ANALOG DEVICES

KEEPING UP WITH THE WIRELESS GS:
Role of Software-Defined Radios and Standard Interfaces

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Workshop Agenda

Hossein Yektaii:

- Evolution of Wireless Standards from 1G to 6G
- Challenges Faced by Mobile Network Operators (MNOs) and Wireless Infrastructure OEMs
- How Multiple Generations of Software-Defined Radios Have Risen to the Challenge

Kevin Gard:

- Base-Station Enabling Technology: Integrated Software-Defined Radios

Nehal Parikh:

- Deep Dive into the ADI's Latest Full-Functionality Software-Defined Radio

Evolution of the Wireless Standards From 1G to 6G

In 40 years, cellular wireless evolved from unencrypted analog voice calls to software-defined, cloud-native networks optimized as much for sensors and AI as for people.

File:Mobile Phone Evolution 1992 - 2014.jpg - Wikimedia Commons

Evolution of Cellular Wireless Technology

1G

Voice Calls

First Deployment of Cellular Communication and Handover between Base Stations
Analog FM Modulation
30kHz Channels
800MHz to 900 MHz

2G

Voice Calls, **Short Message Service (SMS)**

GMSK Digital Modulation
200kHz Channels
Digital Voice Encoders
9.8kbps Data Rate
SIM Card-Based Authentication
800MHz to 900 MHz
1700MHz to 2000MHz

3G

Voice Calls, SMS, **E-Mail and Basic Web Browsing**

CDMA Spread Spectrum Modulation
5MHz Channels
2Mbps Data Rate
150ms to 500ms Latency
800MHz to 900MHz
1700MHz to 2200MHz

4G

Voice calls, SMS, Mobile Internet, **Video Calling**, Internet of Things **IOT, Mobile App Economy**

First Worldwide Standard
OFDM Modulation
20MHz Channels
300Mbps Data Rate
30ms to 70ms Latency
700MHz to 900MHz
1700MHz to 2700MHz

5G

Enhanced Mobile Broadband (**eMBB**)
Massive Machine Type (**mMTC**), Ultra-Reliable Low-Latency (**URLLC**) Communication

OFDM Modulation
Energy Efficiency
100MHz Channels in Sub-6GHz
400MHz Channels in mmWave
2Gbps Data Rate
5ms to 20ms Latency
600MHz to 900MHz
1700MHz to 2700 MHz
3GHz to 4GHz
28GHz and 39GHz

6G

Immersive and AI Native Communication
Ubiquities Connectivity Using **Terrestrial** and **Satellite** Networks
Integrated Communication and Sensing **(ICAS)**

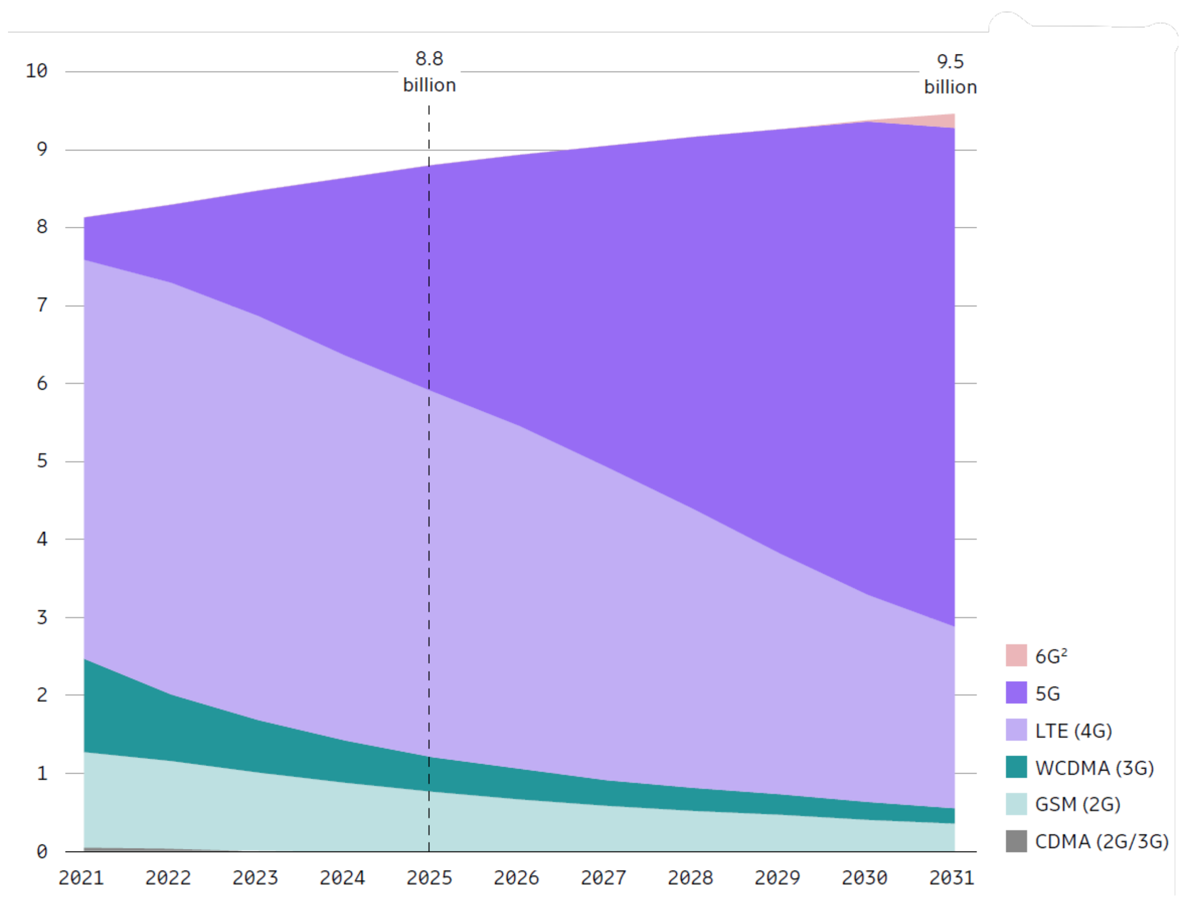
Backwards Compatibility with 5G and 4G
Cost Efficiency
Energy Efficiency
Security
20+Gbps Data Rate
Deterministic Latency
600MHz to 900MHz
1700MHz to 2700 MHz
3GHz to 5GHz
7GHz to 15GHz
28GHz, 39GHz, 47GHz, 70GHz

1990 | 2000 | 2010 | 2020 | 2030

Global Wireless Network Subscription by Generation

Key Takeaways

- As of November **2025**, there were **8.8 billion total** wireless subscriptions. Expected to reach **9.5 billion in 2031.**
- **5G** subscriptions have reached **2.9 billion** worldwide by the end of **2025** and are forecasted to reach **6.4 billion** by the end of **2031.**
- **4G LTE** still plays a significant role with **4.8 billion** subscriptions at the end of **2025.**
- **2G GSM is** not going away, even beyond 2030, **36 years** after early deployments in **1990**!



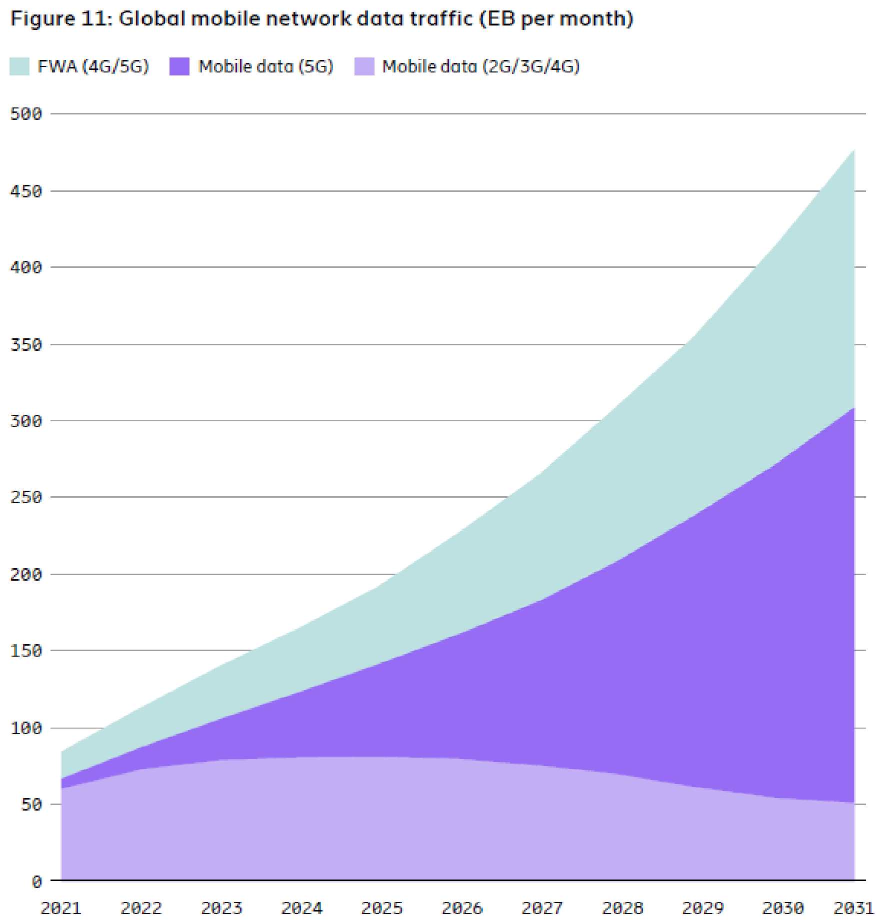
Source: Ericsson Mobility Report November 2025

Global Wireless Network Data Traffic

Key Takeaways

- At the end of **2025**, total monthly global mobile network data traffic reached **~200EB (200 × 1018 bytes).**
- **Year-on-year growth** in data traffic has slowed down from **>100%** at the **end of 2020** to **~20%** at the **end of 2025.**
- The share of mobile data carried over **5G** is forecast to rise from **43%** at the end of **2025** to **83%** in **2031.**
- **FWA** (fixed wireless access) is a major driver of the data traffic now, expected to reach **350 million** connections **by 2031.**
- **Average** mobile data traffic per **smartphone** is **21 GB** globally in **2025** mainly driven by video.

Source: Ericsson Mobility Report November 2025



Challenges Faced by the Mobile Network Operators (MNOs) and Wireless Infrastructure OEMs

83× More Data, 30% Less Revenue from 2010 to 2025

Key Takeaways

- AT&T, Verizon, and T-Mobile have been delivering great value, but not getting paid for it!
- The **average data usage** among the top 3 MNOs in the U.S. has **increased 83-fold** between **2010 and 2025.**
- The average revenue per user **(ARPU)**, adjusted for inflation, is **reduced** by **more than 30%** between **2010 and 2025.**

MNO	2010 ARPU (Monthly) Inflation Adjusted	2010 Avg. Data Usage	2025 ARPU (Monthly)	2025 Avg. Data Usage
AT&T	~$93	**340MB**	~$57	**~23GB**
Verizon	~$77	**420MB**	~$59	**~25GB**
T-Mobile	~$77	**130MB**	~$51	**~30GB**

At the turn of the century, the top four global telecom network operators employed over 800k people.

...

Now the same network operators hire less than 450k employees!

Network Operator	Employees in 2000	Employees in 2025
AT&T	~215k	~133k
Verizon	~260k	~90k
Vodafone	~130k	~92k
Orange	~189k	~127k

At the turn of the century, the top 7 global telecom OEMs employed close to 800k people.

...

Now, only two main OEMs, Ericsson and Nokia, serve North America and European markets with less than 170k employees!

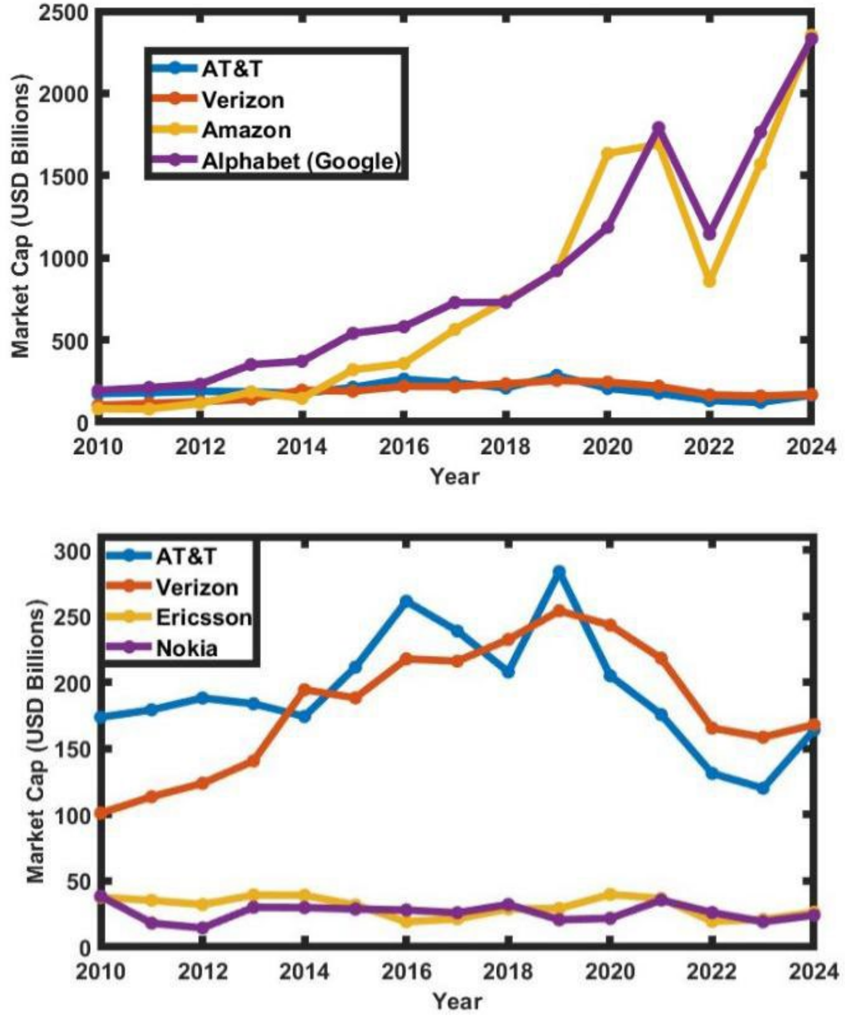
Telecom OEM	Employees in 2000**	Employees in 2025
Lucent Technologies	~157k	Gone*
Nortel Networks	~95k	Gone*
Ericsson	~107k	~89k
Alcatel	~110k	Gone*
Nokia	~60k	~78k
Motorola	~150k	Gone*
Siemens I&C	~115k	Gone*

*Some of these companies have been acquired/merged or no longer operate in the wireless infrastructure business.
**Not all the employees in 2000 were working in wireless networks.

Who Benefited the Most from the Build Out of 4G and 5G?

Key Takeaways

- While mobile network operators invested heavily in expanding the wireless data pipeline, service providers such as video streaming and e-commerce reaped the benefits.
- U.S.-based MNOs spent more than **$100 billion** on C-band (3GHz to 4GHz) **spectrum** auctions and over **$200 billion** on developing the 5G network **between 2019 and 2024.**
- While the market cap of **AT&T** and **Verizon** has hovered around **$200 billion** between **2010 and 2024, Amazon** and **Alphabet** market caps have exploded by more than **10×**, to surpass **$2 trillion!**
- The market cap of the network equipment suppliers **Ericsson** and **Nokia** has hovered around **$30 billion** in the same period, putting immense cost pressure on them.



K. Chuang et al., "From Dusk to Dawn: An Industry Perspective on the Transition From 5G to 6G Wireless Communications Infrastructure," in IEEE Microwave Magazine, vol. 26, no. 12, pp. 44-63, Dec. 2025.

The Infrastructure Paradox:

Wireless connectivity is now a vital utility behind water and electricity, yet its ecosystem is severely strained ...

The industry's defining challenge is to radically optimize cost-per-bit without sacrificing the innovation roadmap.

