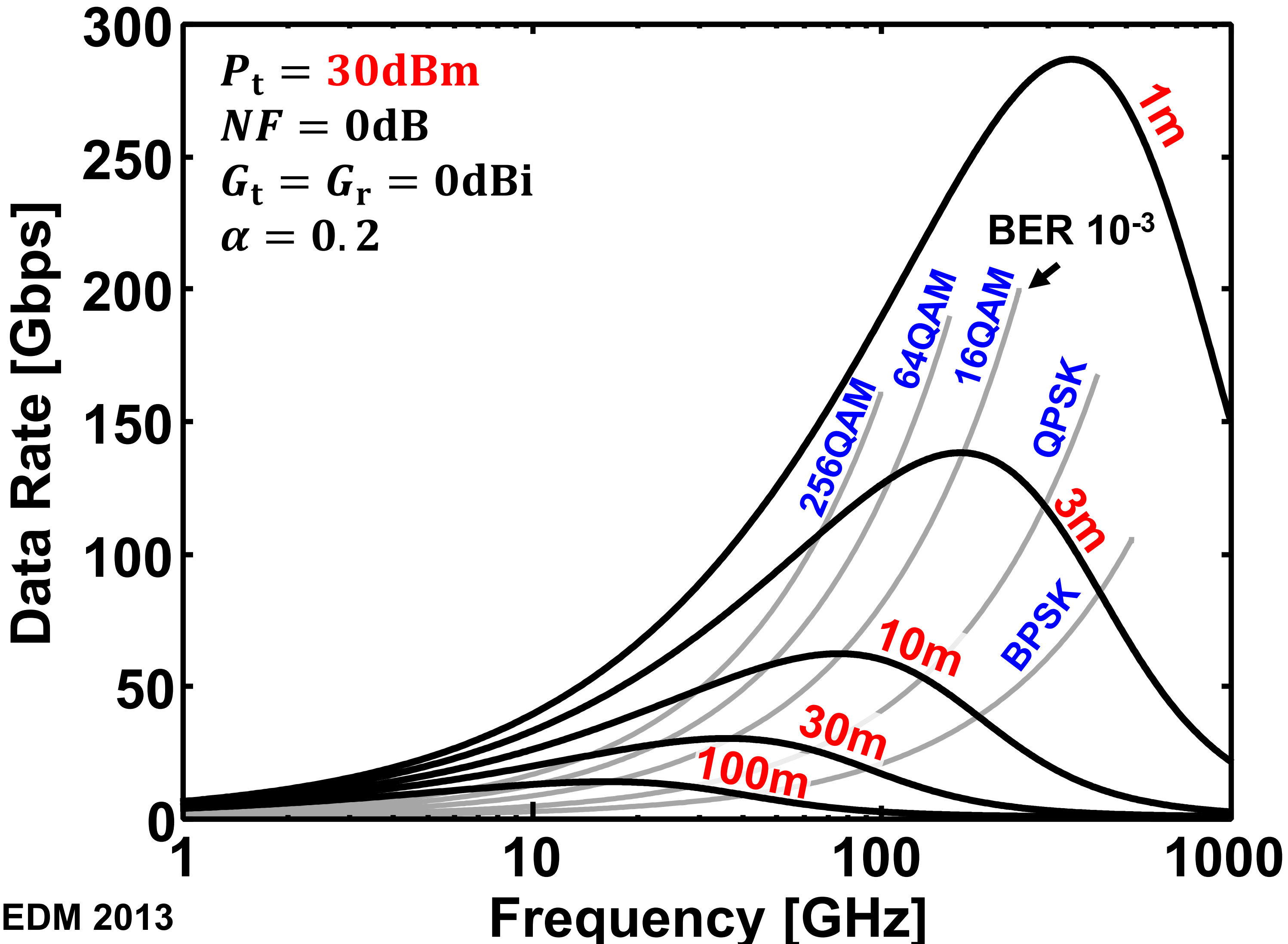
new assumption

$$C_\mathrm{peak} = C_0 \alpha^{\frac{2}{3}} \left(\frac{P_\mathrm{t} G_\mathrm{t} G_\mathrm{r}}{d^2} \right)^{\frac{1}{3}}$$
$$C_0 = 822\mathrm{Gb/s}$$

C: channel capacity
B: bandwidth
S: signal power
N: noise power
P_t: transmitting power
P_r: receiving power
G_t G_r: antenna gains
f_c: carrier frequency
c: light of speed
d: distance btw Tx and Rx

