Tu2C - 1

Future Trends in Cellular Infrastructure and Radio Technology for Sustainable Networks

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June 13, 2023

AHEAD OF WHAT'S POSSIBLE™

Outline

- Motivation
- Future Trends in Cellular Infrastructure
- Future Trends in Power Amplifier Architecture
- Future Trends in Linearization System
- Summary

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How many basestation antennas are required to build out the City of San Diego?

How many basestation antennas are required to build out the City of San Diego?

2,188 Cell Phone Towers → **>700,000** Antenna Feeds

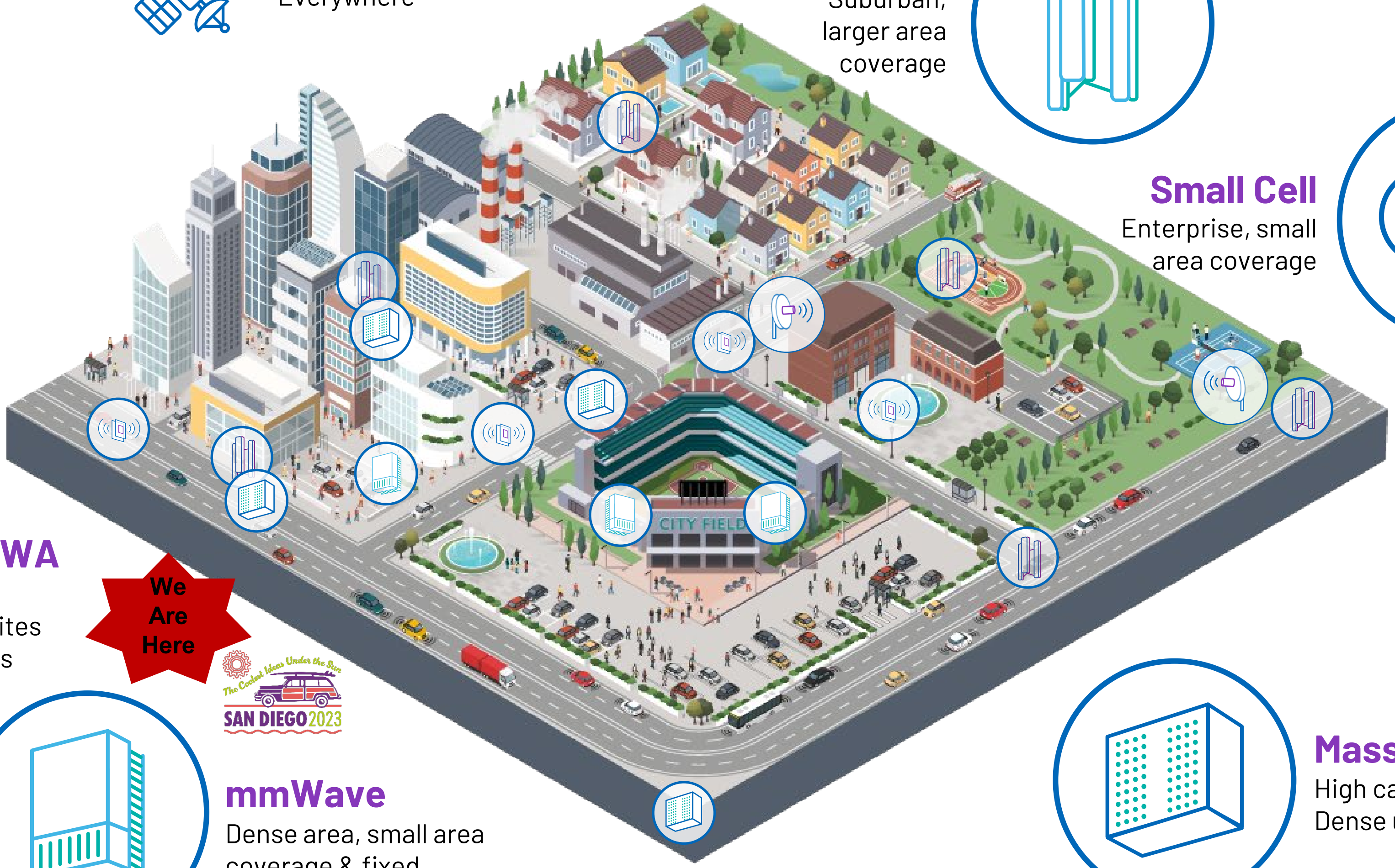
Network Complexity

- Sub-6GHz for Blanket Coverage.
- Multi-band Radio, more Massive MIMO & co-location create complex RF challenges
- Energy Consumption & Sustainability a major challenge for mobile carriers

LEO/NTN*
Coverage Everywhere

Macro
Suburban, larger area coverage

Small Cell
Enterprise, small area coverage



Pt-Pt & FWA
Backhaul of basestation sites & conferences

mmWave
Dense area, small area coverage & fixed wireless access

Massive MIMO
High capacity & coverage
Dense urban

Network Sustainability

TELECOMS INDUSTRY ENERGY USAGE

1.6%

of Total Global Co2 Emissions[1]

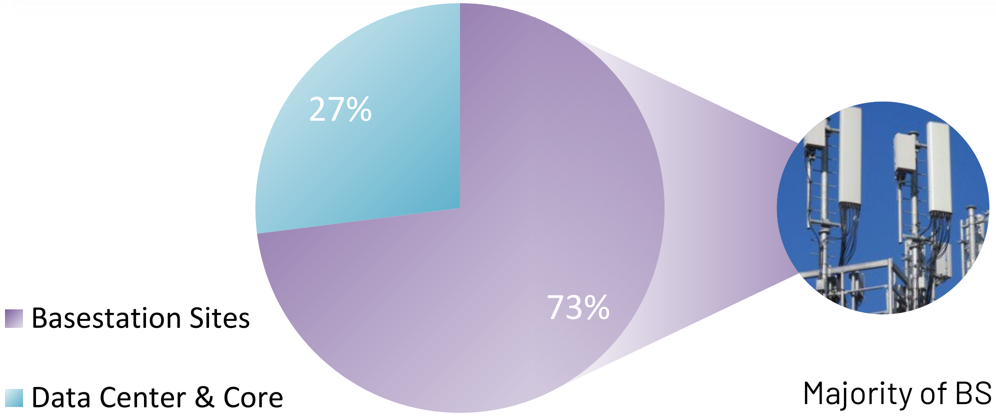
580M

tons of Co2 Emissions in 2021[2]

+160%

in total energy consumption 2020-2030[3]

WHERE IS THE ENERGY BEING CONSUMED?



Majority of BS power consumed by the Radio Unit[4]

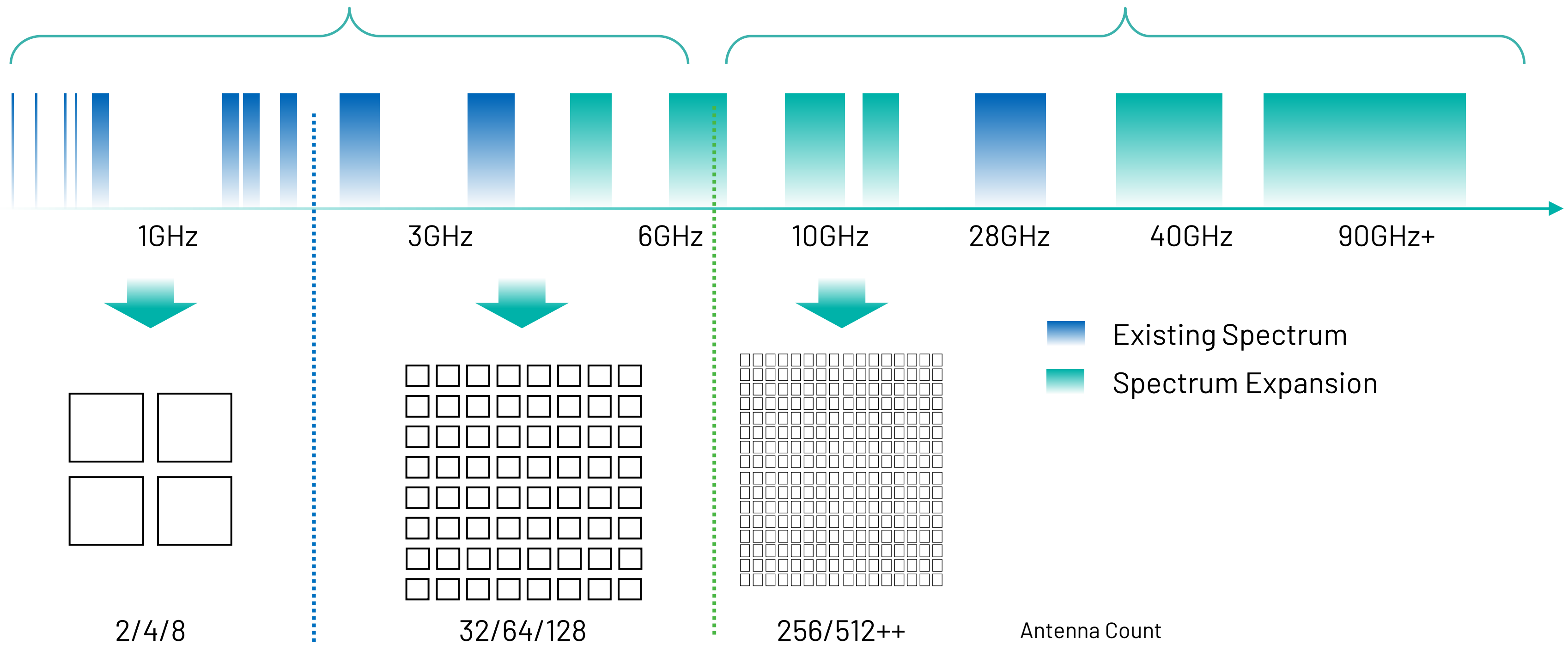
Innovations in RF Signal Processing & Energy Saving Algorithms at the network level required to drive down power consumption & minimize carbon footprint

1. BCG report Jun 2021
2. IEA press release Mar 2022; total global emissions 2021 = 36.3Bn tons
3. ABI/Interdigital Report Nov 2020
4. GSMA Intelligence A blueprint for Green Networks, Oct 2022