How Multiple Generations of Software-Defined Radios Have Risen to the Challenge

Zero-IF Architecture Solves Multiple Industry Challenges

1990s—Double Conversion

- DAC/ADC limited to <10MHz signals
- Two-stage frequency conversion required

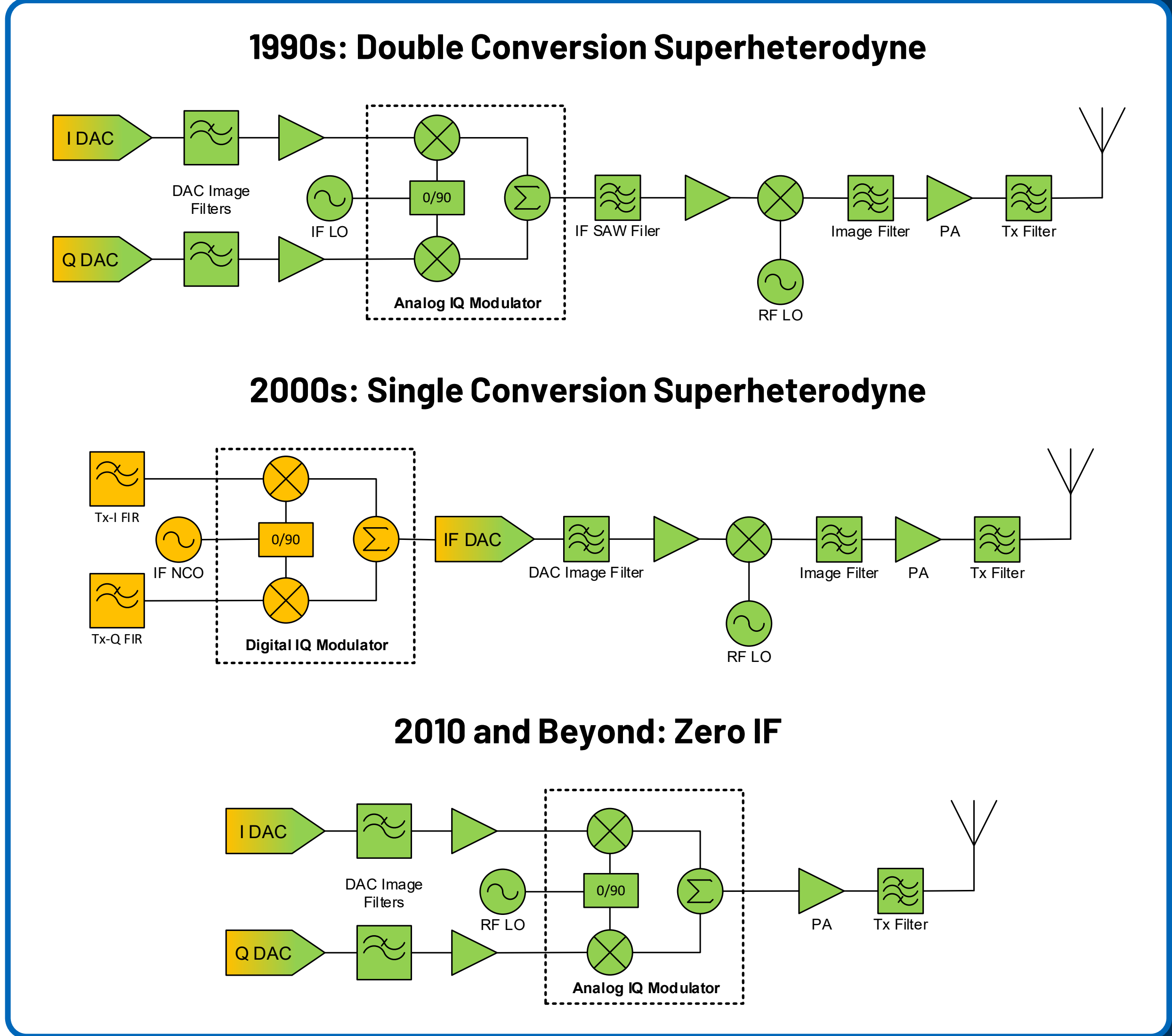
2000s—Single Conversion

- Finer CMOS enabled 100MHz+ IF frequency
- Eliminated one frequency conversion stage

2010s—Zero-IF (ADI Innovation)

- Previously impractical for base stations due to image rejection and LO feedthrough challenges. ADI solved these with innovative circuit design and advanced correction algorithms
- Later **digital front-end (DFE)** functions, such as **crest factor reduction (CFR)** and **digital predistortion (DPD)**, were added to improve the PA efficiency.

Results: Dramatic reduction in radio **size**, **weight**, **power**, and **cost,** while increasing the **channel density and bandwidth.**



K. Chuang, et.al., "Radio Challenges, Architectures, and Design Considerations for Wireless Infrastructure: Creating the Core Technologies That Connect People Around the World," in IEEE Microwave Magazine, vol. 23, no. 12, pp. 42-59, Dec. 2022.

Six Generations of ADI Integrated Transceivers 2010 - 2025

AD9371, 100MHz
2Tx/2Rx, DPD

First SDR to enable
3G/4G macro cell radios

ADRV9029, 200MHz
4Tx/4Rx, CFR/DPD

First SDR to enable
5G massive MIMO radios

ADRV9060 4Tx/4Rx, 400MHz
O-RAN eCPRI and Low PHY channelizers, CFR/DPD

First SDR to enable
5G massive MIMO radios

2010 — **More Channels, More Bandwidth, More Functionality, Less Power and Cost per Channel** — **2025**

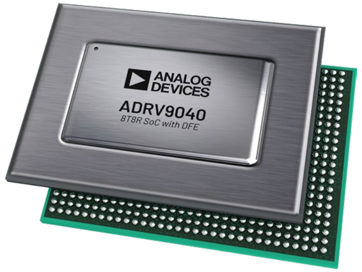
AD9361
2Tx/2Rx, 60MHz

First general-purpose SDR

ADRV9009
2Tx/2Rx, 200MHz

First SDR to meet the stringent
multicarrier GSM requirements

ADRV9040 8Tx/8Rx, 400MHz
channelizers, CFR/DPD



First 8-channel, 400MHz SDR
with complete DFE functionality

Radio Access Network (RAN) Building Blocks and Partitioning

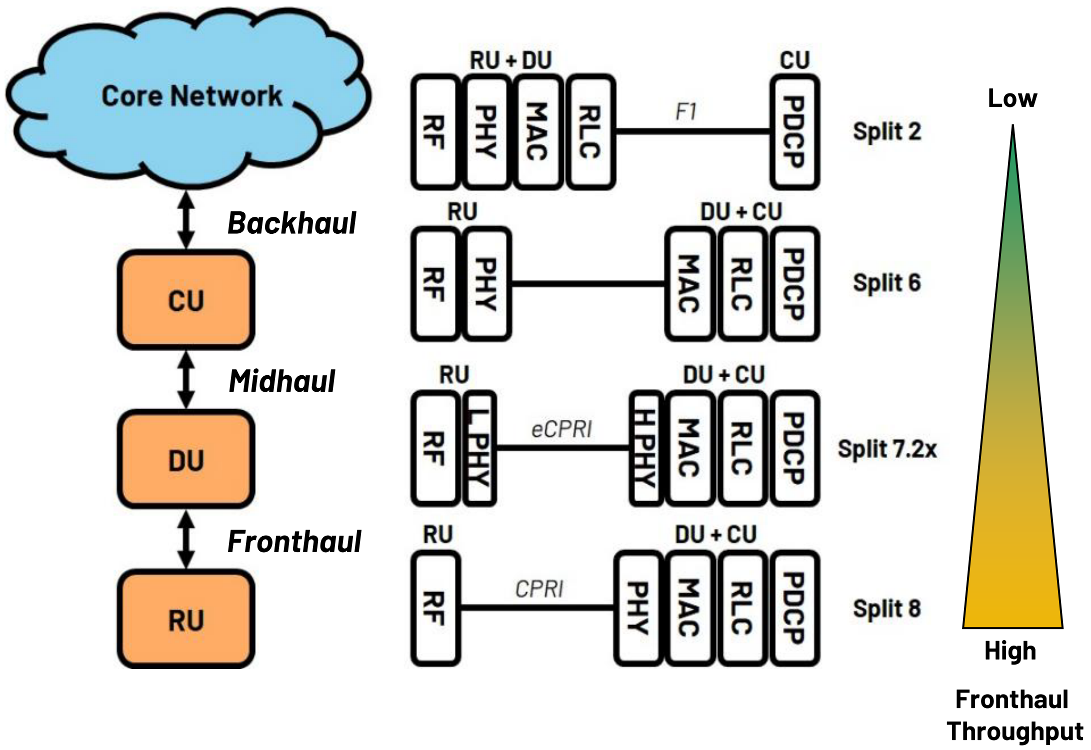
RAN Architecture
Three blocks: **RU** (radio unit), **DU** (distributed unit), **CU** (central unit).

Split Trade-Off
Higher splits → more fronthaul throughput and tighter latency.

4G/LTE (Split-8)
Time-domain I/Q samples sent via CPRI protocol to the baseband unit (DU + CU). A single 20MHz carrier in a 4-transmit/4-receive configuration needs 5Gbps.

5G Macro/Massive MIMO (Split 7.2x)
Split-8 impractical for wider channel BW and more transmit/receive chains in 5G. By moving the low PHY processing from DU to RU, the fronthaul throughput is significantly reduced.
In Split 7.2x, frequency domain I/Q samples are transferred via eCPRI protocol between the DU and RU.

All-in-One Small Cell Radios (Split 6)
For a self-contained small cell with limited coverage and capacity, it may make sense to put RU and DU in the same box.



- **PDCP** (packet data convergence protocol)
- **RLC** (radio link control)
- **MAC** (media access control)
- **PHY** (physical layer)

Formation of the Open Radio Access Network (O-RAN)

Mission: Transformation of the RAN into an Open, Intelligent, and Virtualized system

O-RAN ALLIANCE

Over 300 Members

32 Mobile Network Operators

Over 147 Unique Technical Titles

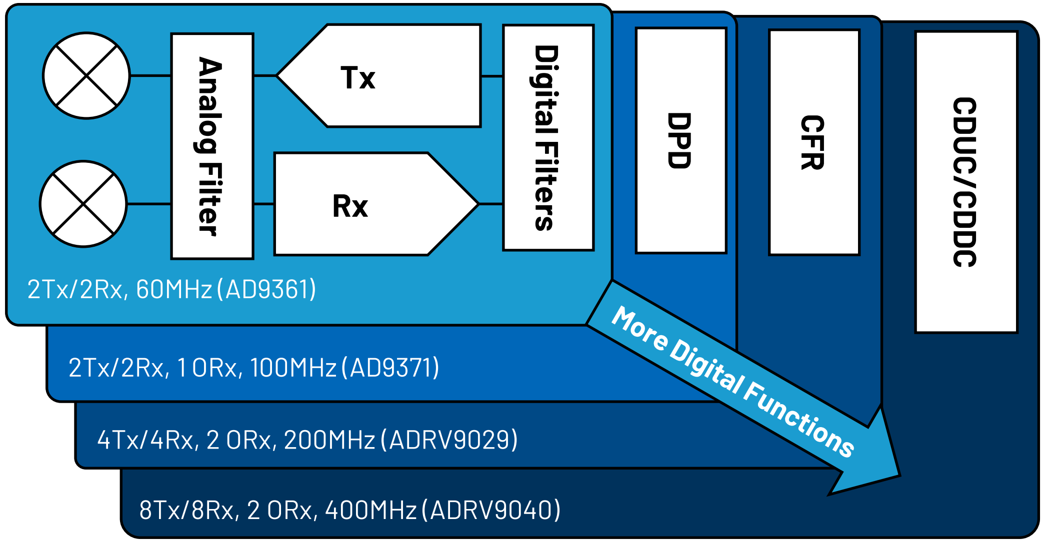
Supply Chain Diversity
Open and interoperable interfaces enable RU, DU, and CU to purchase from best-in-class vendors

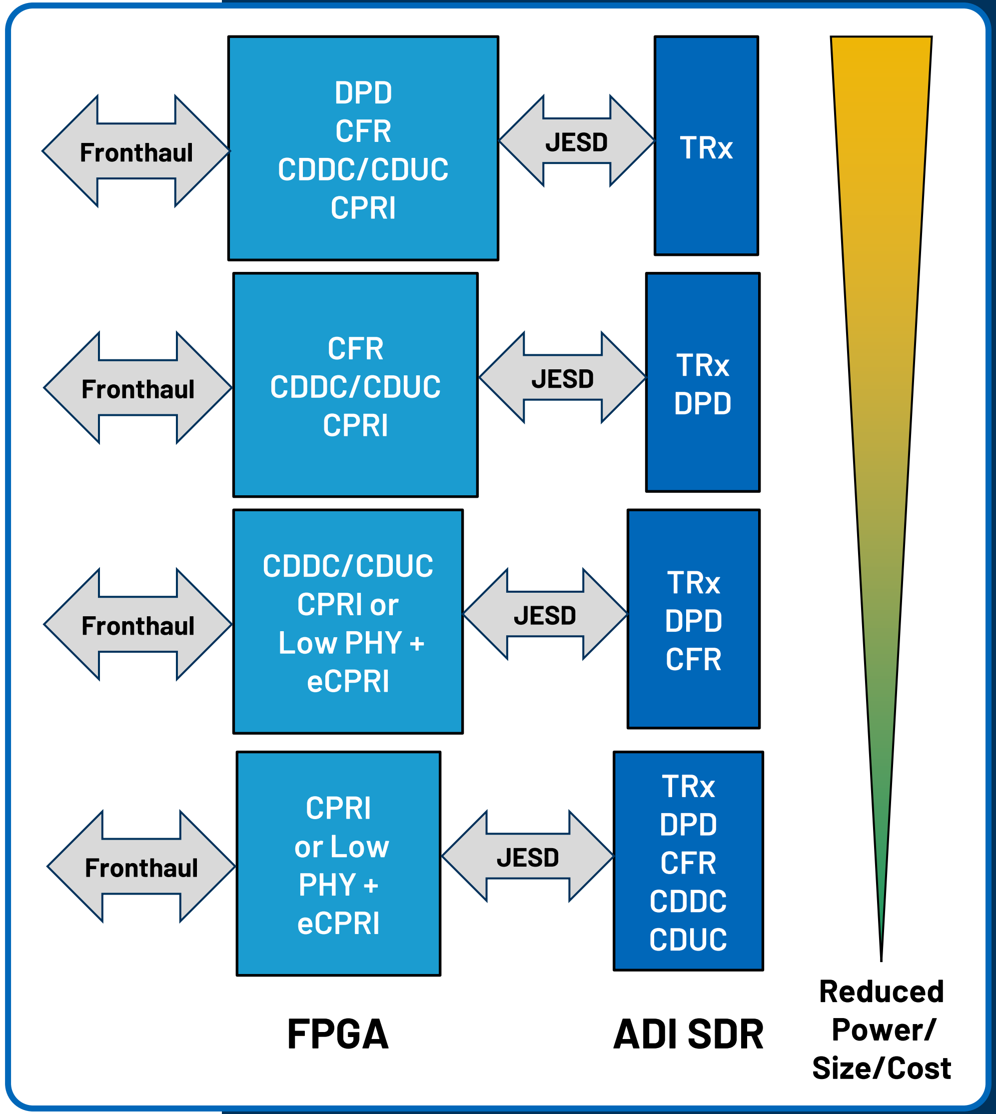
Increased Innovation
Separate hardware and software enable a large community of innovators

Lower Costs
RAN virtualization (mainly in DU and CU) enables the use of COTS servers, similar to data centers

More Digital Functionality Absorbed in ADI SDRs over Generations

but an FPGA was always needed to make a complete radio unit …



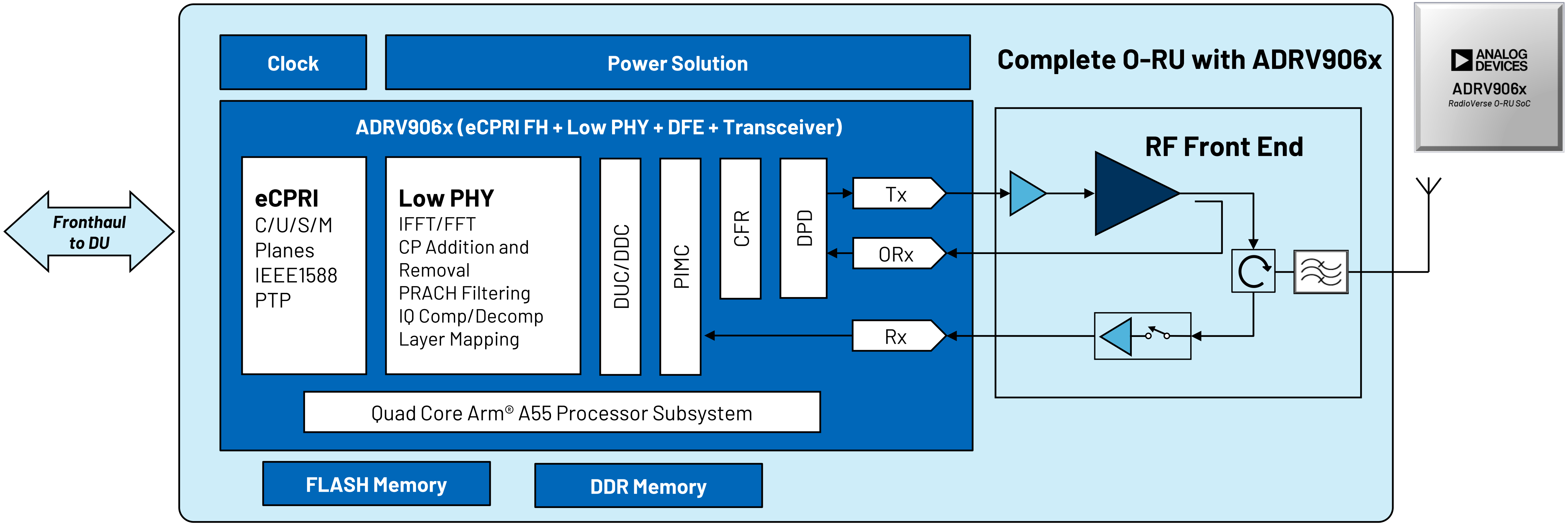


- **DPD**: digital predistortion
- **CFR**: crest factor reduction
- **CDUC**: channel digital upconverter
- **CDDC**: channel digital downconverter
- **CPRI**: common public radio interface (time domain IQ samples)
- **eCPRI**: enhanced common public radio interface (frequency domain IQ samples)

Radio on a Chip

Fronthaul to RF with ADRV906x (Samana)

No FPGA Required!