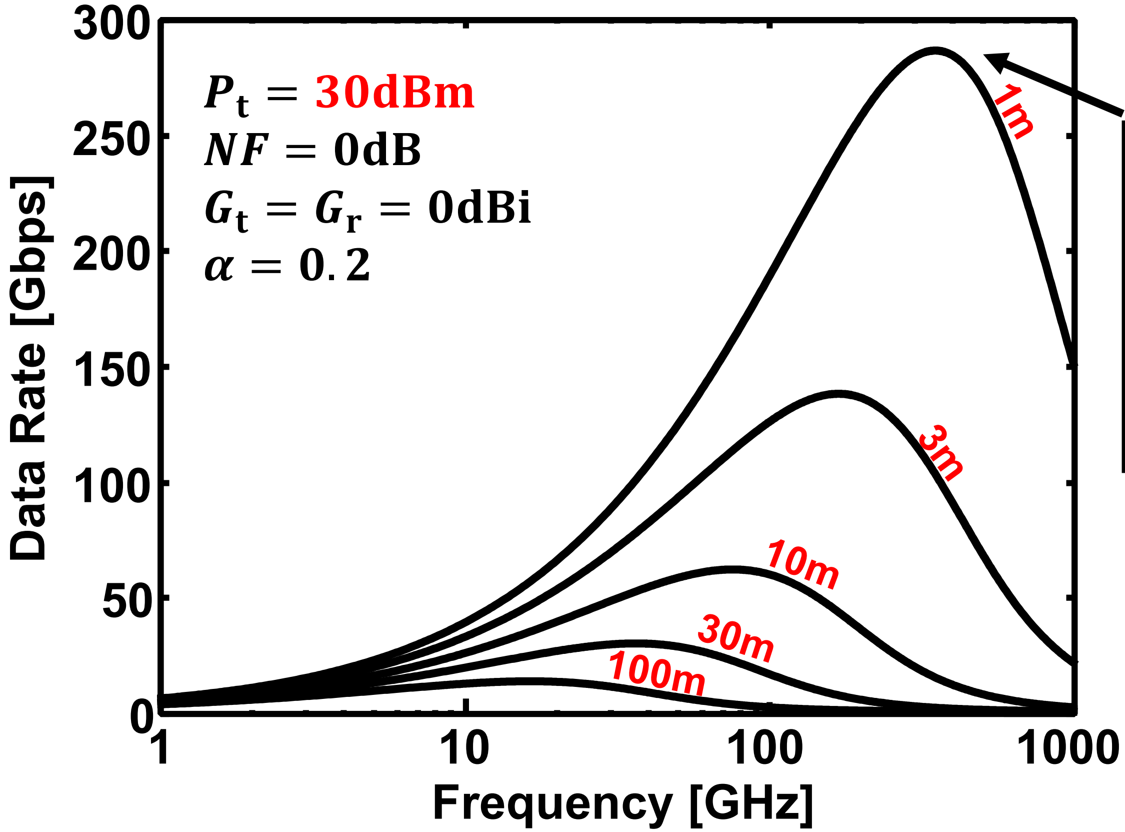
K. Okada, IEDM 2013
K. Okada, IMS 2019, WSF-2
K. Okada, BCICTS 2019

Theoretical Data Rate Limit



K. Okada, IEDM 2013
K. Okada, IMS 2019, WSF-2
K. Okada, BCICTS 2019

Theoretical Data Rate Limit



280Gbps @ 350GHz
1m, 30dBm
= 0.1m, 10dBm
= 6.4m, 10dBm, 16 array
= 100m, 10dBm, 100 array

K. Okada, IEDM 2013
K. Okada, IMS 2019, WSF-2
K. Okada, BCICTS 2019

Capacity with Multiple Antennas

$$C = B\log_2\left\{\det\left(I + \frac{\gamma_0}{n}H^H H\right)\right\} \qquad \gamma_0 = SNR$$

① SISO

$$C = B\log_2(1+\gamma_0)$$

② MIMO (spatial correlation=1) *e.g.* $H = \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix}$