More MIMO, Extreme MIMO

More MIMO
For enhanced spectrum efficiency

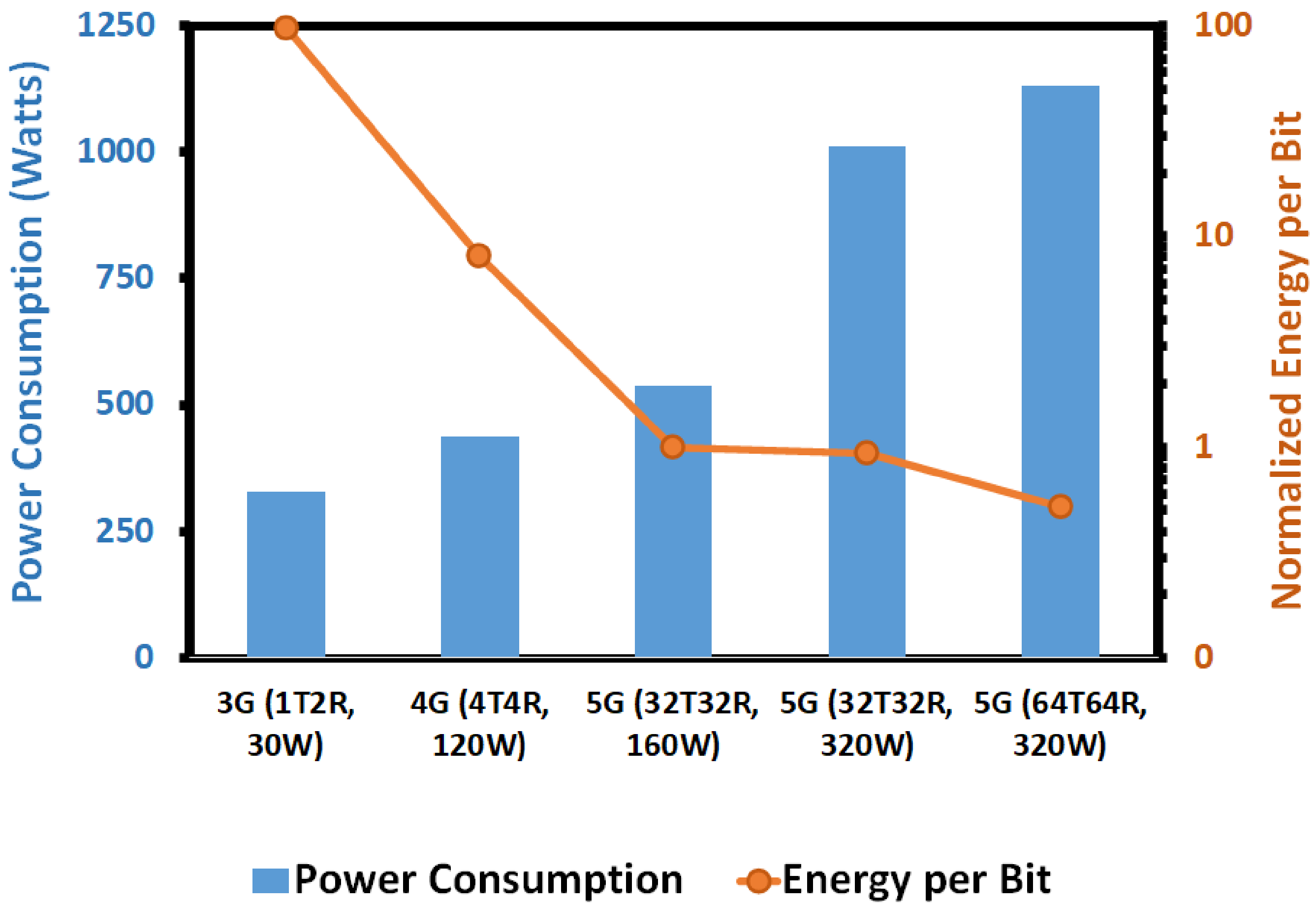
Extreme M-MIMO
Required to overcome propagation challenges, increase layer count



2/4/8	32/64/128	256/512++	Antenna Count
20MHz	100MHz	400MHz	Bandwidth
2-4	8-16	32-64	Layers (DL)

More Channels, More Bandwidth, Better Efficiency, Hybrid Beamforming

Trends in Efficiency



Be more Energy Efficient but also Carbon Negative

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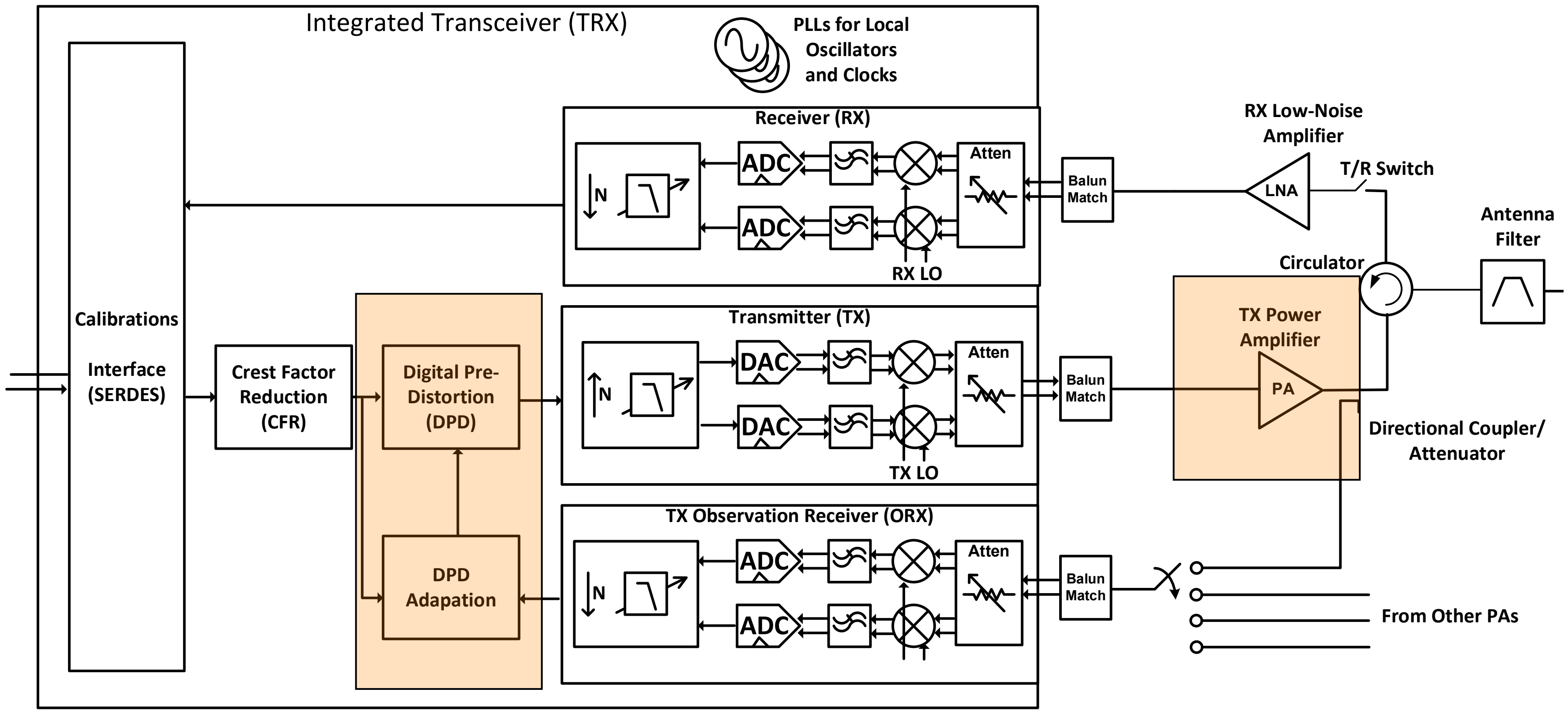
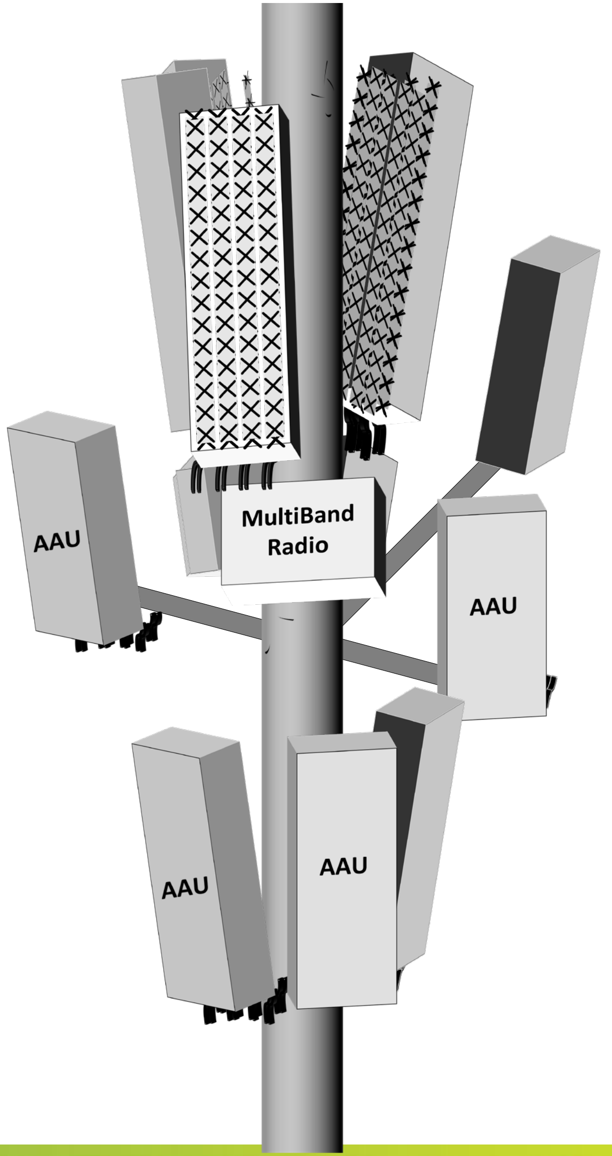
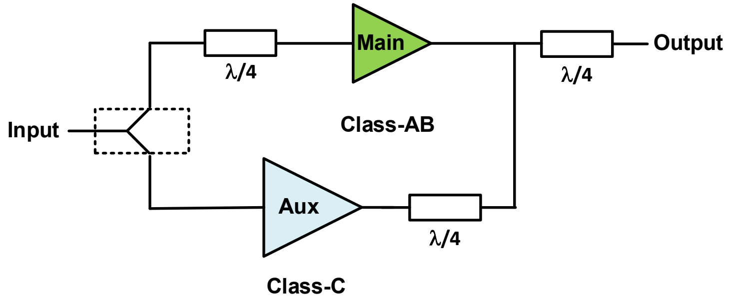
Radio Technology





