Design and Prototyping of a Multi-Channel Wideband SDR-Based VSG/VSA for Standard-Compliant Signal Testing

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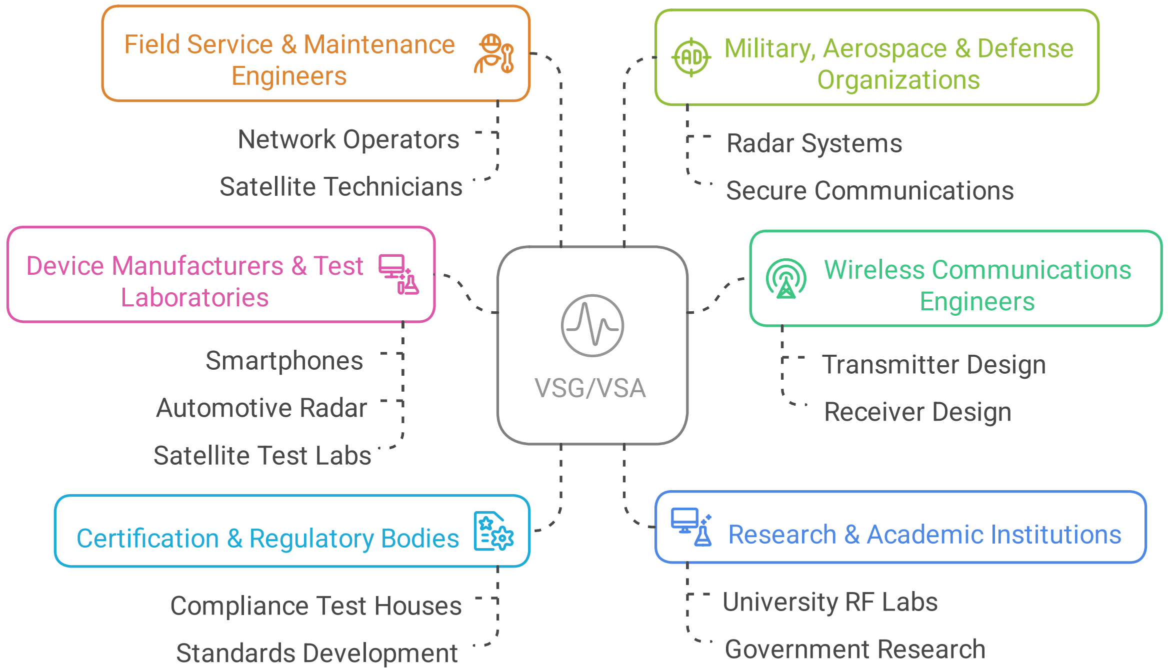
9, September 2025

VSG and VSA: Fundamentals and Applications

- A Vector Signal Generator (VSG) is used to create complex modulated signals for testing wireless systems.
- A Vector Signal Analyzer (VSA) captures and analyzes these signals to evaluate system performance and validate designs.



Trends in Wireless Comm. Systems

5G NR Bandwidth Configuration

TS 3GPP TS 38.101-2, V15.2.0, Table 5.3.2-1: Maximum transmission bandwidth configuration N_{RB}