$$C = B\log_2(1+n\,\gamma_0)$$

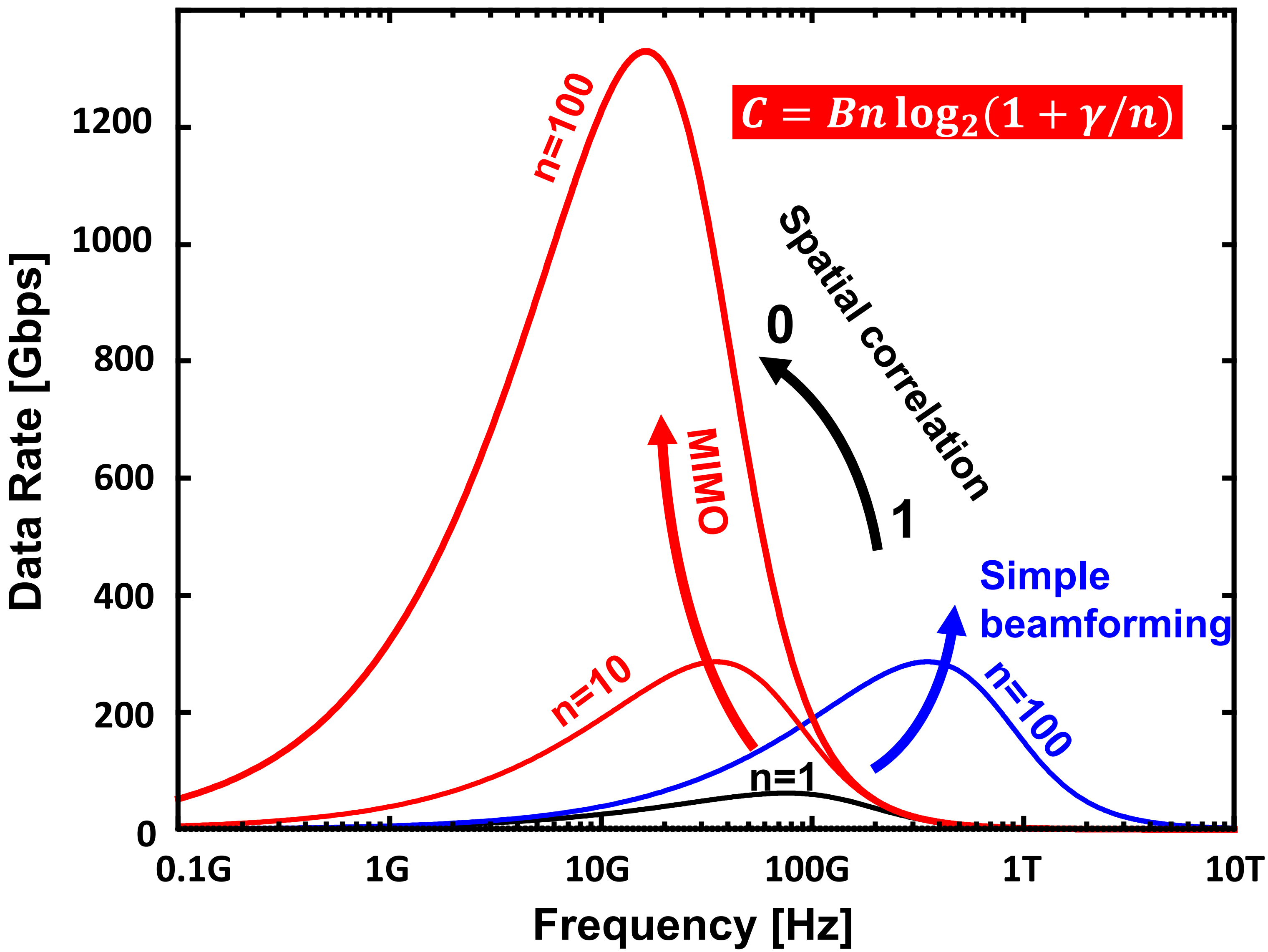
*equivalent to phased array

③ MIMO (spatial correlation=0) *e.g.* $H = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$

$$C = B\,n\log_2(1+\gamma_0/n)$$

E. Telatar, "Capacity of Multi-antenna Gaussian Channels," European transactions on telecommunications, vol. 10, no. 6, pp. 585-595, Nov. 1999.

Capacity with Multiple Antennas

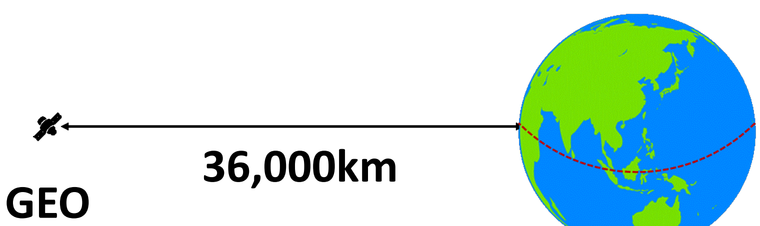


まとめと今後の方向性

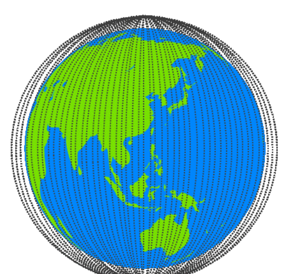
- ミリ波の高度化
- フェーズドアレイの高度化・大規模アレイ対応
- 低消費電力・高エネルギー効率化

Satellite(non-terrestrial) for beyond 5G

- **GEO** (Geostationary Earth Orbit): 36,000km
- **LEO** (Low-Earth Orbit): 400-2000km
  - 7.6km/s, orbital period 95min @500km height
- **HAPS** (High-Altitude Pseudo-Satellite): 20km (stratosphere)



静止軌道



500km

低軌道 LEO

Solar-powered airplane, NASA, 1997

成層圏 HAPS @20km