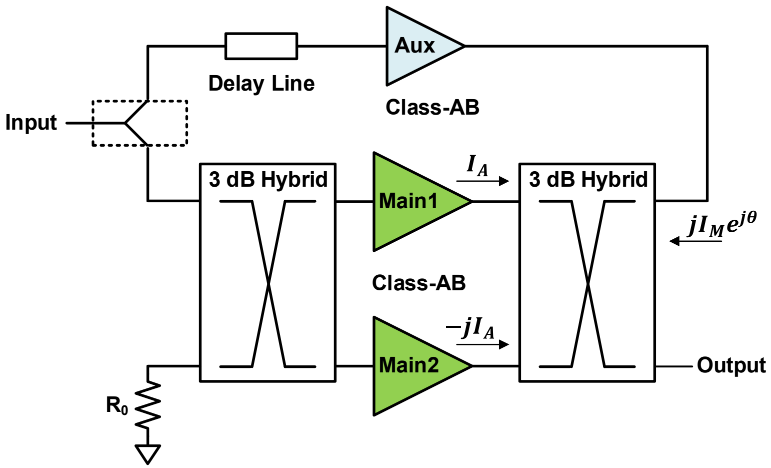
- High Efficiency Power Amplifier Architecture.
- Advanced Digital Linearization System.
- Hardware Acceleration Engine.

Power Amplifier Architecture



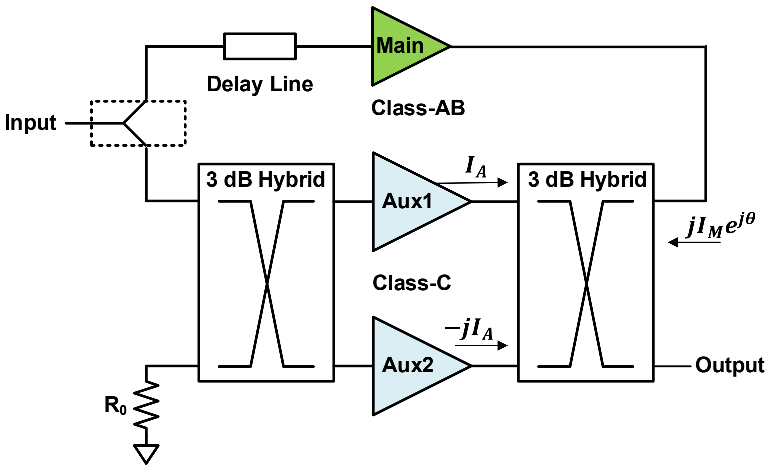
Asymmetrical Inverted Doherty

Inherent bandwidth limitation.



Conventional LMBA

Broadband but lower efficiency ~40% at PBO.

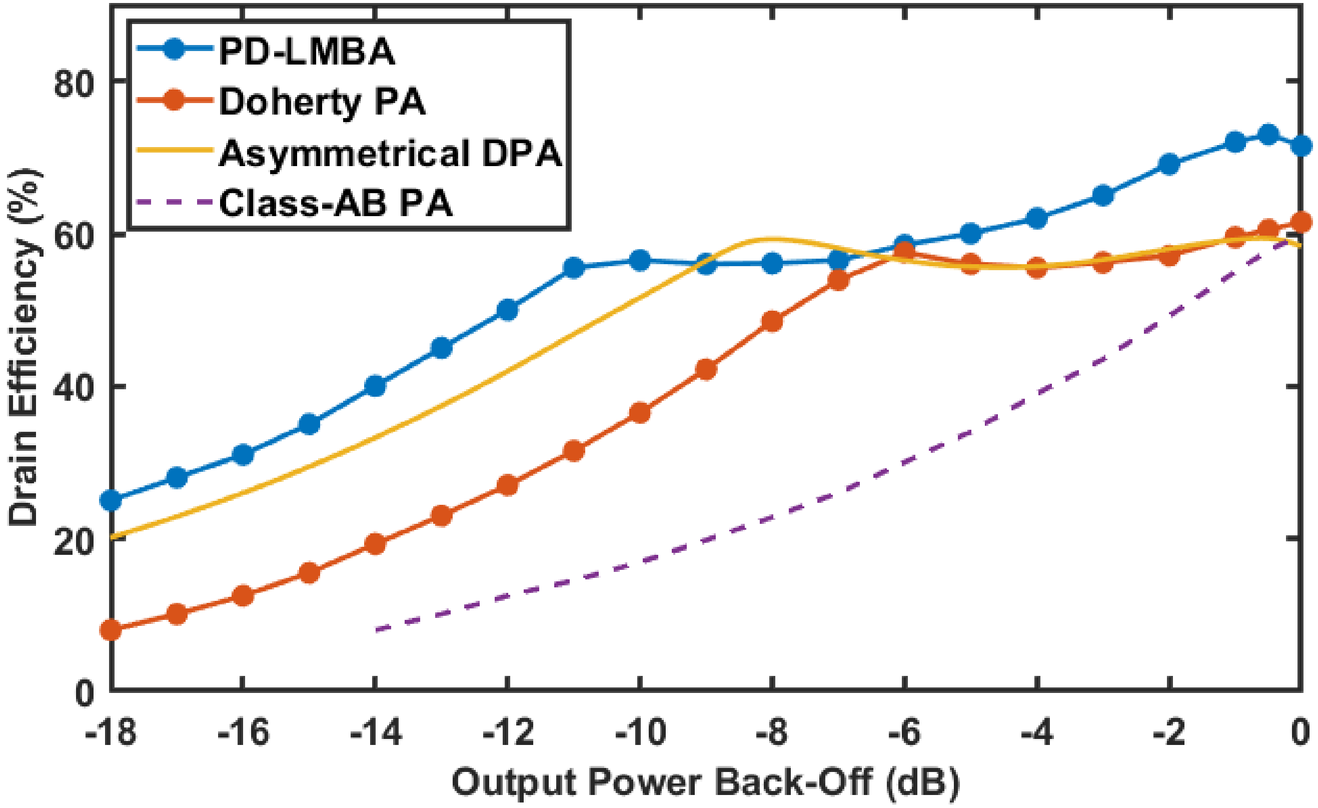


Pseudo-Doherty LMBA

Behaves like a Doherty and offers much higher bandwidth.

Linearity degrades.