O-RAN Split 7.2a compliant radio on a chip. **Only RFFE, power, and clocking are external to ADRV906x!**

ADRV906x (Samana): The Most Integrated SDR Platform for 4G/5G Networks

Base-Station Enabling Technology: Integrated Software-Defined Radios

Base-Station Radio Unit Development Challenges

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Time to Market

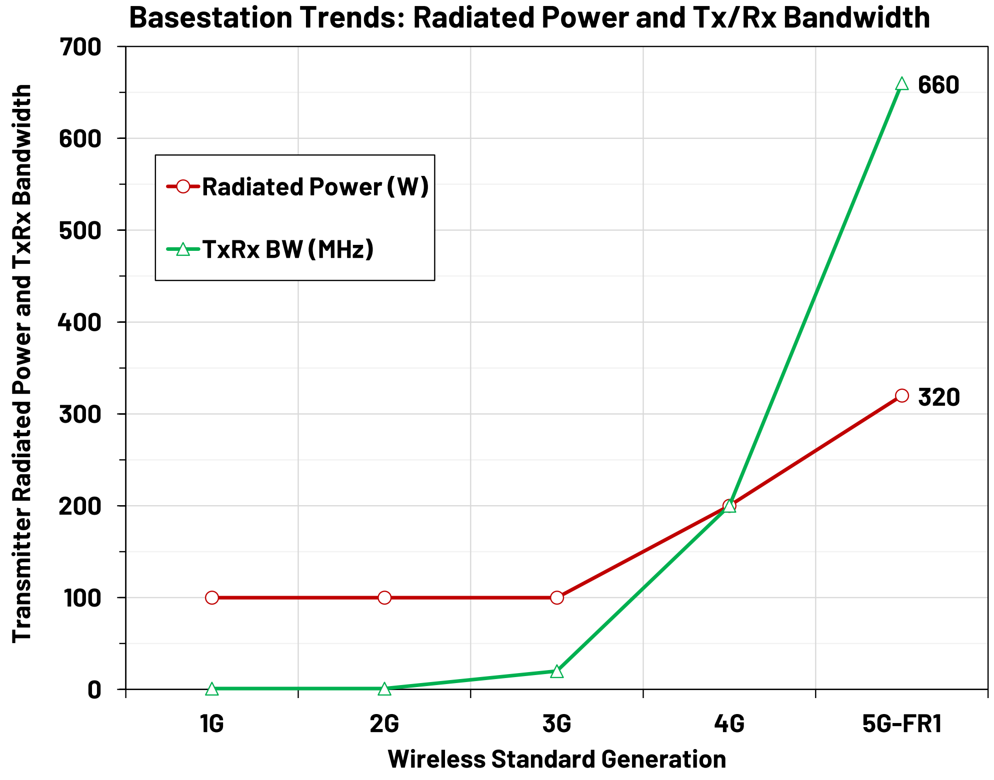
Power Cooling

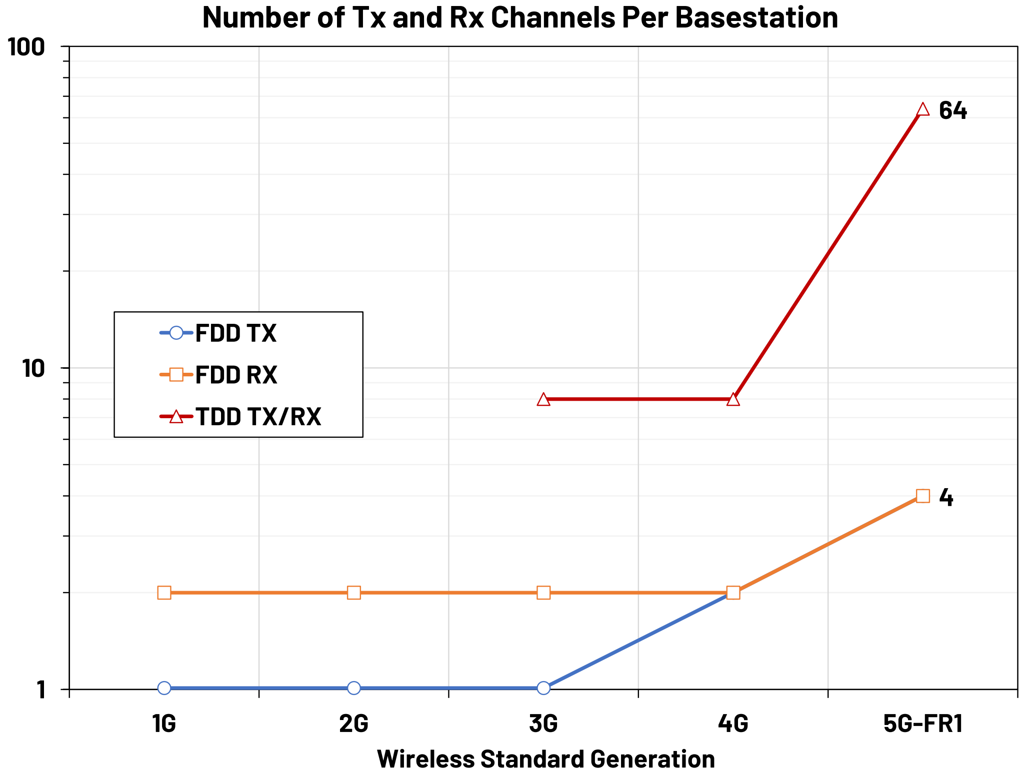
Number of Frequency Variants GSM-6G

System Cost

Increased Antenna Count

Base-Station Trends: More Antennas, Radios, and Power



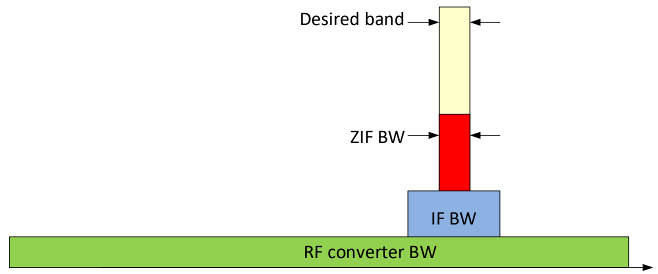


Widest bandwidth for multiband operation per receive/transmit pair.

ADI Software-Defined Radio Architecture Benefits

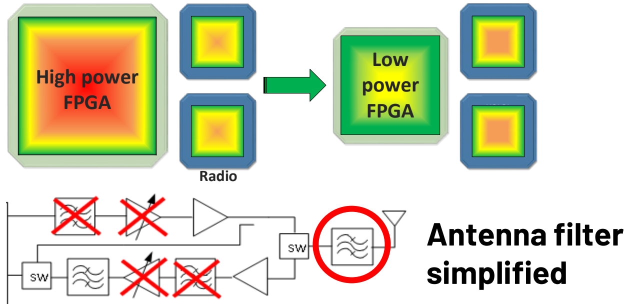
Reduced System Power

- ZIF architecture more power-efficient than RF converter
- Low-power RFFE
- Integrated DPD and CFR



Reduced System Weight

- Reduced thermal hotspots simplifies thermal solution
- ZIF architecture relaxes filtering by 75dB
- ZIF RF architecture enables the elimination of multiple frontend BOM components



Common Platform

- Scalable platform for small cell, M-MIMO, macro
- Highly configurable HW
- API enable customization and integration

Silicon CMOS SDR

Advanced digital radio features add value **to the integrated solution**

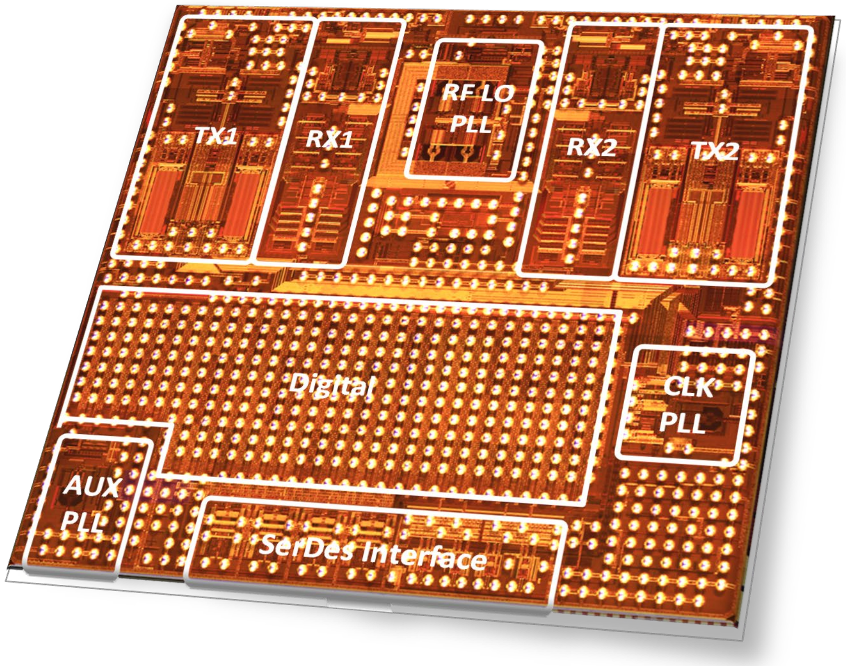
- Lower cost
- Lower power than FPGA

Digital CMOS not the greatest technology for analog/RF performance

- Matching
- Noise
- Loss
- Parasitic capacitance and resistance

Digitally assisted analog/RF: the best of both worlds

- Calibrations
- Amplifier feedback techniques
- Innovative radio architectures
- Wide range of data converter options for different applications



Zero-IF: Integrated Transceiver Workhorse

Advantages:

Frequency agile—single/dual LO

Minimal RF circuitry

ADC/DAC architectures

- Eliminates filters

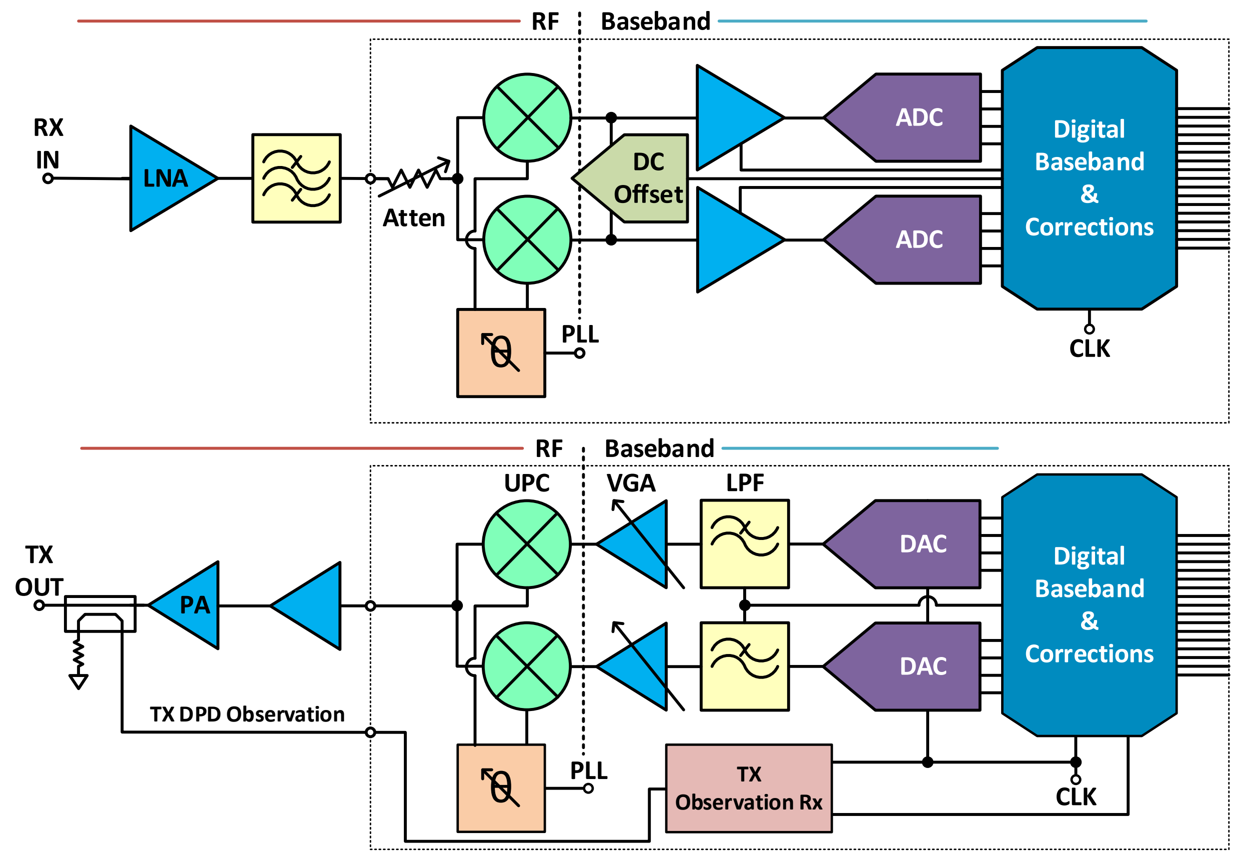
High dynamic range baseband analog

Performance scales with technology

- Bandwidth
- Linearity

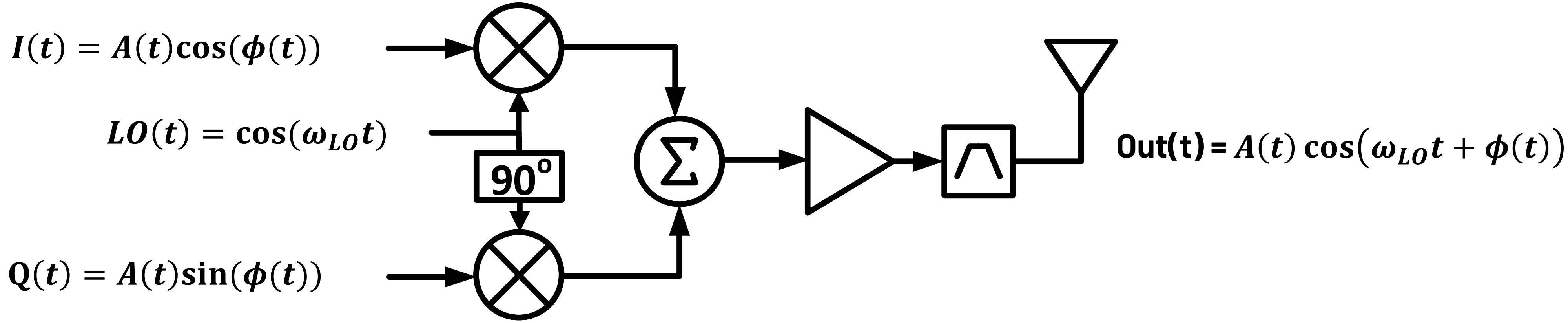
Digital for RF/analog corrections

Leverage correction algorithms



Quadrature Modulator/Demodulator

Baseband-to-RF (TX) and RF-to-baseband in one step



I(t) is the "in-phase" component, Q(t) is the "quadrature" component.