SCS (kHz)	50MHz	100MHz	200MHz	400 MHz
	N_{RB}	N_{RB}	N_{RB}	N_{RB}
60	66	132	264	N.A
120	32	66	132	264

TS 38.101-2, V17.6

Table 5.3.2-1: Maximum transmission bandwidth configuration N_{RB}

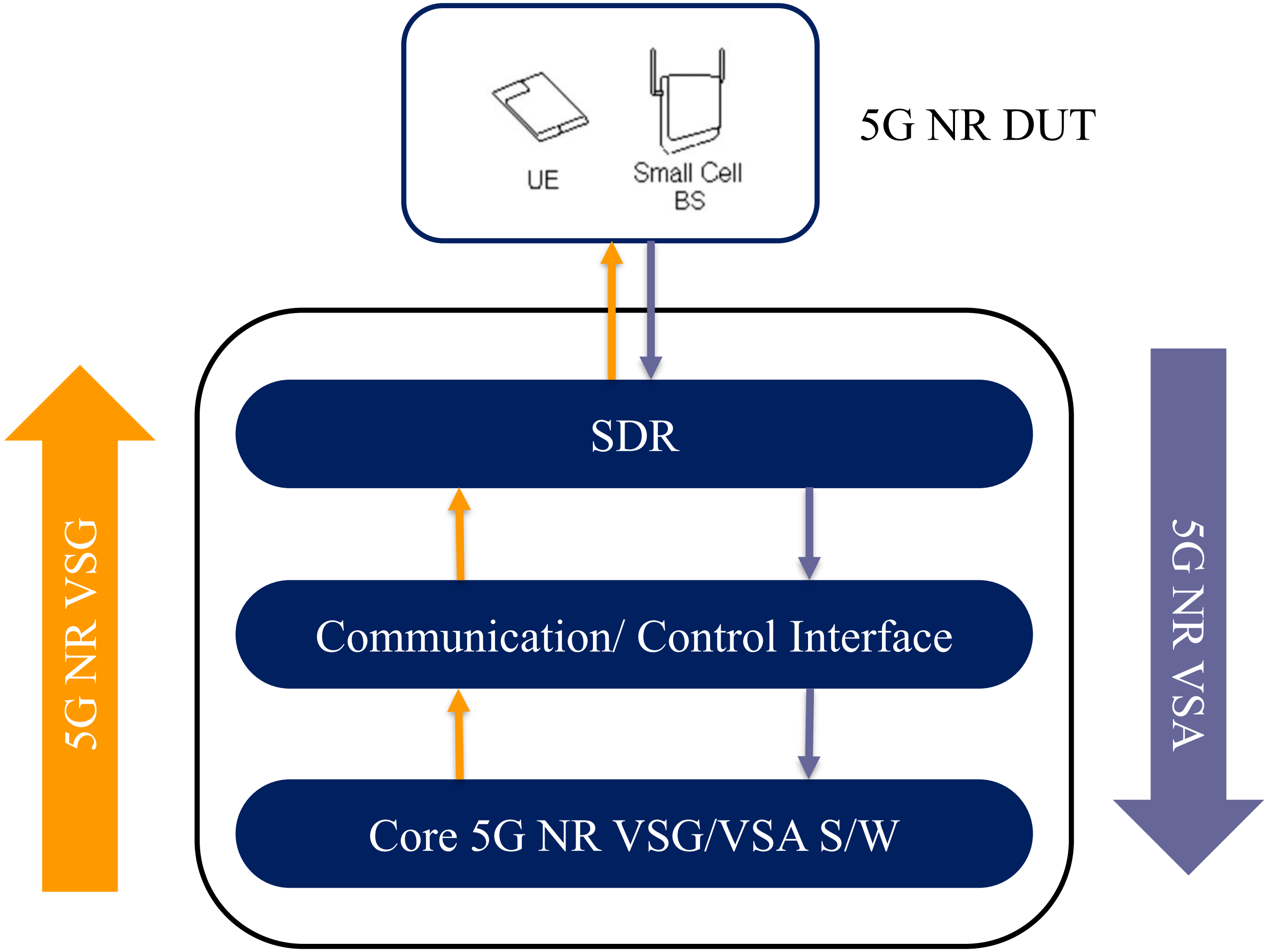
SCS (kHz)	50 MHz	100 MHz	200 MHz	400 MHz	800 MHz	1600 MHz	2000 MHz
	N_{RB}	N_{RB}	N_{RB}	N_{RB}	N_{RB}	N_{RB}	N_{RB}
60	66	132	264	N/A	N/A	N/A	N/A
120	32	66	132	264	N/A	N/A	N/A
480[1]	N/A	N/A	N/A	66	124	248	N/A
960[1]	N/A	N/A	N/A	33	62	124	148
Note 1: This SCS is optional in this release of the specification.							