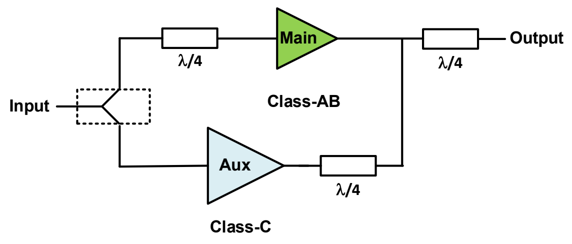
System Design Consideration

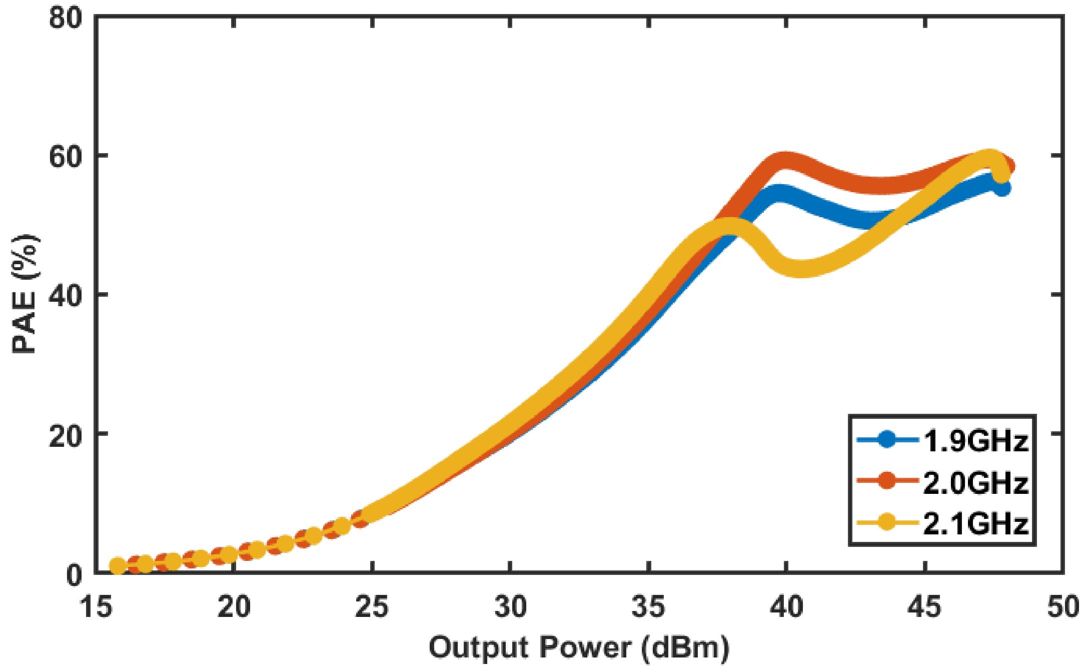


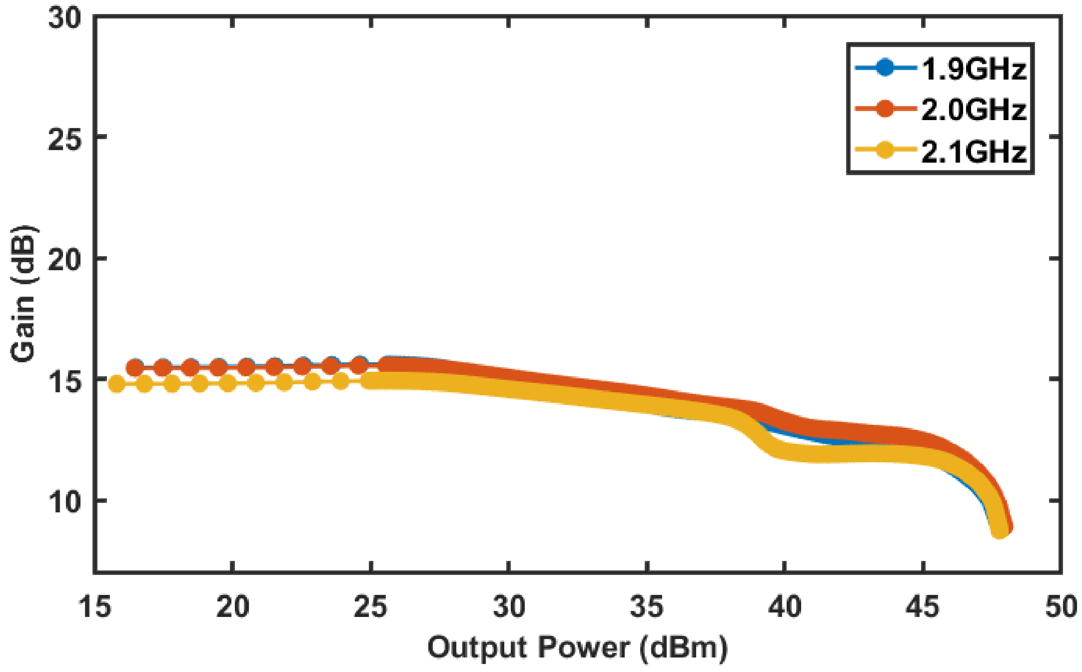
Efficiency to Peak at Larger Power Back Off

Asymmetrical Inverted Doherty

- Today's Workhorse for cellular transmitters.
- Linearizable ~10% fractional bandwidth.

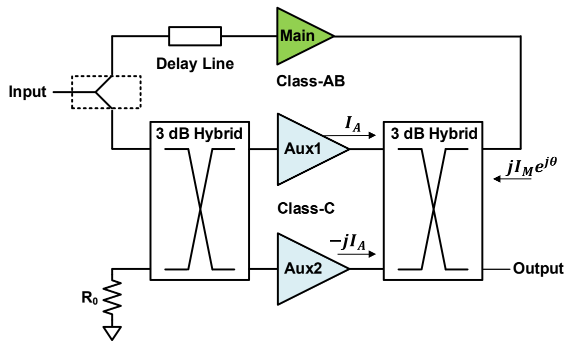


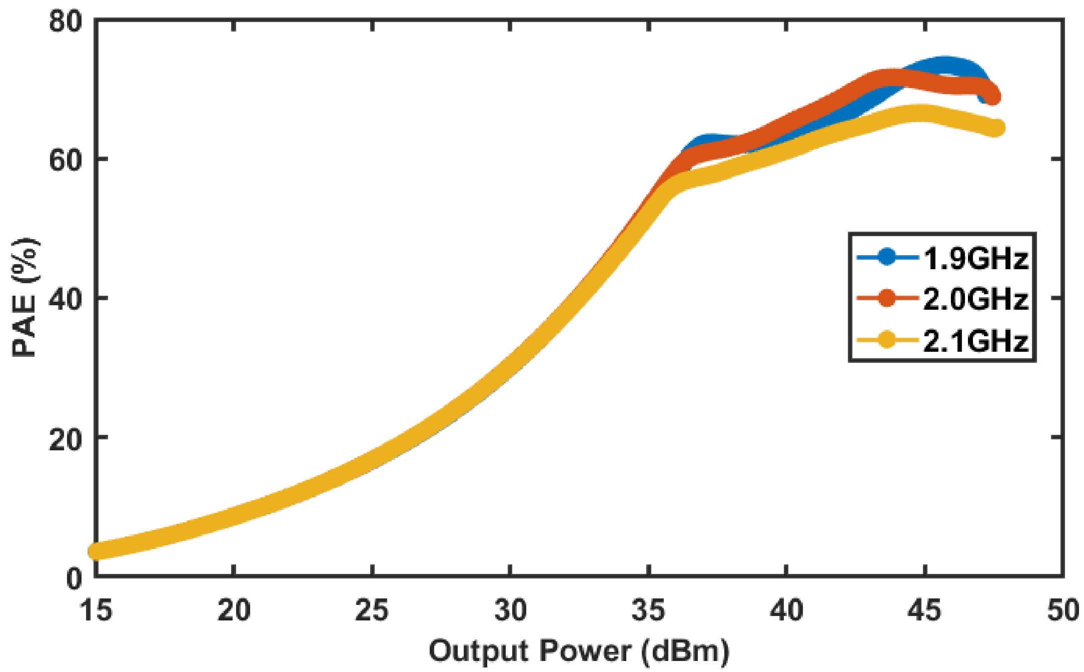


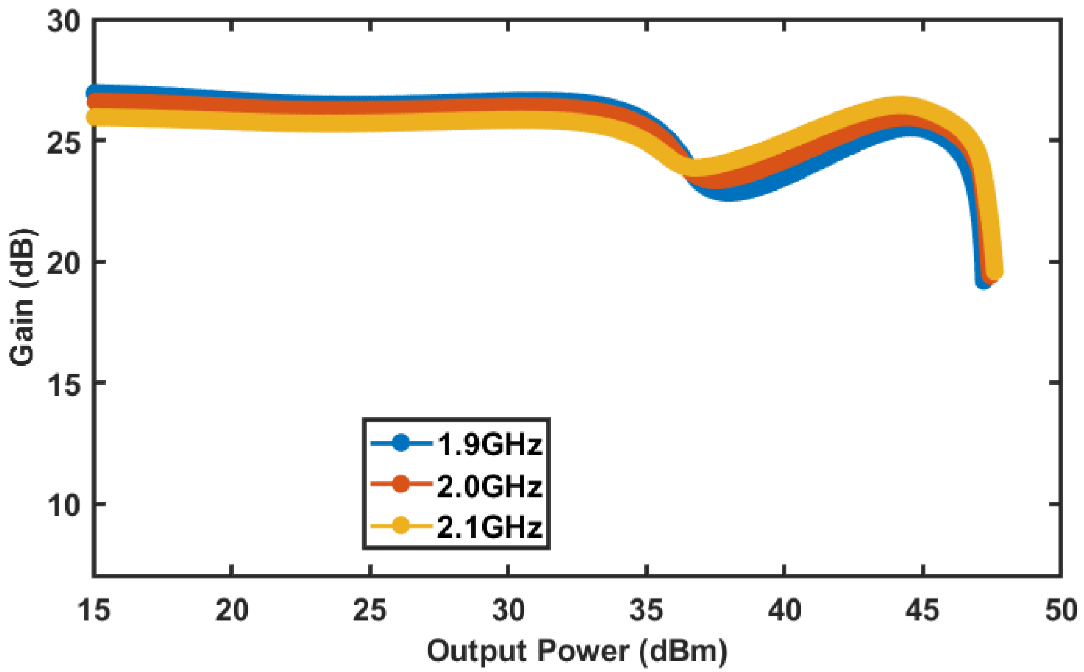


Pseudo-Doherty LMBA

- Twice the bandwidth compared to Doherty.
- Delay between the paths is optimum for a limited range of RF frequencies.