Amplitude Modulation — **Phase Modulation**

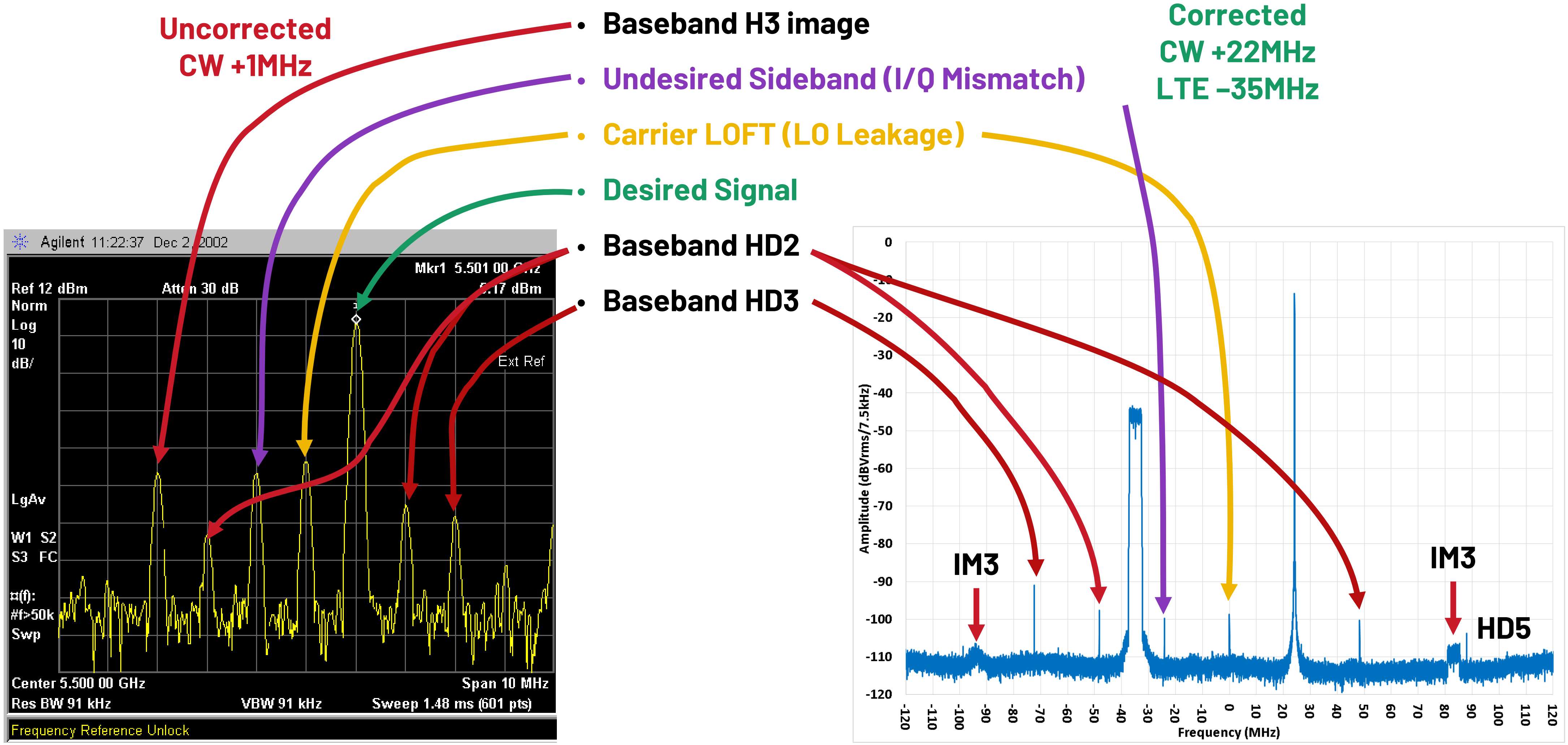
$$A(t) = \sqrt{I(t)^2 + Q(t)^2} \qquad \phi(t) = \tan^{-1}\left(\frac{Q(t)}{I(t)}\right)$$

Gain errors between I(t) and Q(t) paths and quadrature phase error distort the modulation accuracy.

Want the modulation accuracy to be very good. Need better than

–65dBc Tx and –75dBc Rx. → **0.020°** quadrature phase error OR
0.036% amplitude error

What Do We Get Uncorrected and Corrected?



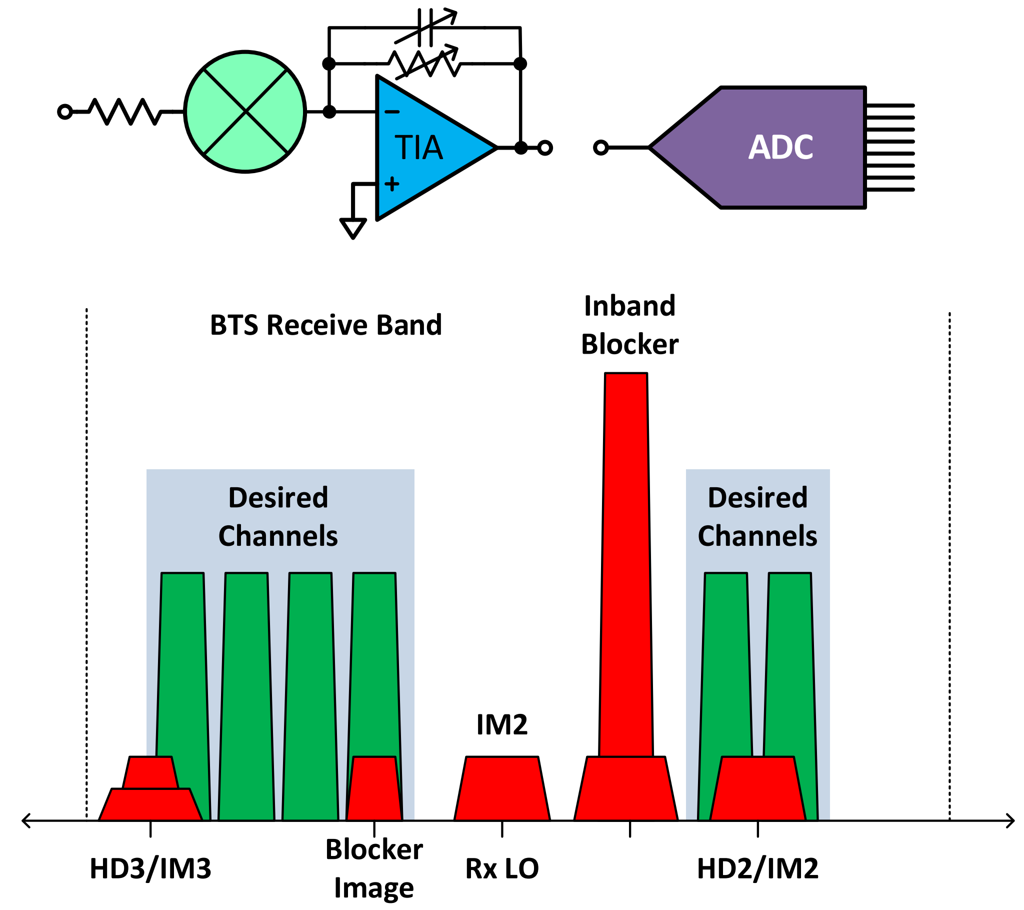
Observation, Algorithms, and Circuits

ZIF performance achieved by

High dynamic range analog baseband circuits
- Feedback techniques for stable gain and linearity
- ADCs with built-in antialiasing filtering

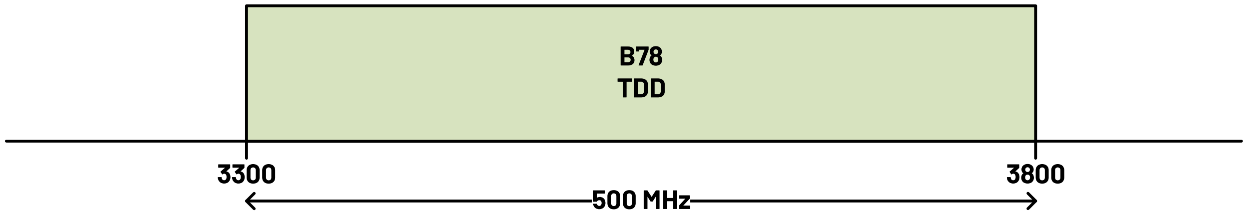
Operational corrections:
- RX/TX quadrature error correction
- TX LO leakage cancellation
- RX DC offset correction
- RX automatic gain control

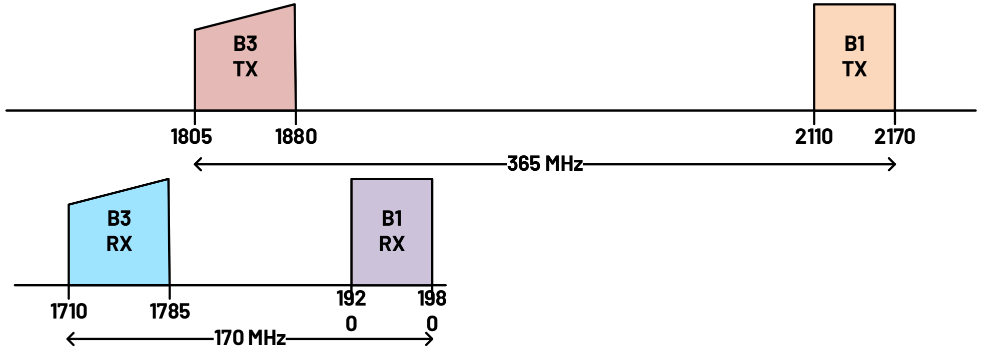
Static corrections:
- Initial QEC/LOL
- Filter tuning
- DAC/ADC corrections



Advantages of Wideband Transceivers

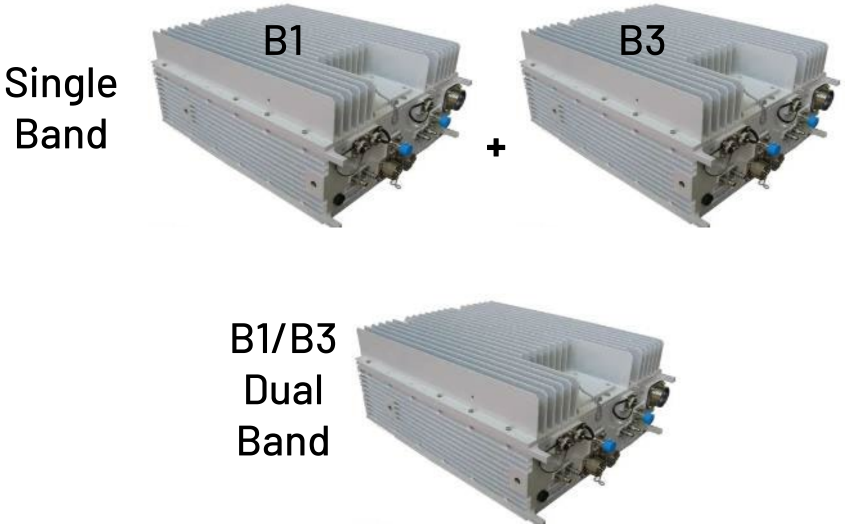
Operate over large bandwidths





Single-radio dual-band solutions

- Saves 2× radio HW and 2× lower power for two band operation
- DSP to separate, filter, and process two different bands
- AGC aware of blockers in either band



RF Converters

Ultimate flexibility with new challenges

Power vs. bandwidth

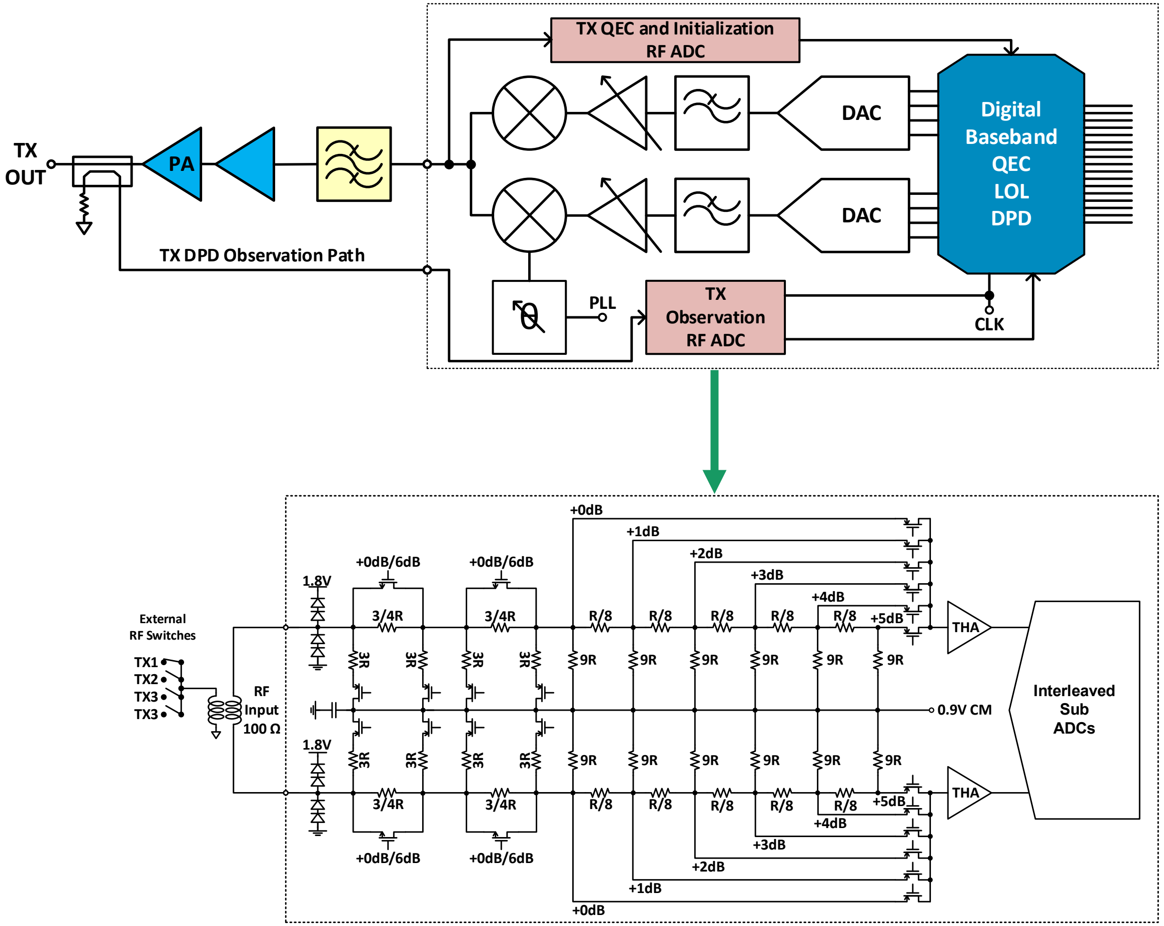
- Digital lower power with technology
- Wideband analog adds power

Analog operates at RF frequencies

No local oscillator

Alias frequency planning

TX QEC operates independently of DPD



Evolution of Integrated Transceiver Performance

ADI Part	UNIT	AD9371	ADRV9009	ADRV9026	ADRV9040
Process technology	(nm)	65	65	28	16
Number of Tx/Rx/ORx	Channels	2/2/1	2/2/1	4/4/1	8/8/2
Tx/Rx bandwidth	(MHz)	100	200	200	800/660
Max RF frequency	(MHz)	6,000	6,000	6,000	7,100
Tx output power	(dBm)	7	7	6.5	4.5
Tx noise floor	(dBFS/Hz)	–155	–155	–155	–157
Tx output IP3	(dBm)	27	27	29	22
Tx image rejection	(dBc)	65	65	75	65
Tx LO leakage	(dBFS)	–81	–82	–84	–84
Rx noise figure	(dB)	12	12	11.5	12
Rx input IP3	(dBm)	22	12	17	16
Rx image rejection	(dBc)	75	75	75	75

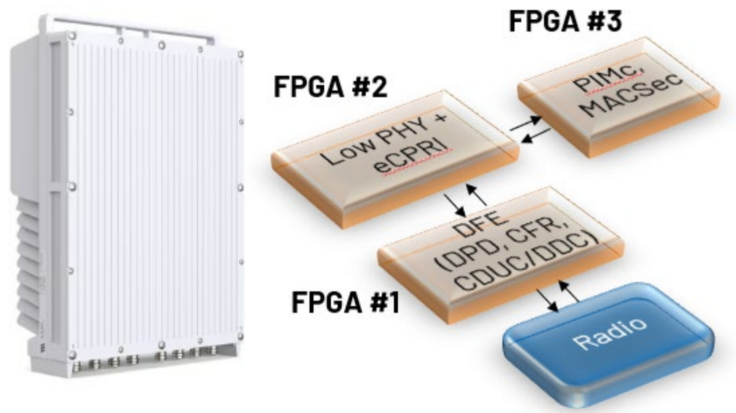
Deep Dive into the ADI's Latest Full-Functionality Software-Defined Radio

ADRV906x (Samana)

Full-featured radio on a chip—No FPGAs!