Wi-Fi 6/7 System Parameters

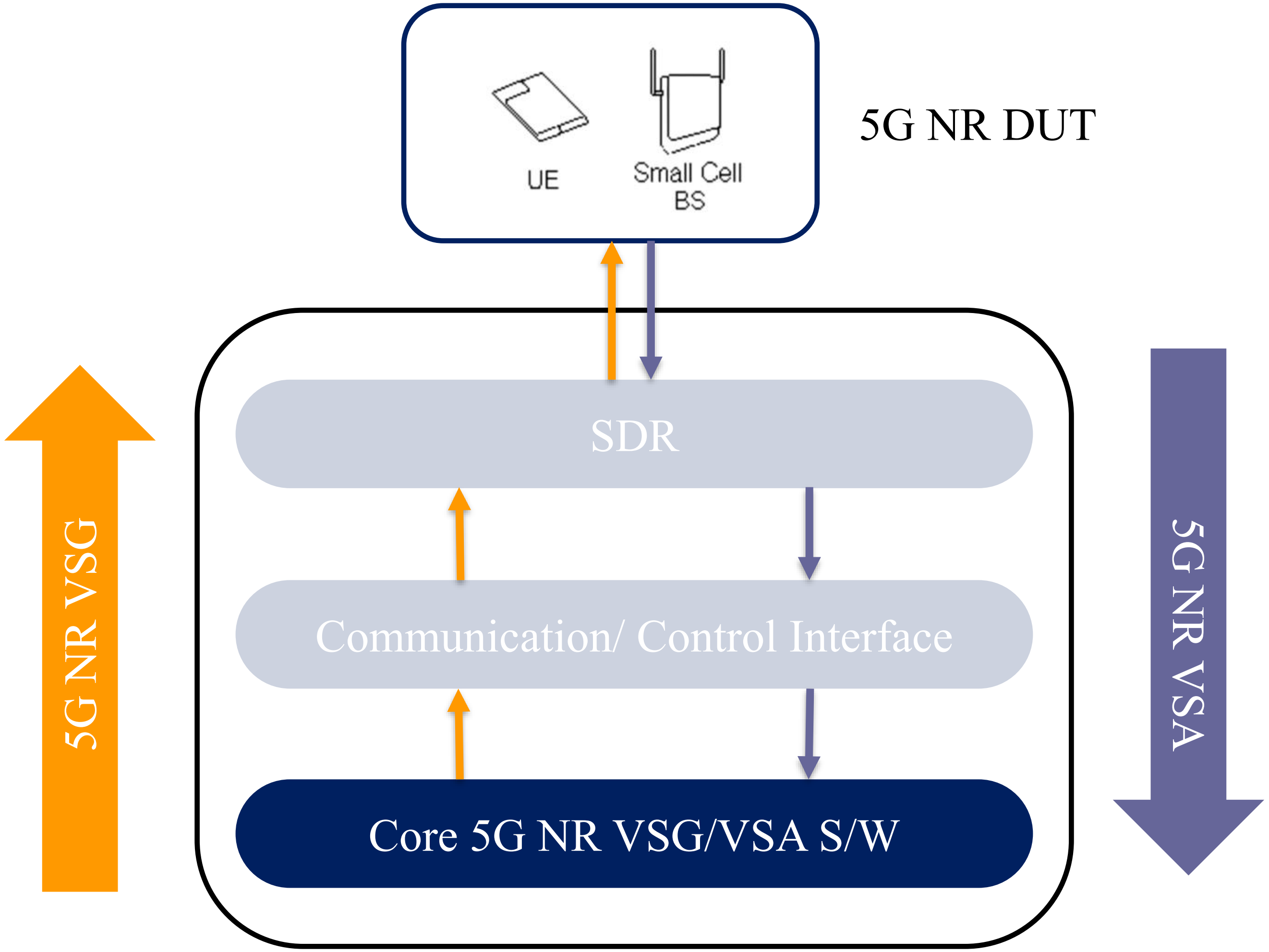
IEEE 802.11		802.11ax	802.11be
Transmission Vector Format		HE (High Efficiency)	EHT (Extreme High Throughput)
Definition		2021	Planned in 2024
Freq.	2.4 GHz	✓	✓
	5 GHz	✓	✓
	6 GHz	✓	✓
Bandwidth [MHz]		20/40/80/160/80+80	20/40/80/160/320
Maximum throughput rate [bps]		9.6G	30G or more
Modulation scheme		BPSK QPSK 16QAM 64QAM 256QAM 1024QAM	BPSK QPSK 16QAM 64QAM 256QAM 1024QAM 4096QAM
Stream		8 Stream OFDMA	16 Stream OFDMA
RU		RU	Multi RU

https://www.anritsu.com/zh-tw/test-measurement/solutions/wireless-lan/wi-fi-7?click-from-wireless-lan-solutions