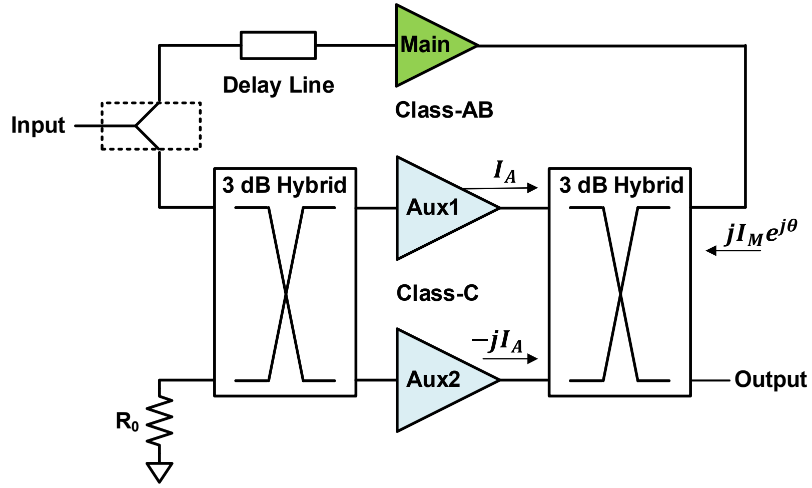


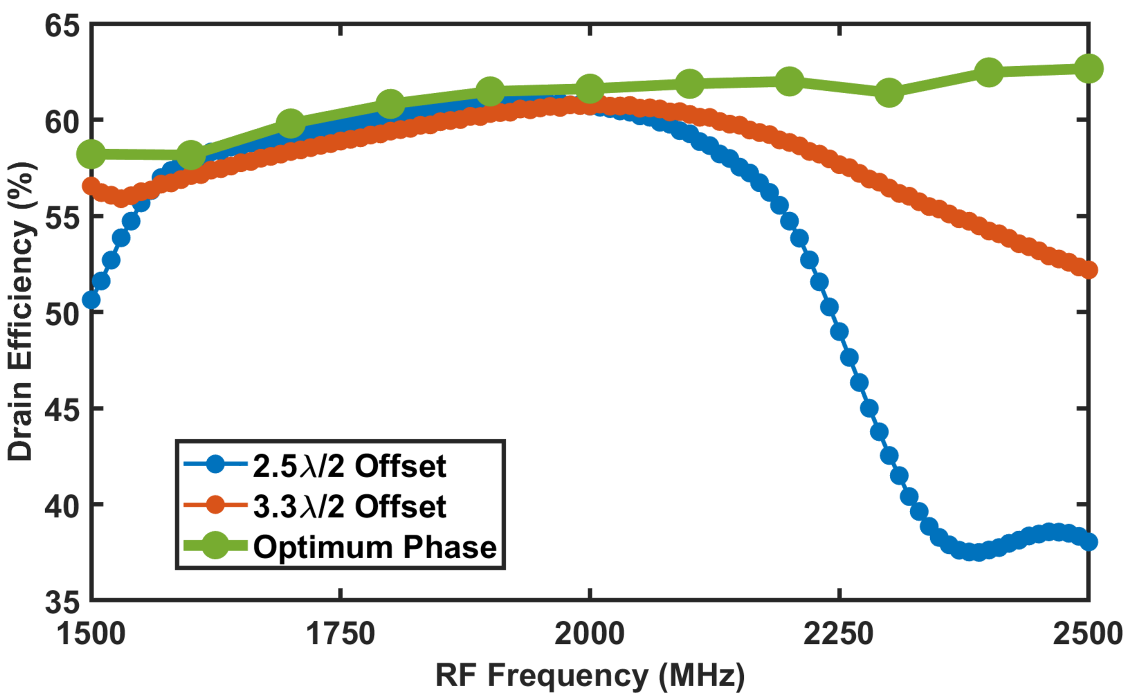




SISO Pseudo-Doherty LMBA

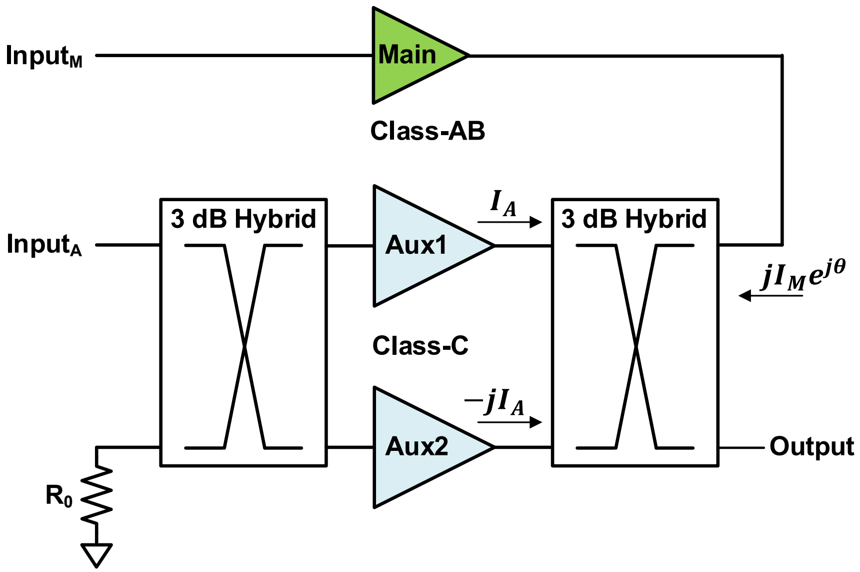
PA Configuration	Input Offset Line Length [cm]	Frac. BW [%]	DE [%]
SISO PD-LMBA	11.2	25	~55%
SISO PD-LMBA	14.8	40	~55%
MISO PD-LMBA	N/A	>50	~60%



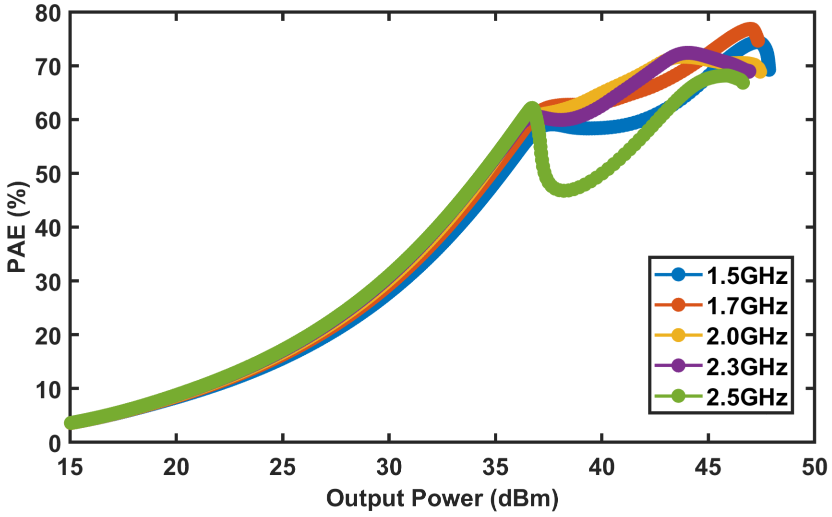


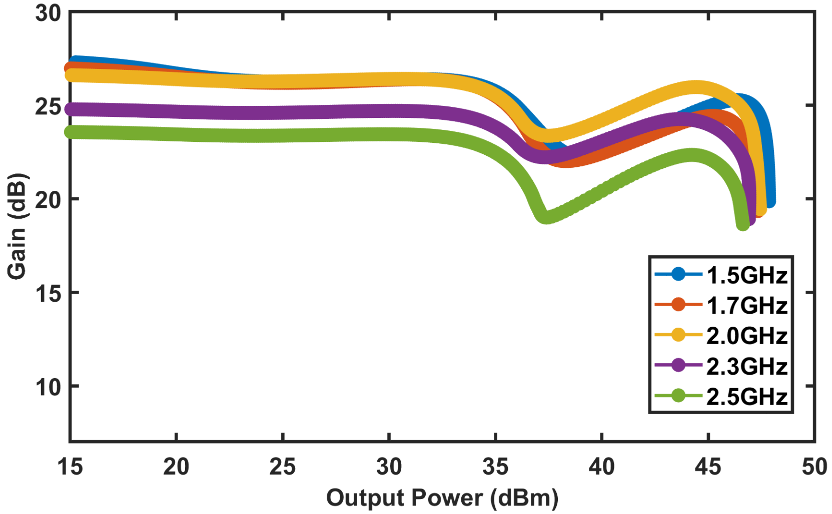
MISO Pseudo-Doherty LMBA

- The Path Forward for Sustainability.
- Adoption of splitting the main and auxiliary paths to compensate for phase variation.