4G/5G Macro Radio Unit

Implementation with FPGAs



Samana
Radio on a chip

Total Power 15W*

Application requirements

Small and lightweight

Low power

Cost Optimized

Challenges with FPGAs

FPGAs drive **high cost and power** (>50W)

Power drives **weight**

High IP integration effort for customers

Samana provides

Low-power consumption RU SoC (**15W***)

Full system integration into single IC

Up to **30% BOM cost savings** by eliminating FPGAs

*15W is for TDD 4Tx/4Rx, 200MHz Carrier BW and 70/30 DL/UL ratio

Introduction to O-RAN Open Front Haul Interface

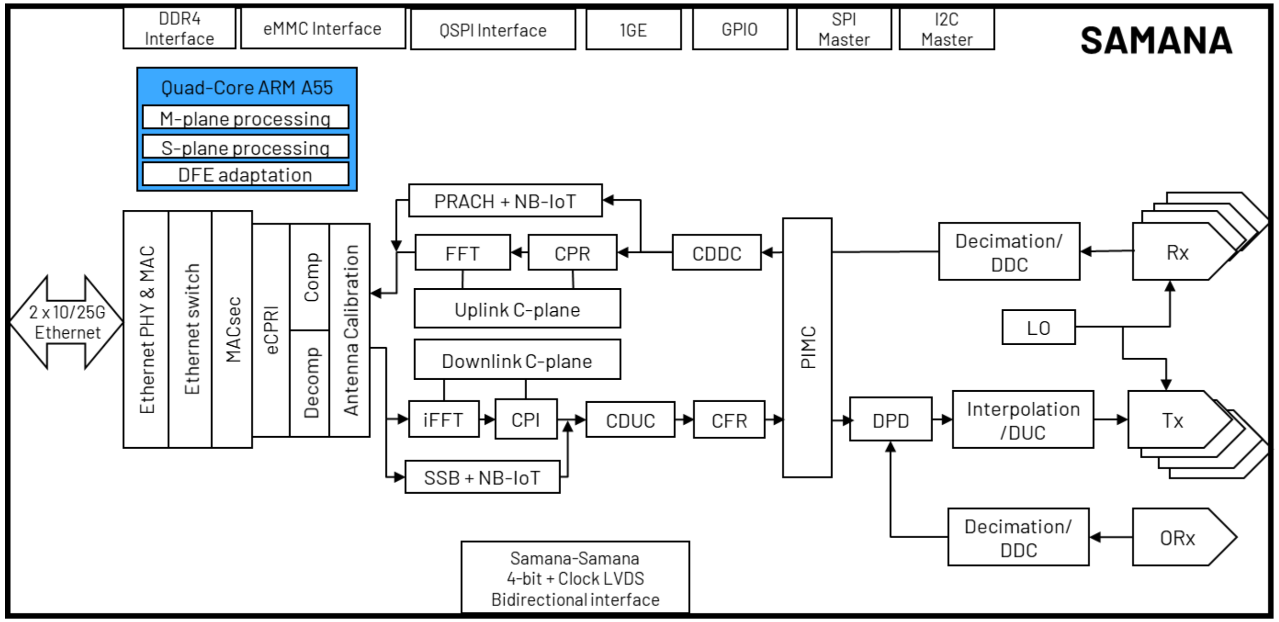
ADRV906x (Samana) integrates an eCPRI fronthaul interface compliant with O-RAN split 7.2a standard

- **eCPRI** (enhanced common public radio interface): standard Ethernet-based protocol for transferring data and control signals between RU and DU. O-RAN Open Fronthaul Interface complies with eCPRI and further specifies:
- **User Plane** (**U-Plane**): messages containing frequency domain I/Q data samples that are transmitted or received.
- **Control Plane** (**C-Plane**): real-time control information regarding handling of User Plane data, such as how to map the IQ samples to each antenna port.
- **Synchronization Plane** (**S-Plane**): precision time protocol (PTP) messages based on IEEE 1588 to synchronize the RU to the rest of the network.
- **Management Plane** (**M-Plane**): slow control and **radio configuration** information **(USE CASE CONFIG)**

Samana

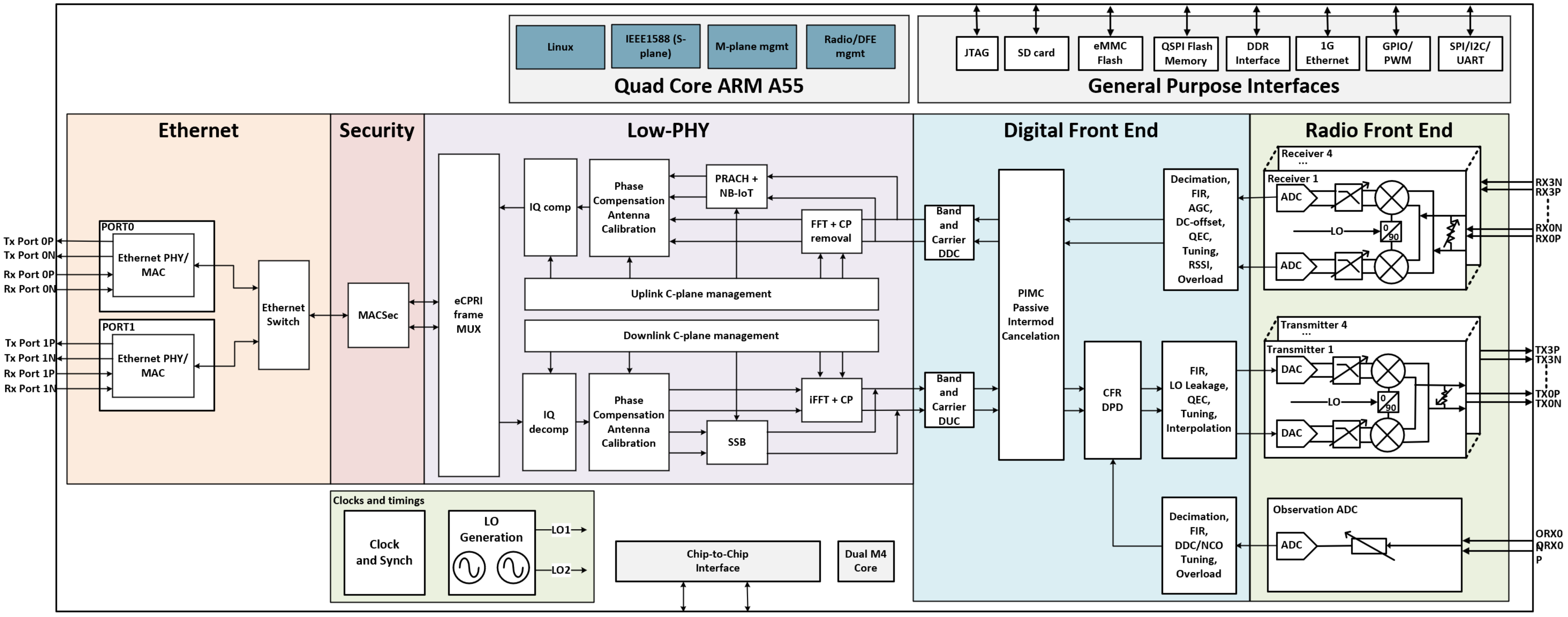
4T4R/8T8R Radio + DFE + Low PHY

Feature	Support
Antennas	4T4R (expandable to 8T8R)—16nm
Air Interface	NR FR1, LTE, NB-IoT
Functional Split	7.2x cat A, no beamforming
Duplexing	TDD and FDD (including PIM cancellation)
Instantaneous BW	660MHz
Occupied BW	400MHz
Synchronization	IEEE 1588 PTP or 1pps + ToD; SyncE
Processor	Quad-core Arm® A55
DPD Subsystem	DPD Gen6—LDMOS/GaAs/GaN PAs, > 40W
External Memory	DDR4, NAND flash, NOR flash
Fronthaul Interface	2× 10/25G ethernet, O-RAN compliant eCPRI
RF Interface	4T4R1O, 400MHz to 7.125GHz

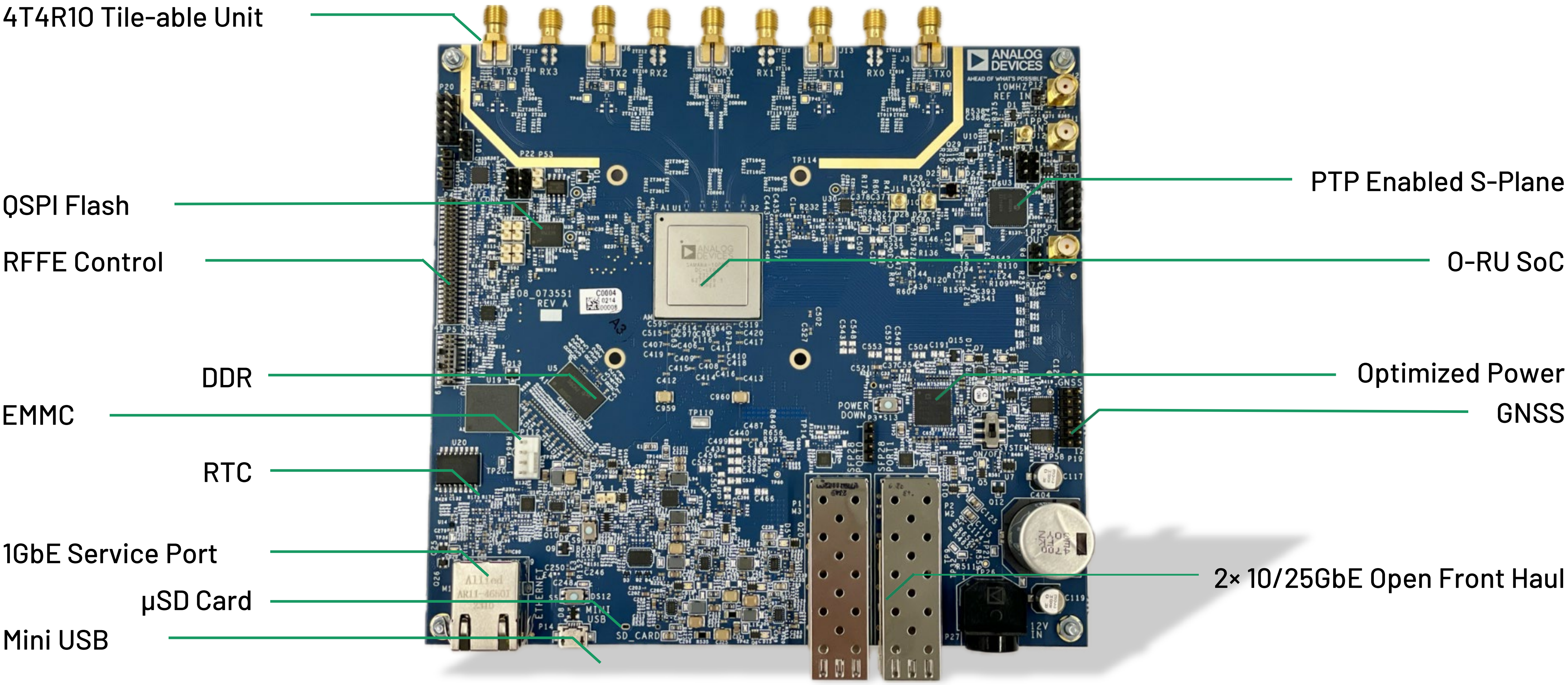


- Adds more processing at the edge (on the radio)
- Reduces the BW that needs to be sent to DU/CU—frequency domain data + on-chip compression
- Adds machine learning performance optimization at the edge

Samana Detailed Block Diagram



Complete Radio Board Design with Samana



Samana Multiband Use Case Support

Samana enables far greater flexibility in use case planning with a single transceiver device

When layered with the LO distribution capabilities, more frequency band combinations can be supported.

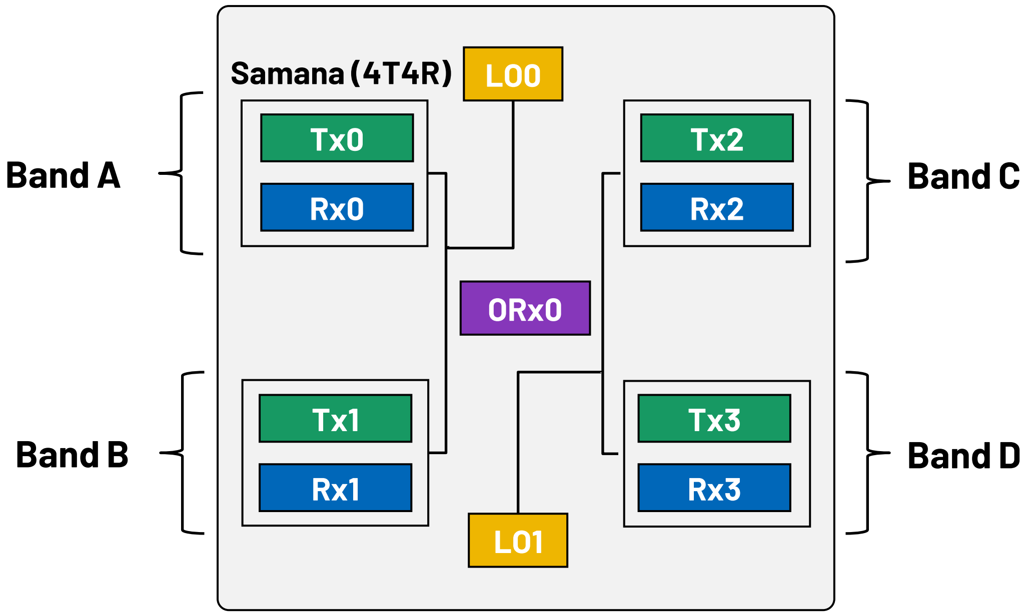
- **Mixed mode TDD and FDD is supported**

With a 4T4R device, up to four band profiles can be supported within a single use case:

- 1× 4T4R → Common profile deployed on all Rx, Tx, ORx channels
- 2× 2T2R → Can use Tx/Rx[0,1] for 100MHz application and Tx/Rx[2,3] for 400MHz application
- 4× 1T1R → Can use a different use case for each pair of Tx/Rx channels