Detachable 3-layer Architecture of an SDR-based Signal Tester



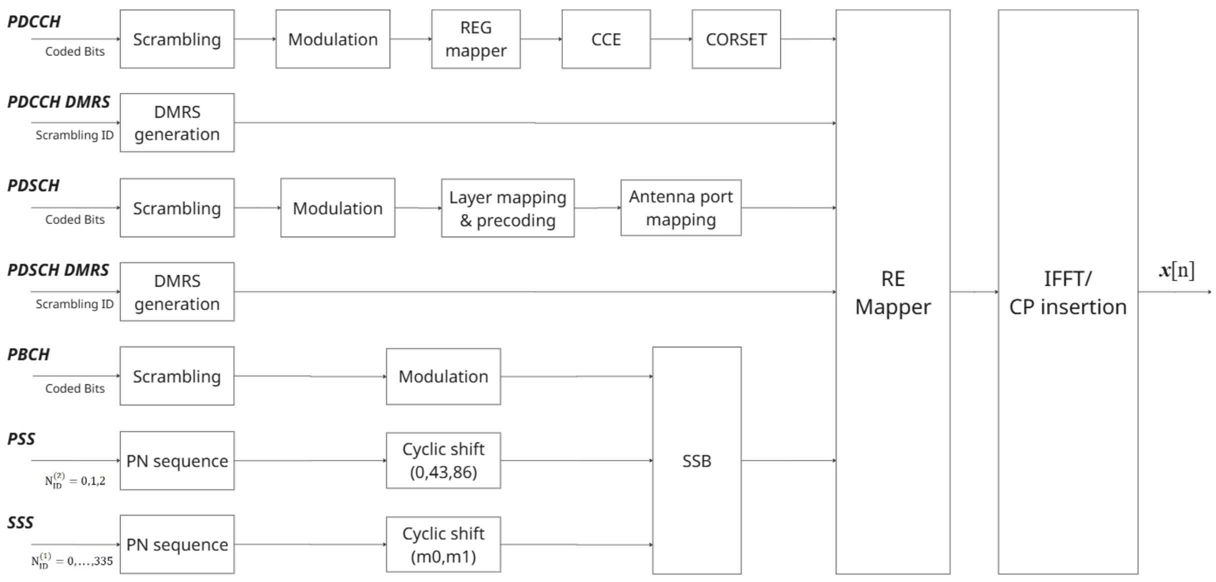
Detachable 3-layer Architecture of an SDR-based Signal Tester



Core 5G NR VSG/VSA Software

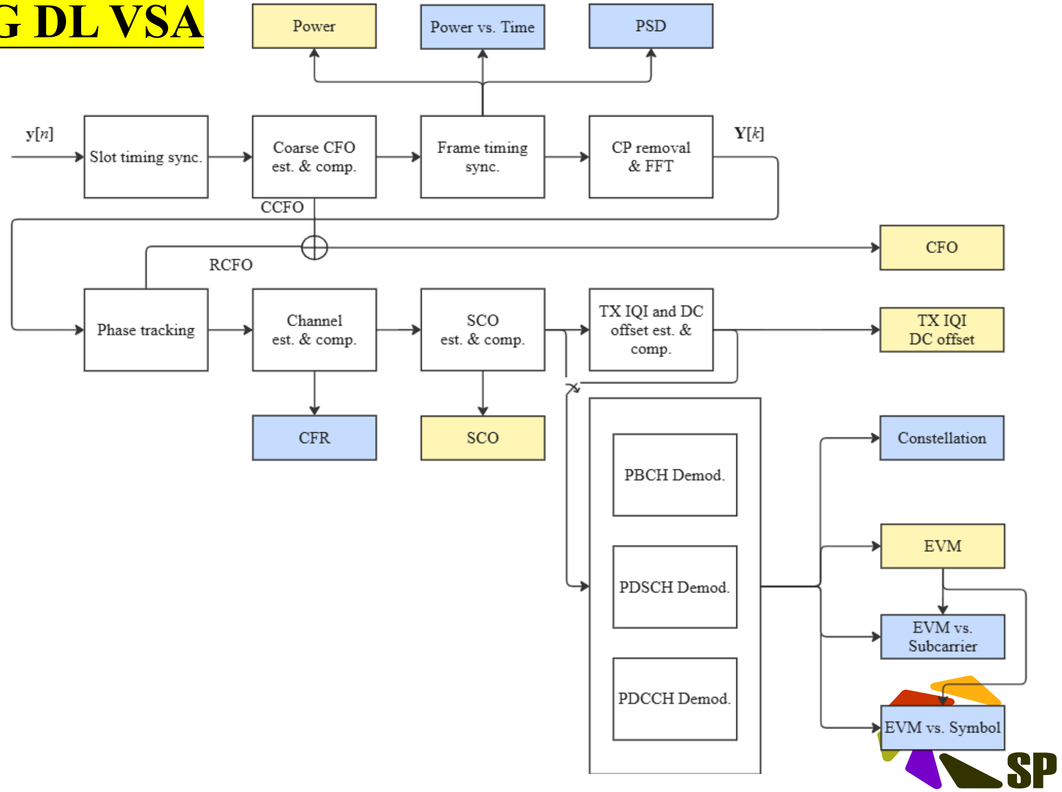
- 5G NR FR1/FR2 UL/DL VSG
  - 3GPP TS 38.211/212/213