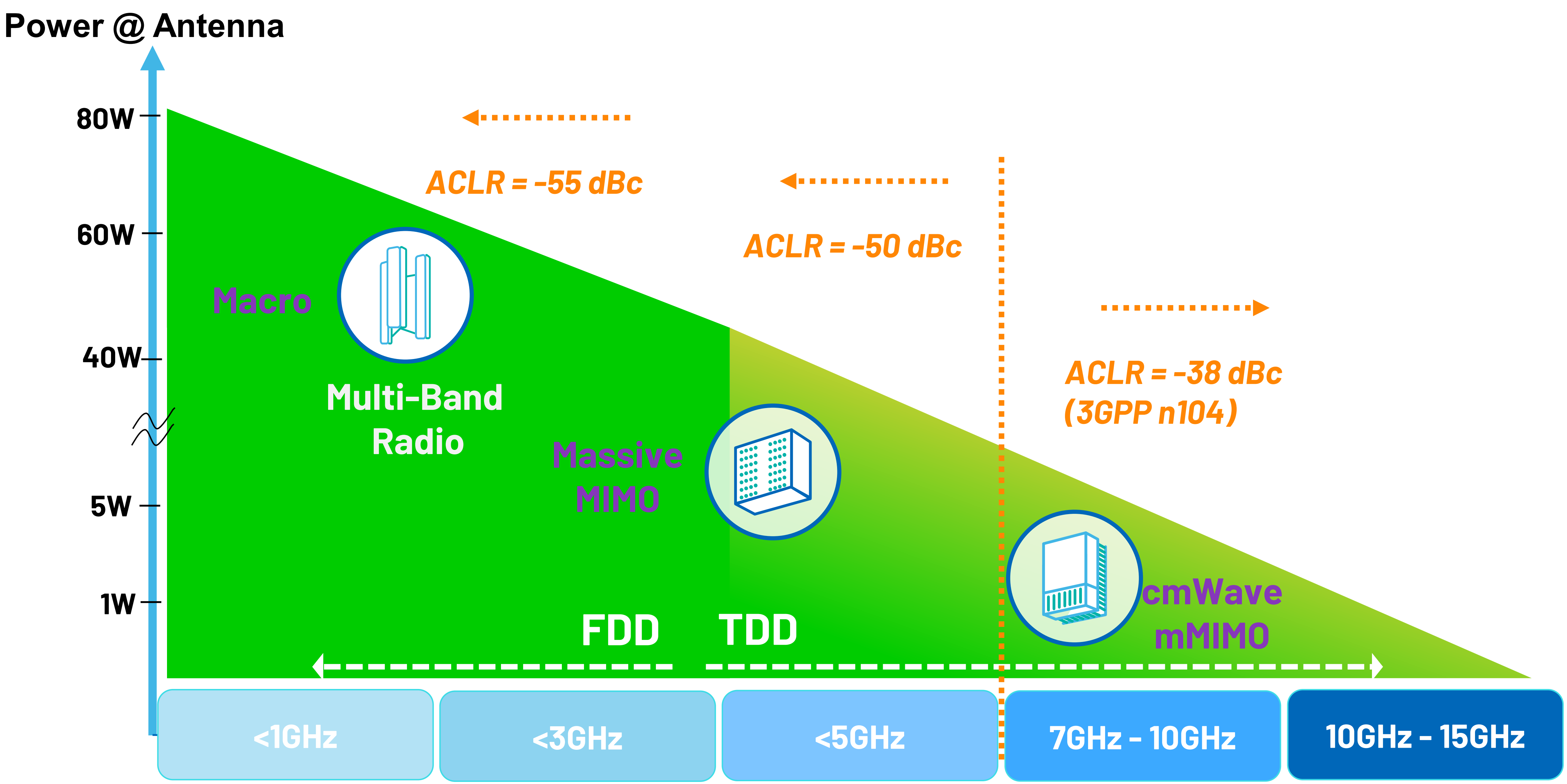


MISO Pseudo-Doherty LMBA

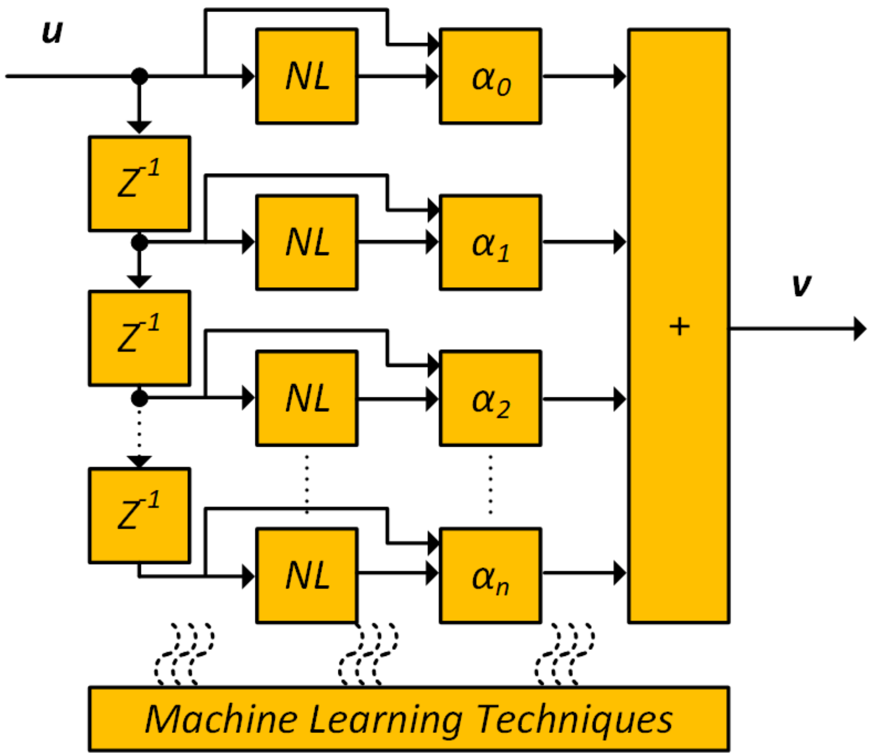




Linearity Requirement



Direct-Form Memory Polynomials

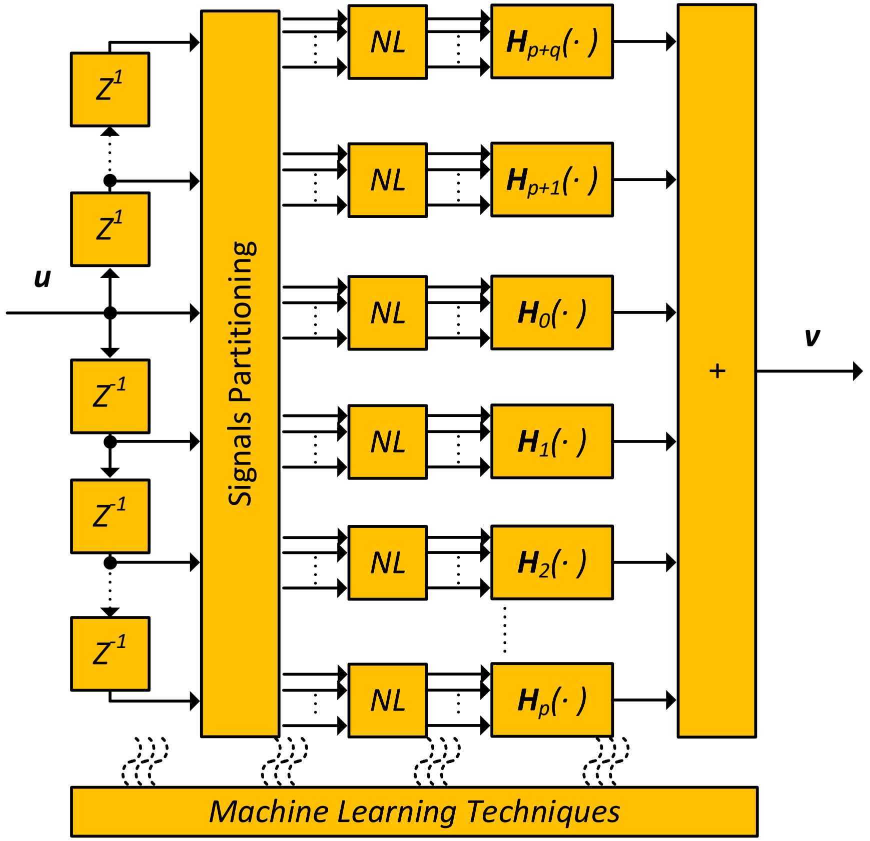


- Most primitive and yet effective form of implementation.
- Phase-invariant non-linear transformation denoted by $\boldsymbol{NL}$: $\mathbb{C} \rightarrow \mathbb{R}$.

$$v[t] = \sum_{k=1}^{K} \sum_{m=0}^{M} \alpha_{k,m} \cdot u[t+\tau_m] \cdot |u[t+\tau_m]|^{k-1},$$

- Hammerstein model combining Taylor series non-linear functions and linear filters, targeting diagonal terms.
- Often primary degrees $\boldsymbol{K} \in [\mathbf{1}, \mathbf{2}, \mathbf{3}, \mathbf{4}, \mathbf{5}]$ are sufficient to achieve good performance for low-power wireless transmitters.

Direct Synthesis of Volterra



- A more accurate generalization of Volterra series for medium to high power wireless transmitters.
- Example choice of NL operation.
  - $NL: \mathbb{C} \rightarrow \mathbb{R}$, followed by $H: \mathbb{R} \rightarrow \mathbb{C}$ implementing the delay operation and applies non-linear transformation using LUT.
  - LUT-based generalized memory polynomial model.

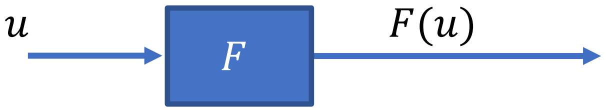
$$v[t] = \sum_{m=0}^{M} u[t+\tau_m] \cdot \varphi(|u[t+\tau_m]|, K, \alpha_{m,k}) + \sum_{m=0}^{M}\sum_{q=0}^{Q} u[t+\tau_m] \cdot \varphi(\left|u[t+\tau_q]\right|, K, \alpha_{m,q,k}),$$

- Another example of NL operation.
  - $NL: \mathbb{C} \rightarrow \mathbb{C}$ producing high-order frequency-dependent non-linearities.
  - Dynamic deviation reduction terms, $u^2 D_n \bar{u}$ and $\bar{u} D_n u^2$.

$$v[t] = \sum_{m=0}^{M}\sum_{q=0}^{Q} u^2[t] \cdot \bar{u}[t+\tau_m] \cdot \varphi(\left|u[t+\tau_q]\right|, K, \alpha_{m,q,k}) + \sum_{m=0}^{M}\sum_{q=0}^{Q} \bar{u}[t] \cdot u^2[t+\tau_m] \cdot \varphi(\left|u[t+\tau_q]\right|, K, \alpha_{m,q,k}).$$

Linear System of Identification

F: RF/Analog impairments



- **How do we approximate function F?**
  - Linear regression model as a weighted sum of $J \cdot I$ features $F(u) = \sum_j^J \sum_i^I \alpha_{j,i} \beta_{j,i}(u)$
  - α is the coefficient, and β denotes the basis function known as variable.
- **Model coefficients are solved by minimizing**

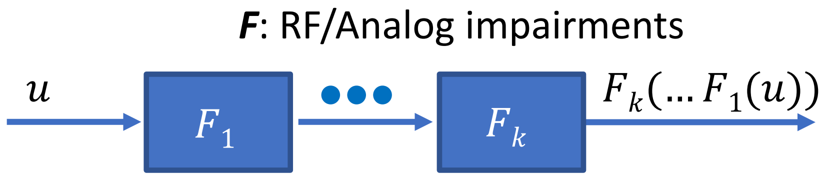
$$\sum_{n=1}^{N} \left| v_n - \sum_{k=1}^{K} \alpha_k \beta_k(u_n) \right|^2 + \lambda L(\boldsymbol{\alpha}) \;\; or \;\; \operatorname{argmin}_{\boldsymbol{\alpha}} \left(\|\boldsymbol{v} - \boldsymbol{\beta\alpha}\|_2^2 + \lambda L(\boldsymbol{\alpha}) \right),$$

- **Solution to be derived as**
  - Closed form solution to quadratic cost function $\tilde{\boldsymbol{\alpha}} = (\boldsymbol{\beta}^H \boldsymbol{\beta} + \lambda I)^{-1} \boldsymbol{\beta}^H \boldsymbol{v}$
  - Iterative method of gradient descent update $\boldsymbol{\alpha}_{i+1} = \boldsymbol{\alpha}_i + \boldsymbol{\beta}^H \mathrm{e}$
- **Direct form polynomials, orthogonal polynomials, PWL functions, arbitrary bases.**

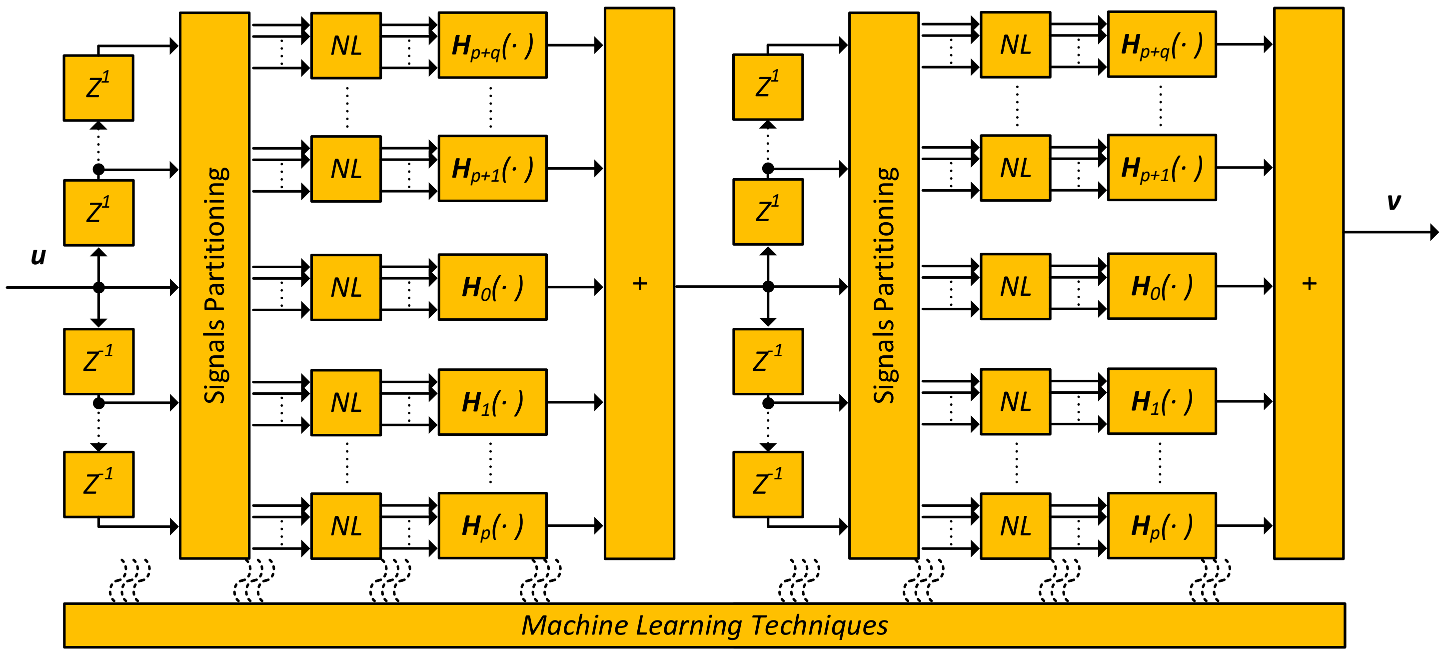
All Supported by Today's Software Defined Radio !