Allows four individual band profiles (>400MHz IBW) to be used in the device

LO0-LO1: 400MHz to 7.125GHz

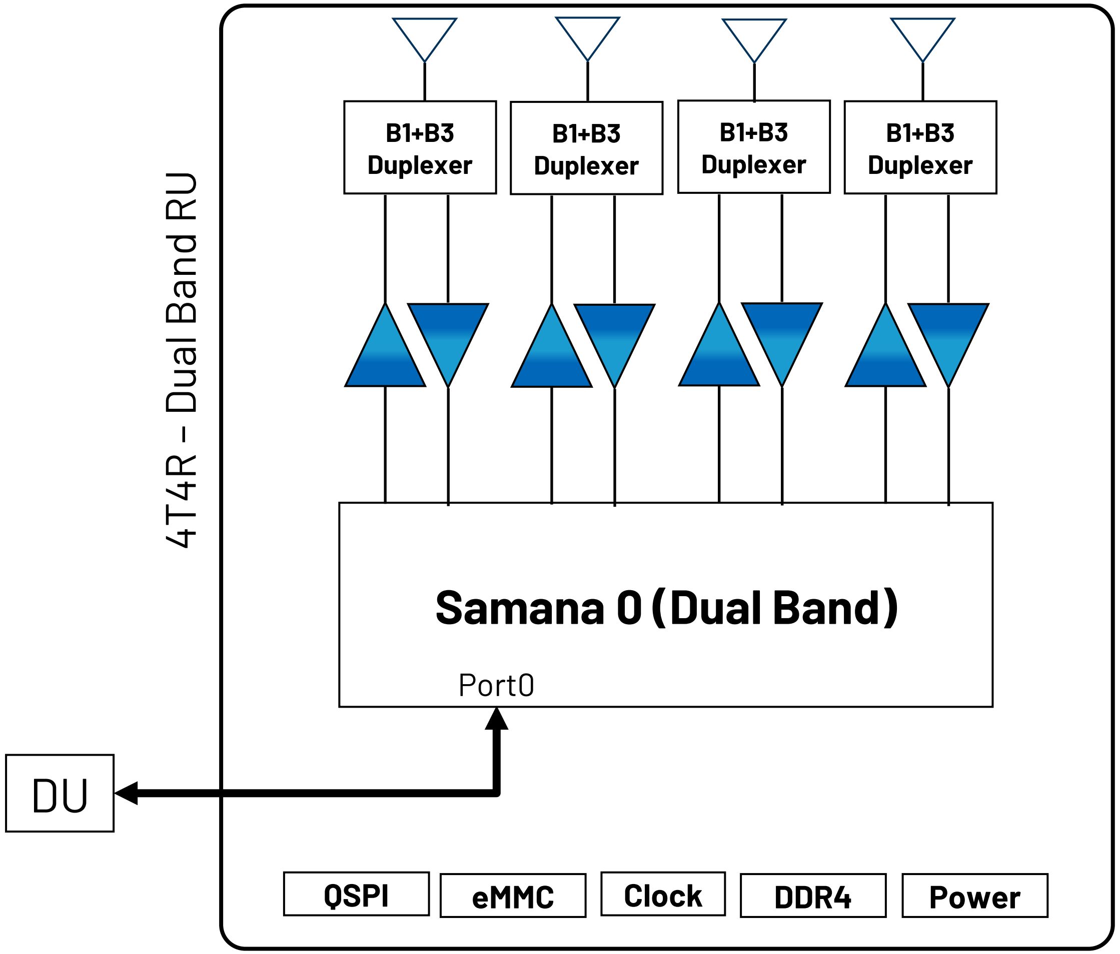


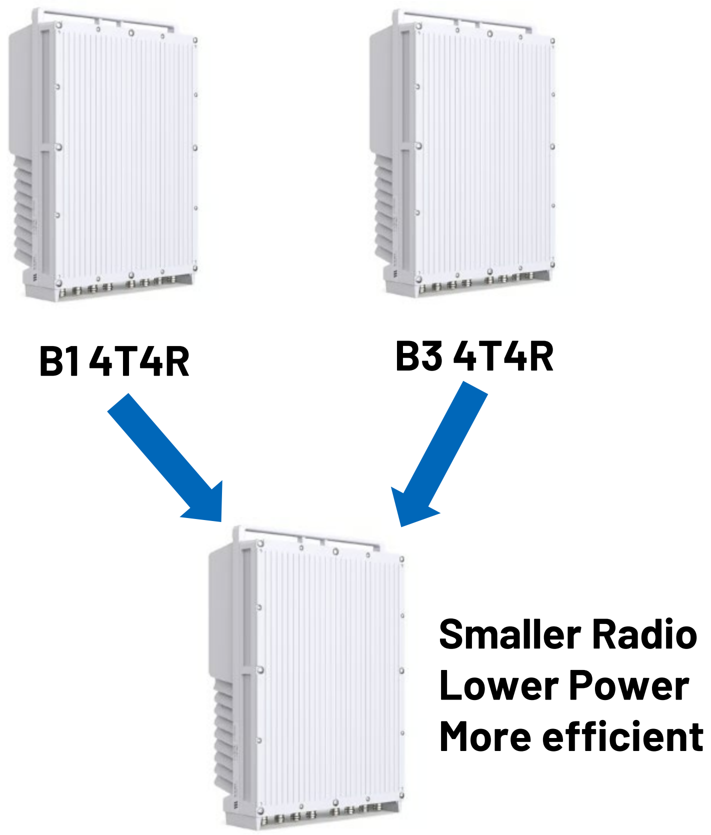
The above example shows support for four bands with single Samana 4T4R

Flexibility in LO0/LO1 routing

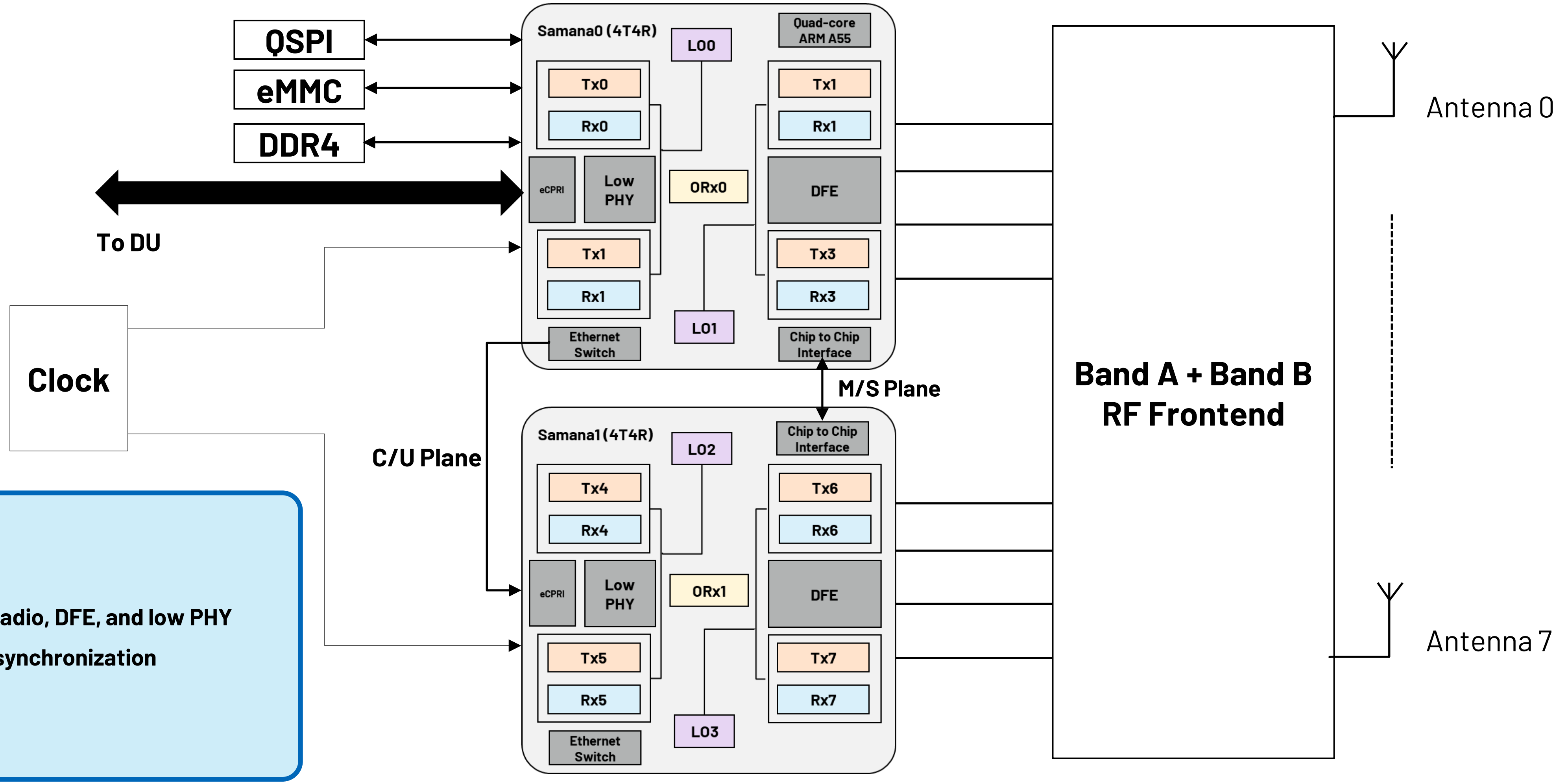
Multiband support limited by RF front-end bandwidth and power

Samana Dual-Band Use Case Example (B1 + B3—4T4R)



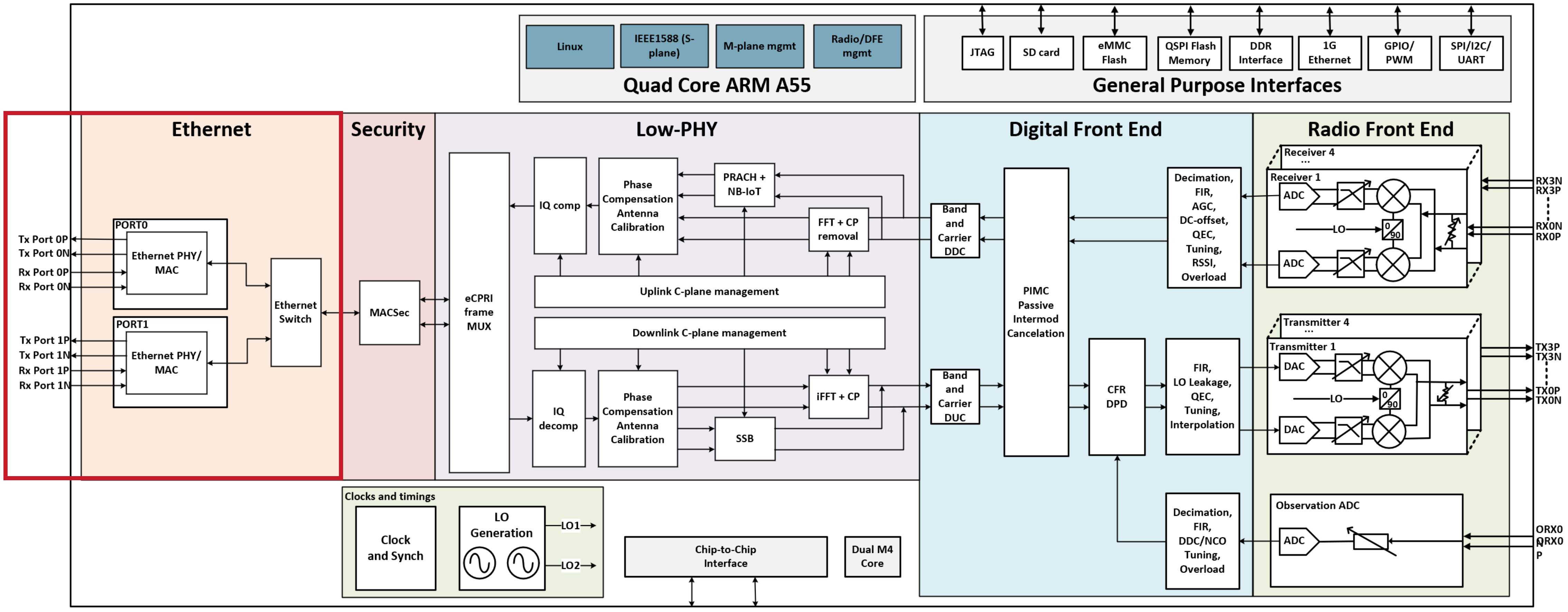


Samana Multiband Use Case Support (8T8R Tiling)



- No FPGA needed in RU
- Operates as single 8T8R
- Multiband support with radio, DFE, and low PHY
- Simplified clocking and synchronization
- Fewer peripherals
- >400MHz IBW supported

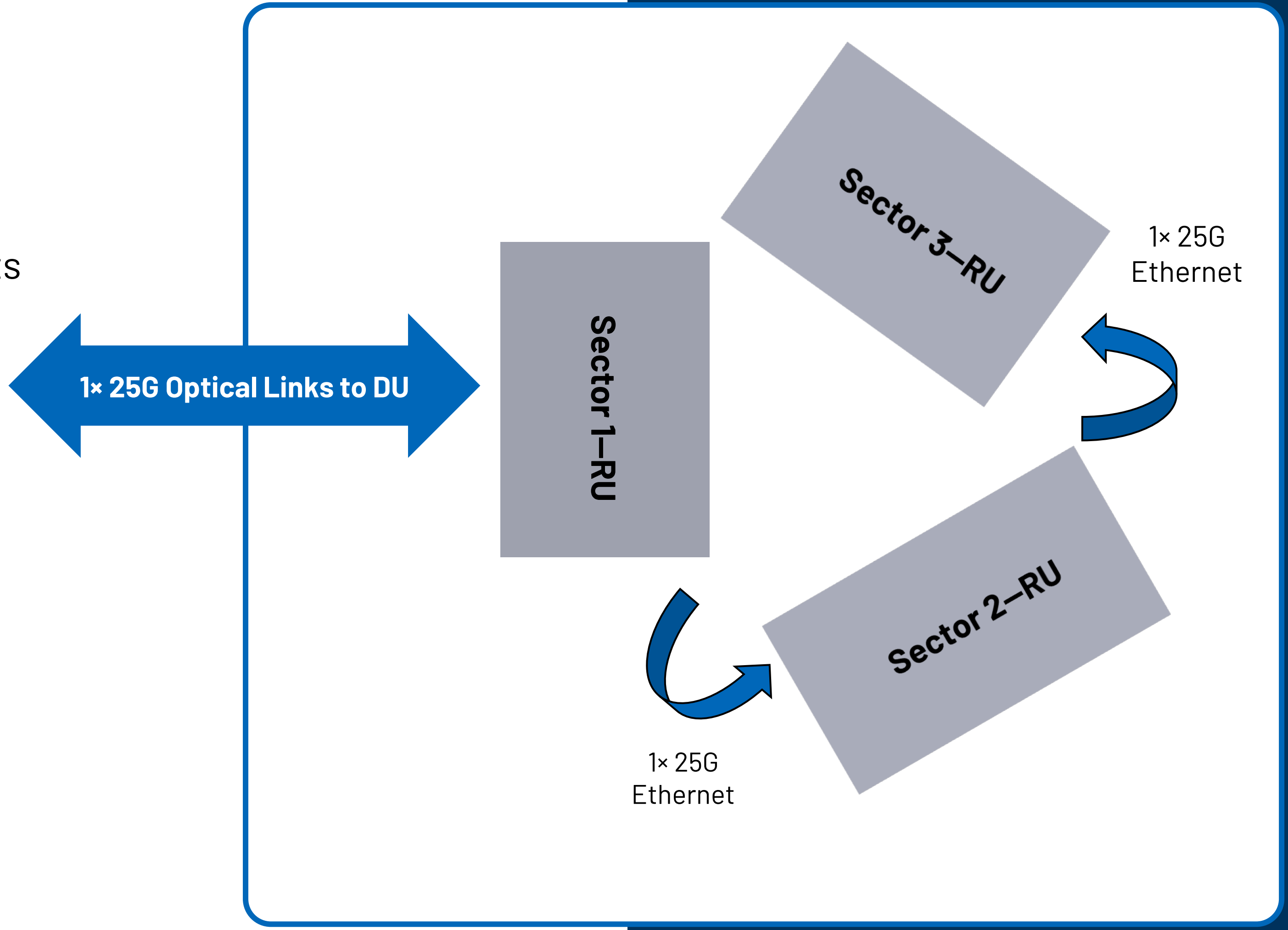
Samana Block Diagram—Ethernet Switch



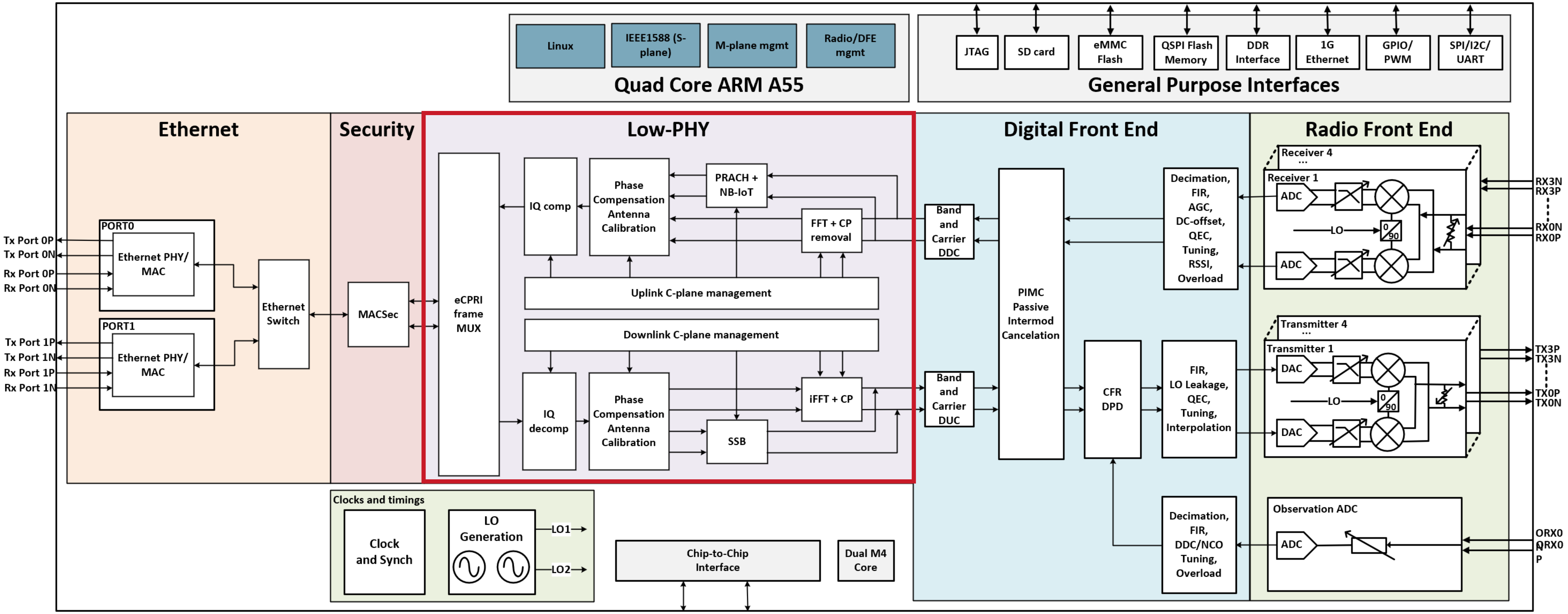
Fronthaul Daisy Chaining Use Case

Supporting Three Sectors with One Optical Connection

- Each cell tower typically consists of three sectors, and each is served with one RU
- Assuming the carrier bandwidth for all three RUs fits on a single 25Gbps fiber, a single fiber can serve all three sectors
- Single optical port assigned to primary Samana
- Internal switches in Samana to the other sectors (CUSM planes)
- 2µs packet delay across two hops
- Samana for sector 1 and sector 2 act as boundary clock