Multi-Stage Network

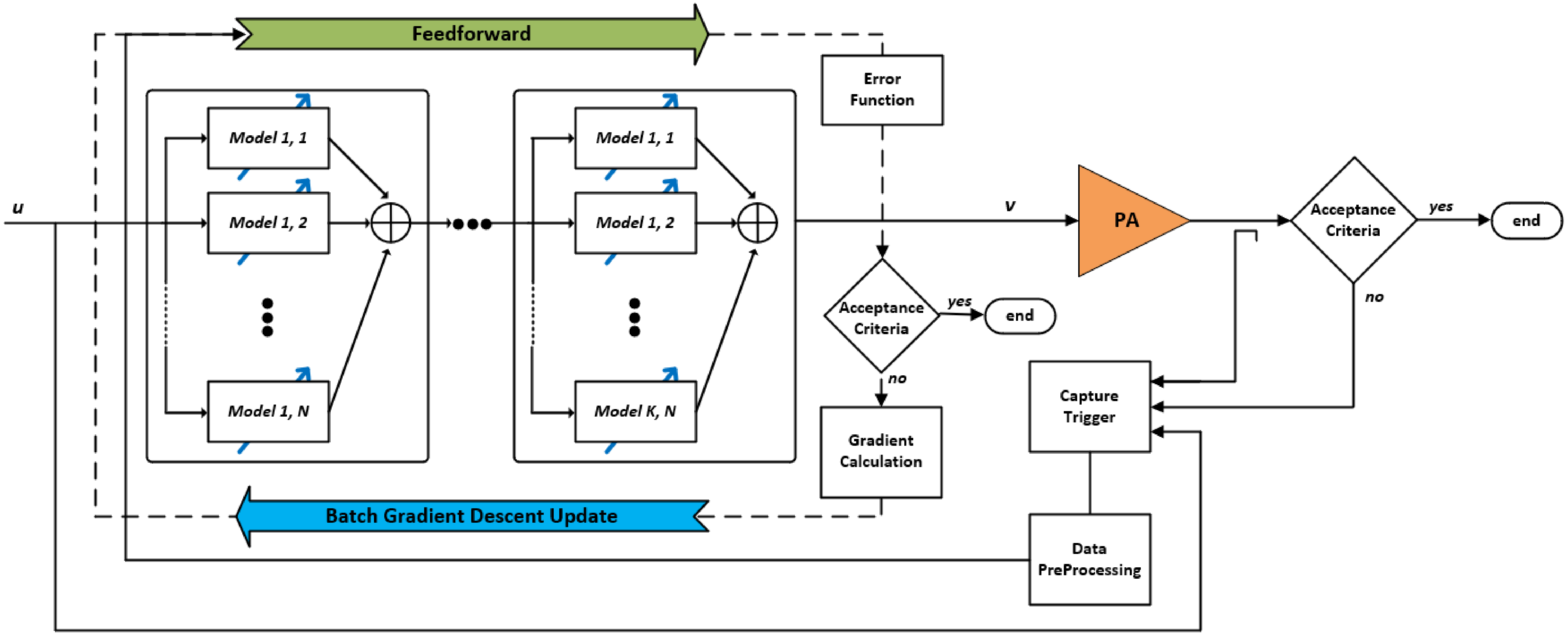
- **Each cascaded model comprises different linear regression models or Volterra-based models.**
- **Solve the non-linear problem using**
  - Gradient descent
  - Back propagation



$$\text{argmin}_{\boldsymbol{\alpha}_k}\left(F_k\left(\boldsymbol{\alpha}_k, \ldots F_1(\boldsymbol{\alpha}_1, \boldsymbol{\beta}_1(\boldsymbol{u}))\right) + \lambda L(\boldsymbol{\alpha}_k)\right),$$



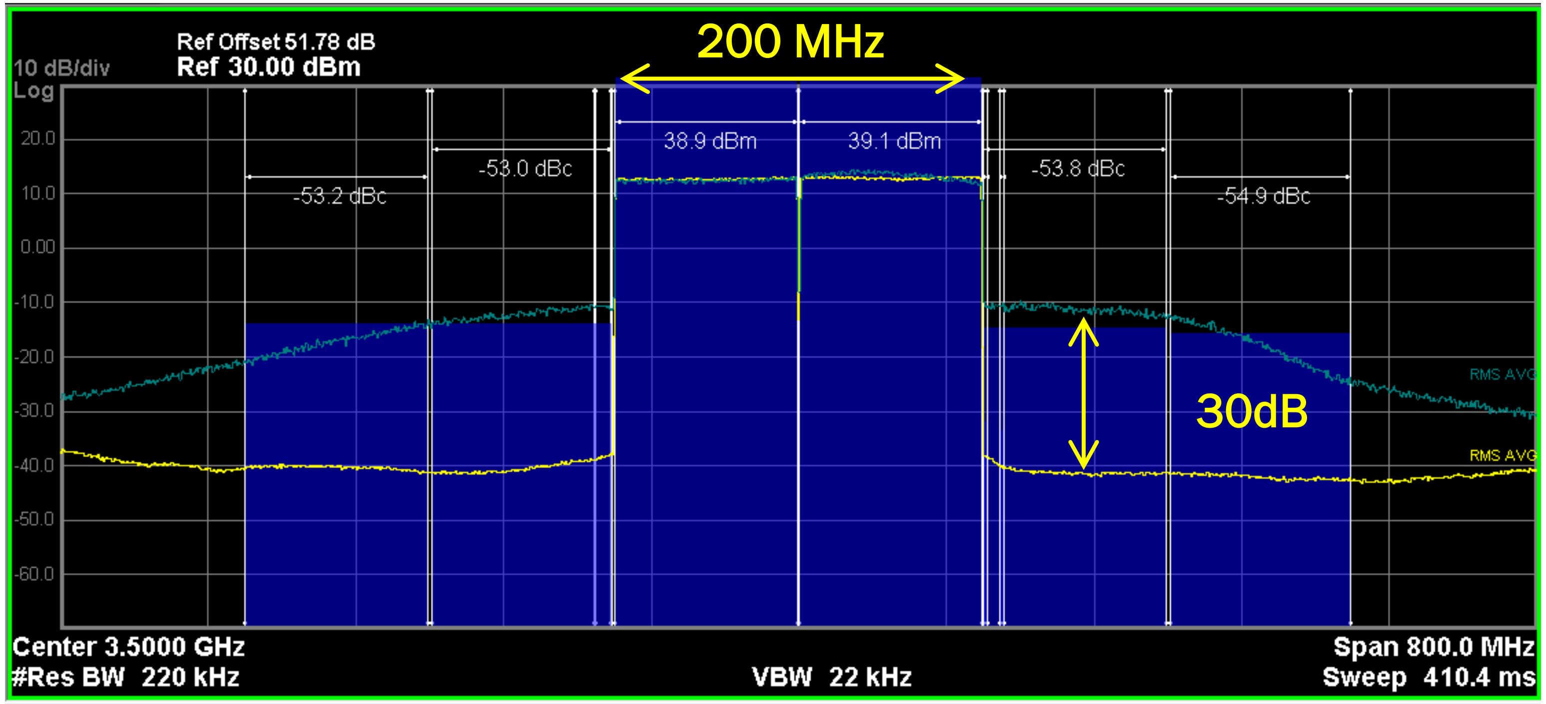
Non-Linear System of Identification



Near Optimal Behavioral Modeling versus Iterative Learning Control

Linearized Output Spectrum

- Linearized efficiency 57% → vs 45% (typ.) 237 Watts saving per RU



Total Carrier Power 42.012 dBm/ 196.00 MHz ACP-IBW

Carrier Power			Filter
1	38.912 dBm /	98.00 MHz	-3 dB
2	39.089 dBm /	98.00 MHz	-3 dB

Offset Freq	Integ BW	Lower dBc	Lower dBm	Upper dBc	Upper dBm	Filter
100.0 MHz	98.00 MHz	-53.04	-13.95	-53.84	-14.75	-3 dB
51.50 MHz	1.000 MHz	-70.47	-31.38	-71.01	-31.92	-3 dB
200.0 MHz	98.00 MHz	-53.17	-14.08	-54.87	-15.78	-3 dB

Pout = 42dBm rms

Psat = 50dBm

PAPR = Psat – Pout = 8dB

ACLR = -53dBc vs
-47dBc (prior art)

OBUE = -31.3dBm/MHz

Comparison Table

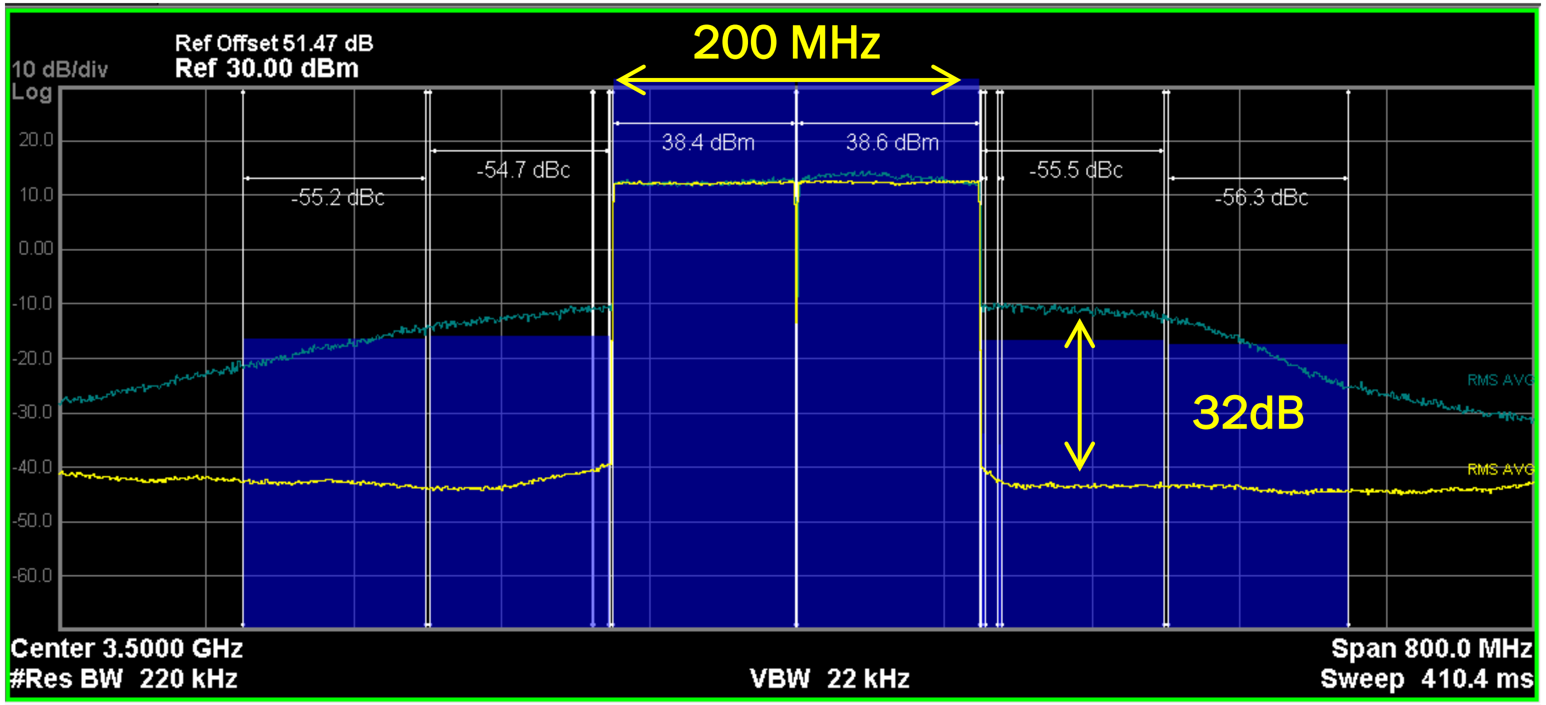
- Including both Academia and Industry

	This Work	[1]	[2]	[3]	[4]	[5]	[6]
Year of Publication	2023	2022	2022	2022	2023	2020	2020
RF Center Frequency (MHz)	3500	3840	3500	2140	2300	3200	3300
Signal Instantaneous Bandwidth (MHz)	200	280	200	100	100	120	80
Signal PAPR (dB)	8	8	--	8.5	8.5	7	10
Maximum Output Power (dBm)	50	47	50.2	45.3	40.5	45	43.7
Average Output Power, Pout (dBm)	42	38.8	41.5	36.2	31.8	37.3	33.0
Linearized Output PBO (dB)	8	8.2	8.7	9.1	8.7	7.7	10.7
Output PBO – Signal PAPR (dB)	0	0.2	--	0.6	0.2	0.7	0.7
Linearized Drain Efficiency (%)	57	45	55.1	54.5	34.2	53.3	48.2
Worst-Case ACLR (dBc)	-53.0	-50.5	-51.0	-45.7	-48.2	-50.4	-45.2

1. K. Chuang et al., "Radio challenges, architectures, and design considerations for wireless infrastructure: creating the core technologies that connect people around the world," *IEEE Microw. Mag.*, vol. 23, no. 12, pp. 42-59, Dec. 2022.
2. MaxLinear, "MaxLinear teams with Qorvo to enable high-efficiency power amplifiers for massive MIMO radio solution," 2022. Accessed: May 1, 2023. [Online]. Available: https://investors.maxlinear.com/press-releases/detail/469/.
3. H. Zhou et al., "A generic theory for design of efficient three-stage Doherty power amplifiers," *IEEE Trans. Microw. Theory Techn.*, vol. 70, no. 2, pp. 1242-1253, Feb. 2022.
4. C. Chu et al., "High-efficiency class-iF^{-1} power amplifier with enhanced linearity," *IEEE Trans. Microw. Theory Techn.*, vol. 71, no. 5, pp. 1977-1989, May 2023.
5. M. Li et al., "Bandwidth enhancement of Doherty power amplifier using modified load modulation network," *IEEE Trans. Circuits Syst. I, Reg. Papers*, vol. 67, no. 6, pp. 1824-1834, Jun. 2020.
6. J. Pang et al., "Analysis and design of highly efficient wideband RF-input sequential load modulated balanced power amplifier," *IEEE Trans. Microw. Theory Techn.*, vol. 68, no. 5, pp. 1741-1753, May 2020.

Linearized Output Spectrum

- A half dB power back off.
- Near optimal behavioral modeling of power amplifier at 55% efficiency.



Total Carrier Power 41.503 dBm/ 196.00 MHz

Carrier Power			Filter
1	38.403 dBm /	98.00 MHz	-3 dB
2	38.580 dBm /	98.00 MHz	-3 dB

ACP-IBW

		Lower		Upper		
Offset Freq	Integ BW	dBc	dBm	dBc	dBm	Filter
100.0 MHz	98.00 MHz	-54.71	-16.13	-55.49	-16.91	-3 dB
51.50 MHz	1.000 MHz	-71.66	-33.08	-72.47	-33.89	-3 dB

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Summary

- The next Wave of radio deployment is in Centimeter Waves, expecting hundreds of antenna feeds per Radio Unit.

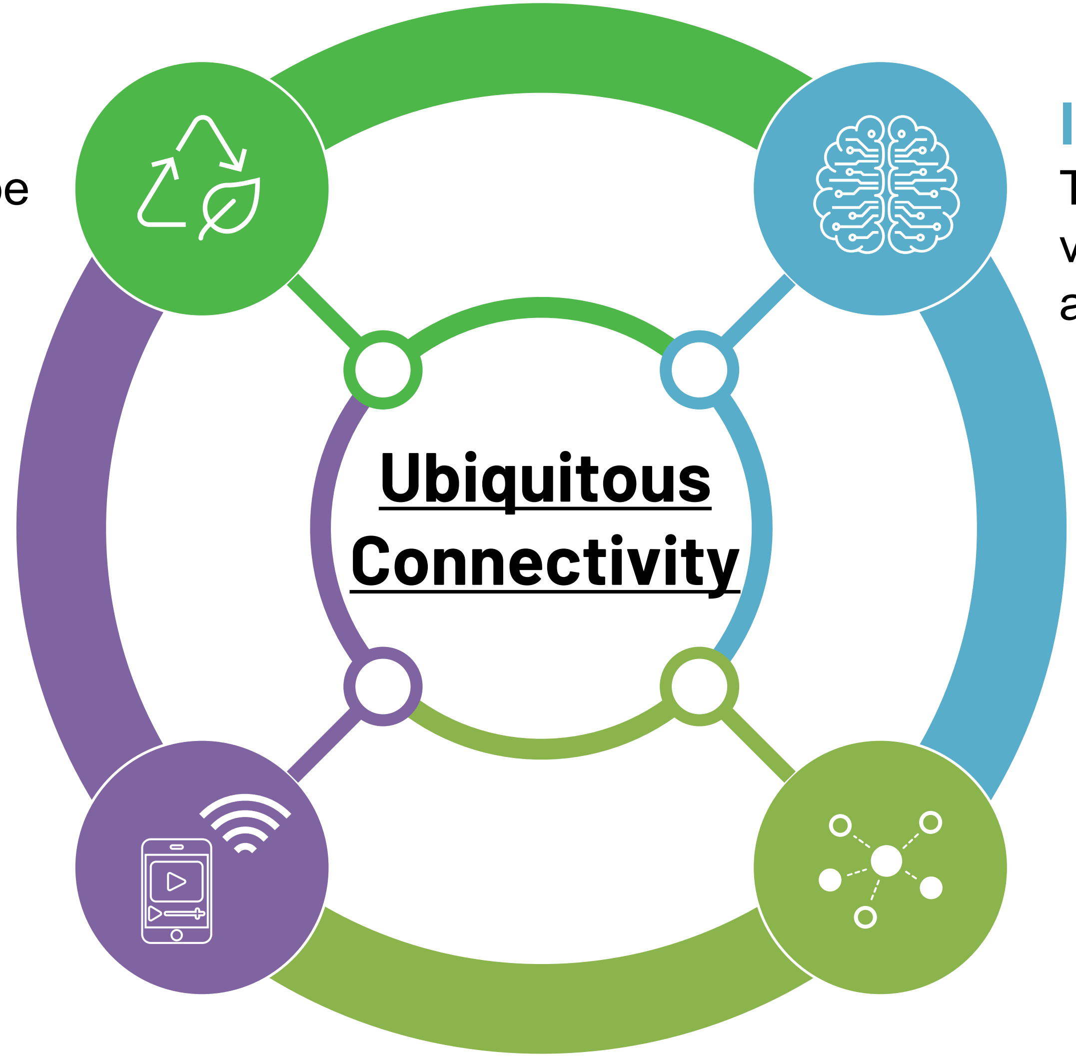
- Continued Innovation is required in
  – Integrated Radio Transceiver SoC,
  – Advanced Linearization Systems,
  – Broadband PA Architectures.

- Require Network Energy Saving features in concert with mobile data traffic demand.

The Power to Deliver

Sustainability
Wireless networks must be carbon negative to thrive

Intelligence Everywhere
The catalyst that delivers the value of the network, more autonomy in every node



Radio Technology
Enables energy-efficient air interface by minimizing power consumption of network.

Co-Innovation & Collaboration
Combination of technologies required. Win-win outcomes.