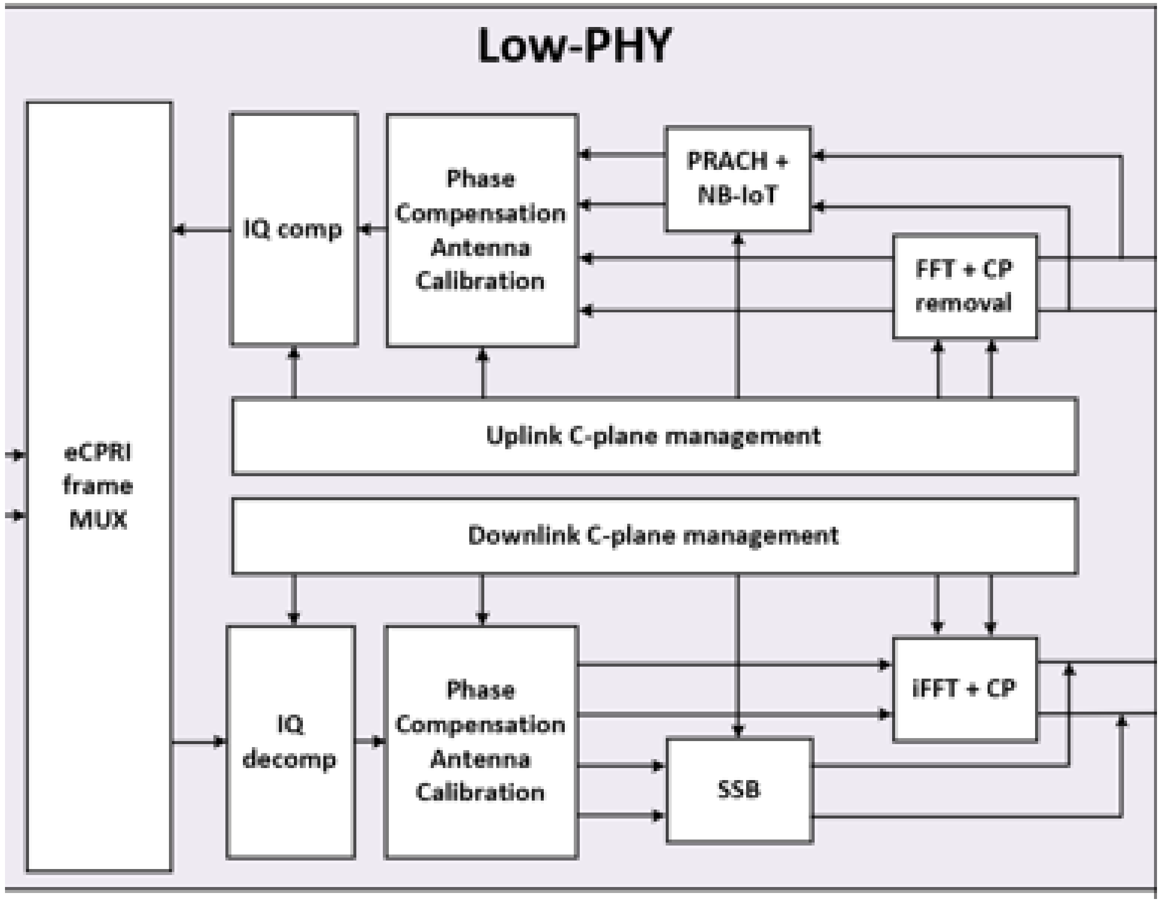


Samana Block Diagram—Low PHY

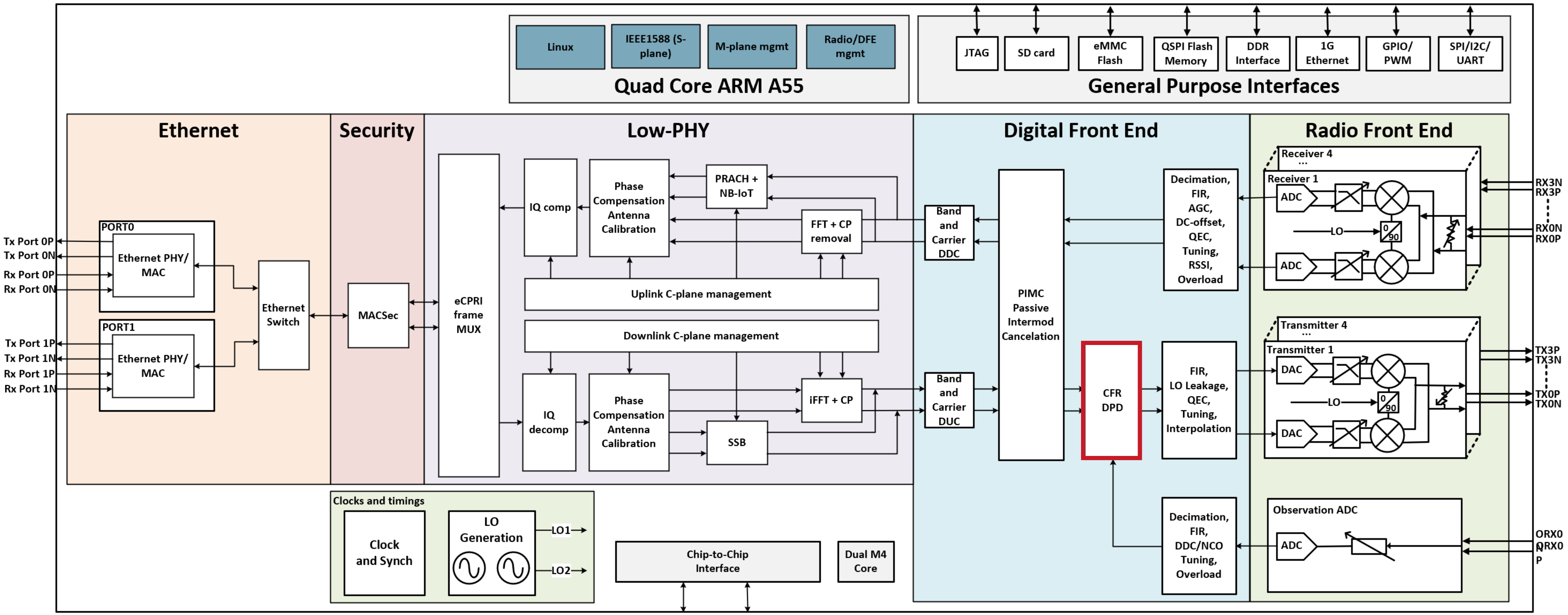


Low PHY Functionality

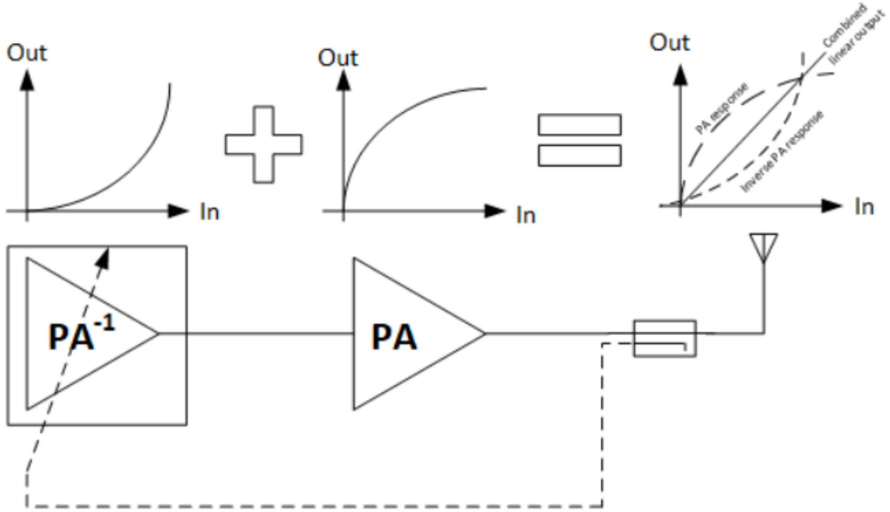
- Translates data from frequency domain to time domain and vice versa
- Interface between C/U plane Ethernet data to Tx/Rx controls on the radio side
- Adds compression to reduce throughput requirement on the Ethernet interface
- Allows for phase compensation
- Adds support for NB-IoT
- Integrates real-time autonomous antenna cal



Samana Block Diagram—CFR and DPD Blocks



DPD Principle of Operation



Why do we need DPD?

Having DPD enables the use of highly efficient nonlinear Pas such as Doherty

Base station can transmit more RF power to cover a larger area while using less power

Reduces heat generated in the system allowing for reduced weight and thermal solution

Evolution of the ADI DPD over Generations

ADRV902x | **ADRV904x** | **ADRV906x**

Generalized Memory Polynomial

- Fix compression
- Memory terms → equalization
- Cross terms → frequency-dependent compensation
- All-purpose DPD

Dynamic Deviation Reduction (DDR)

- Improved frequency dependent compensation
- 3dB to 4dB ACLR improvement on some wideband Pas

Charge Trap Compensation (CTC)

- Semi-physical design with long time constants
- Trapped charge model of GaN Pas
- EVM boost for first symbol and low-power symbols in dynamic waveforms

Machine Learning DPD Optimization

- ML techniques used to optimize DPD hardware resources
- Basic functions learned by ML (vs. standard orthogonal)
- Power savings

Macro PA DPD

- Expanded structures for sample rate DPD to get up to 5dB ACLR improvement and SEM improvement on several macro PAs
- Compensate for effects measured on various high-power PAs
- AI-assisted modelling

DPD Performance on B1+B3 Wideband PA for Macro Cells

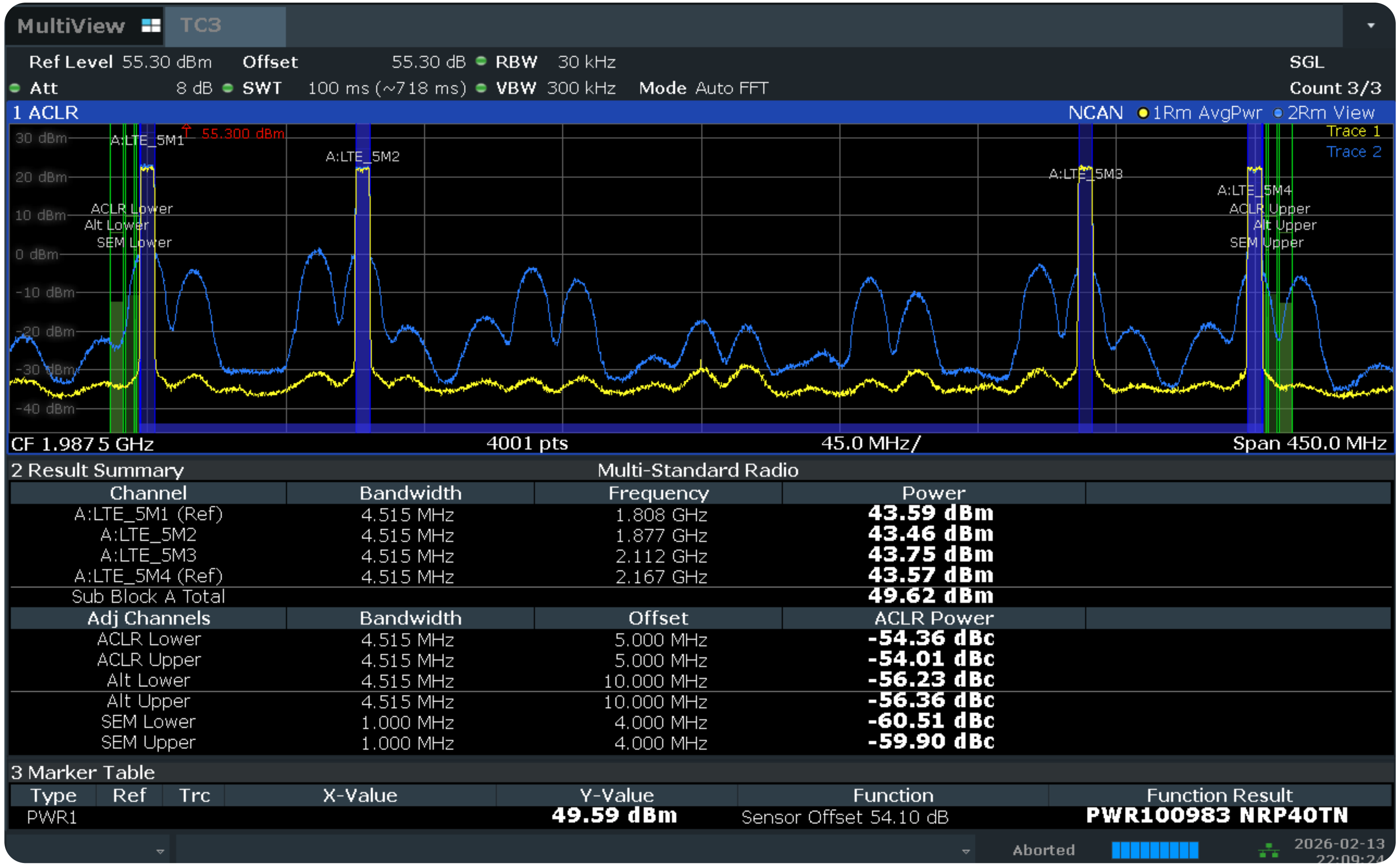
ADI DPD results:

Pout = 49.59dBm

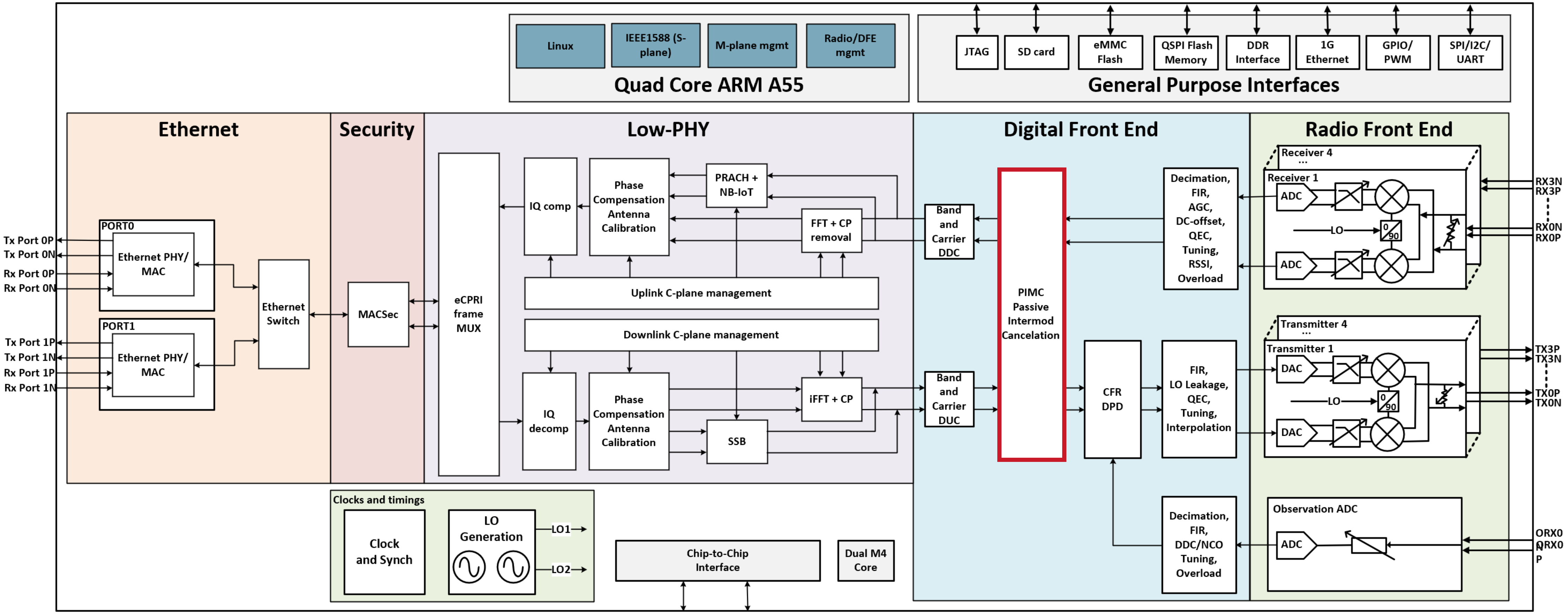
PA drain Eff = 55.5%

Lineup Eff = 51.5%

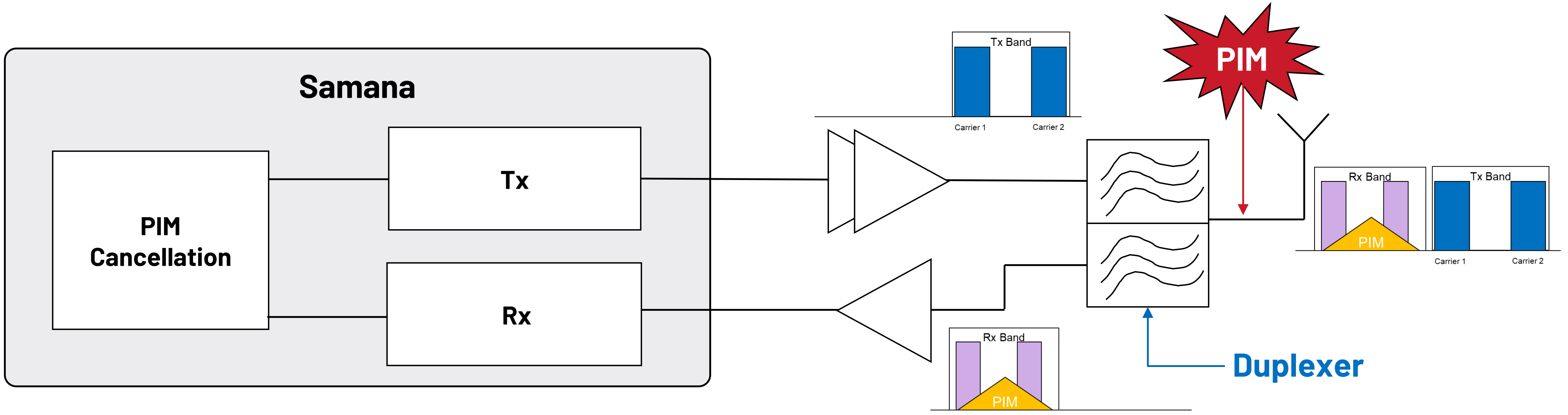
DPD results: −54.0dBc



Samana Block Diagram—Passive Intermodulation Correction



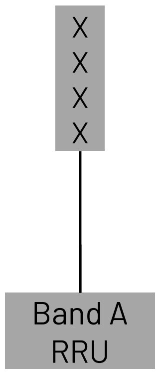
PIM Cancellation and Detection



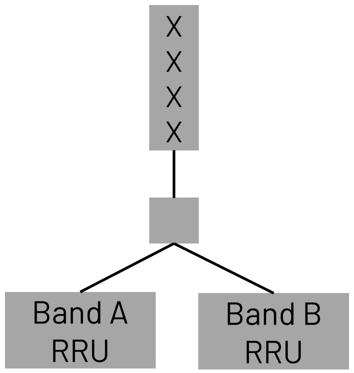
- Passive intermodulation (PIM) product falls in the receive band, and it will desense receive
- PIM cancellation in TRx helps to maintain receive performance
- Firmware can detect **"assembly"** and **"beyond the antenna"** PIM excursions
- This is key for multiband macro high-power PAs to ensure optimum receive performance
- ADI PIM on Samana helps with both interband PIM and intraband PIM

Supported Scenarios for PIM Cancellation

Single Band



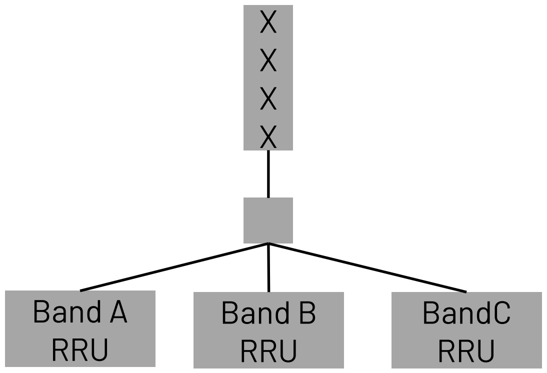
Dual Band



Possible Band Combinations

B20+B8
B28B+B8
B1+B3
B1+B7
B29+B5
B66+B70

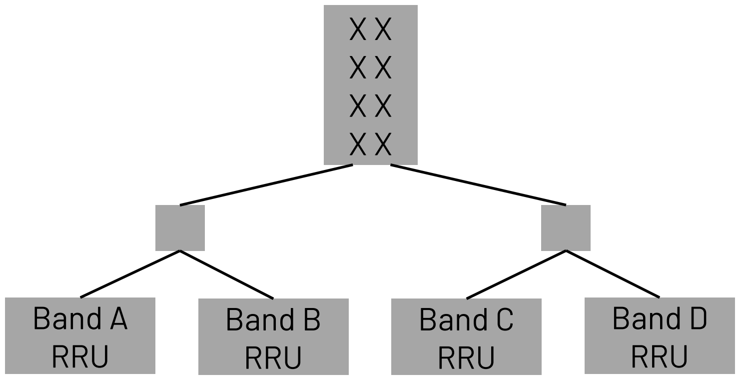
Tri-Band



Possible Band Combinations

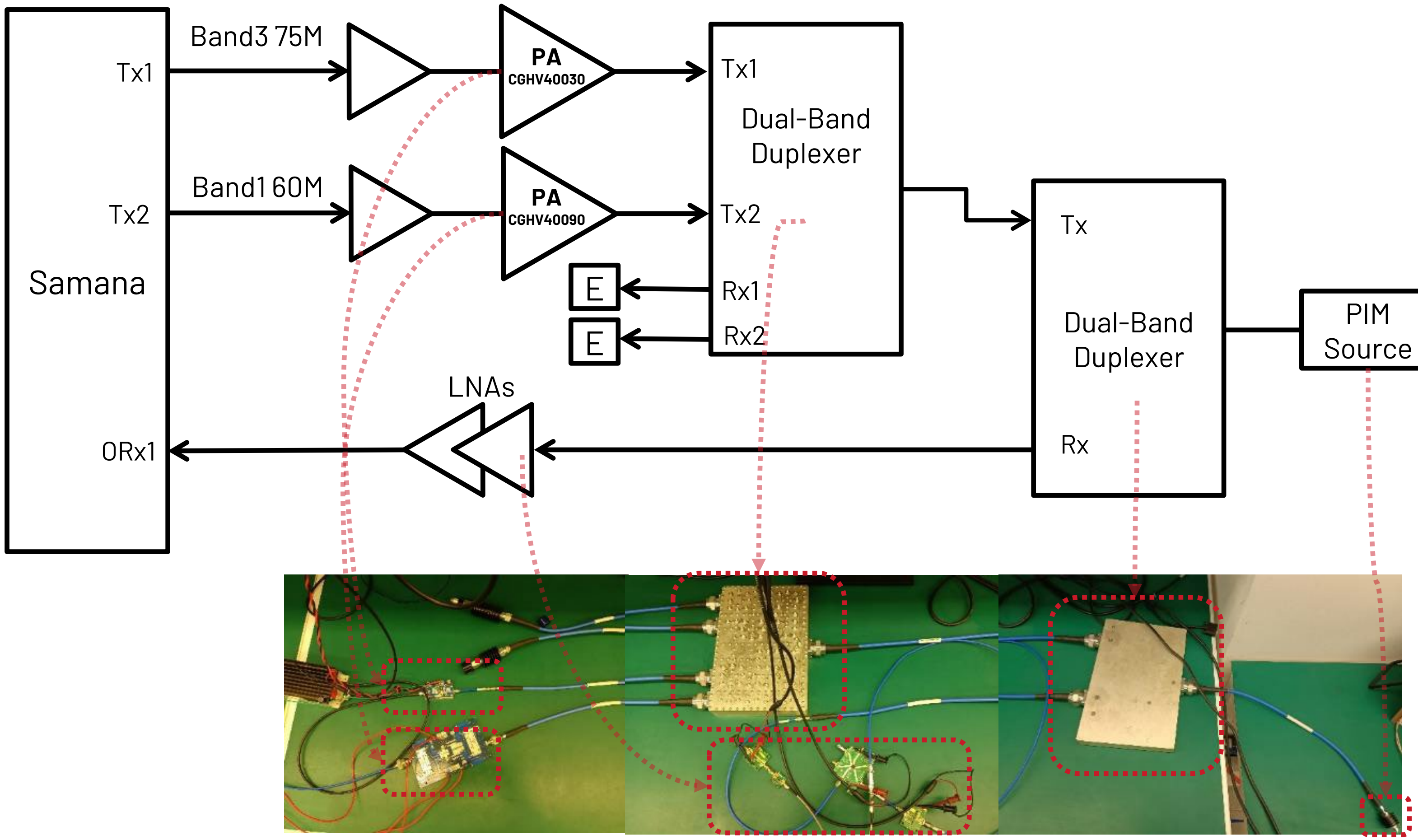
B28B+B20+B8
B1+B3+B7
B26+B29+B71

Multiple Profile

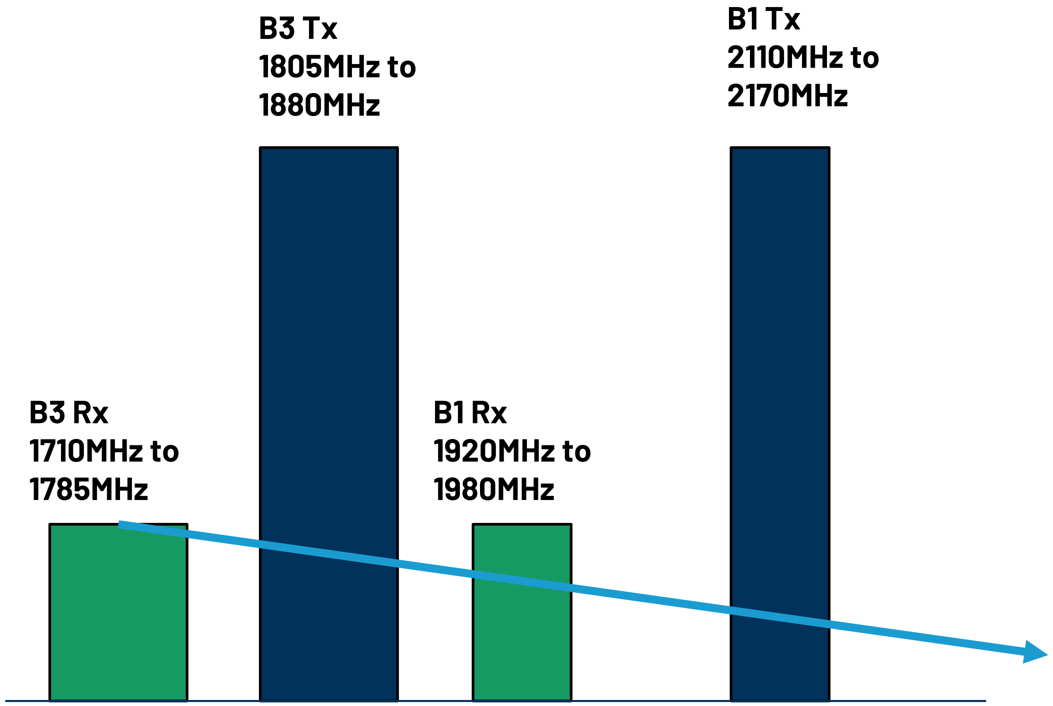


Where Band C and Band D
can be any dual-band combination
(cannot exceed 4 transmit channels)

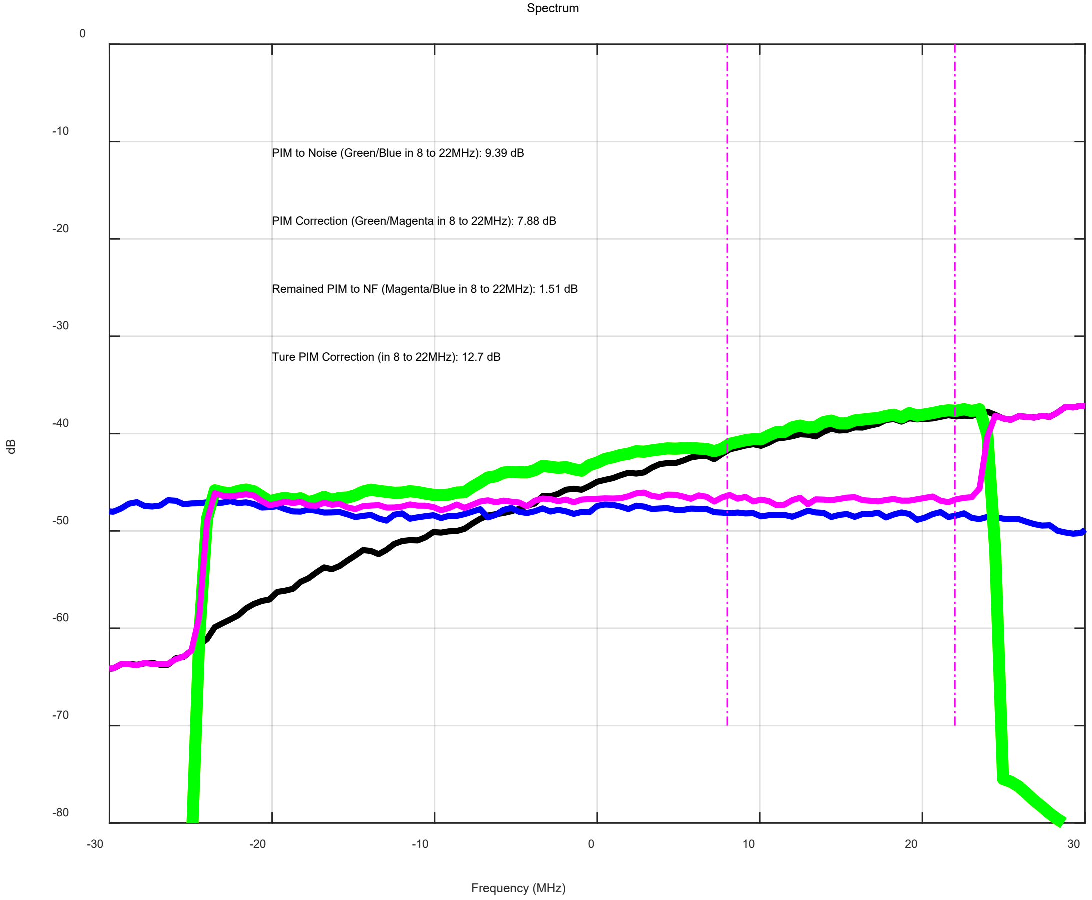
Example PIM Cancellation Test Setup



Example PIM Cancellation Test Results



B3 Rx spectrum



Thank you!

Please join us at ADI Booth for:

Samana AI DPD demo

AI-Enhanced Radio Efficiency at the Physical Edge

For more in-depth information
on circuit design see:

RFIC paper

Ethernet to RF: Single Chip ORAN 4TX/4RX 5G Radio Unit Base-Station Transceiver

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