5G DL VSG



- 5G NR FR1/FR2 UL/DL VSA
  - Design est./sync./eq. algorithms
  - 3GPP TS 38.141-1/38.141-2/38.521-1/38.521-2

5G DL VSA



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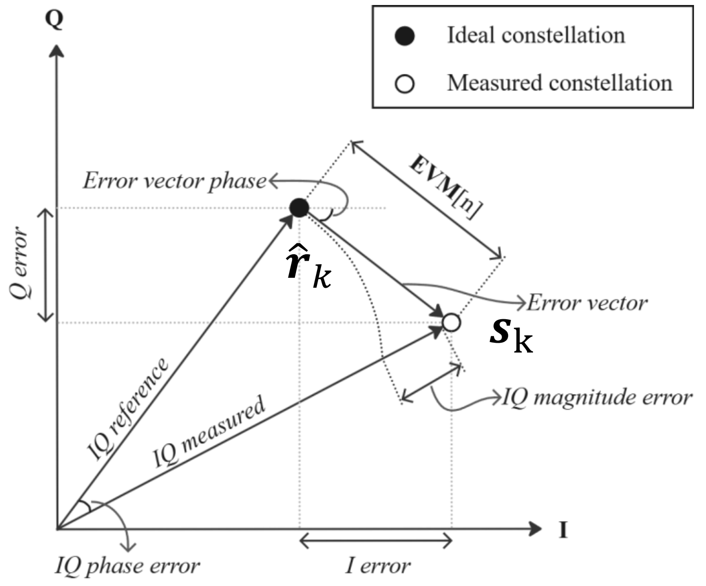
5G NR Conformance Test Specification

$$\text{EVM}(\%) = \frac{\sqrt{\frac{1}{N}\sum_{k=1}^{N}|\hat{\boldsymbol{r}}_k - \boldsymbol{s}_k|^2}}{\sqrt{\frac{1}{N}\sum_{k=1}^{N}|\boldsymbol{s}_k|^2}} \times 100$$

3GPP Specification	Description
TS 38.141-1	Base station (BS) conformance specification (conductive)
TS 38.141-2	Base station (BS) conformance testing (OTA)
TS 38.521-1	User equipment (UE) conformance specification (conductive)
TS 38.521-2	User equipment (UE) conformance specification (OTA)



- 6 Transmitter characteristics
- 6.1 General
- 6.2 Transmitter power
- 6.3 Output power dynamics
- 6.4 Transmit signal quality
- 6.5 Output RF spectrum emissions

- 6.4 Transmit signal quality
- 6.4.1 Frequency error
- 6.4.2 Transmit modulation quality
- 6.4A Transmit signal quality for CA
- 6.4B Transmit signal quality for NR-DC
- 6.4C Transmit signal quality for SUL
- 6.4D Transmit signal quality for UL MIMO
- 6.4E Transmit signal quality for V2X
- 6.4F Transmit signal quality for shared spectrum channel access
- 6.4G Transmit signal quality for Tx Diversity
- 6.4H Transmit signal quality for CA with UL MIMO

- 6.4.2 Transmit modulation quality
- 6.4.2.1 Error Vector Magnitude
- 6.4.2.1a Error Vector Magnitude including symbols with transient period
- 6.4.2.2 Carrier leakage
- 6.4.2.3 In-band emissions
- 6.4.2.4 EVM equalizer spectrum flatness
- 6.4.2.5 EVM equalizer spectrum flatness for Pi/2 BPSK
- 6.4.2.6 Phase continuity requirements for DMRS bundling

- 6.5.2.2 Spectrum emission mask
- 6.5.2.4 Adjacent channel leakage ratio

CSP 5G NR VSA GUI

Instrument Setting
Central frequency :
70 - 6000 MHz (mmW ready)
Rx. Gain :
0 - 40 (dB)
Capture time :
10 - 25 (ms)

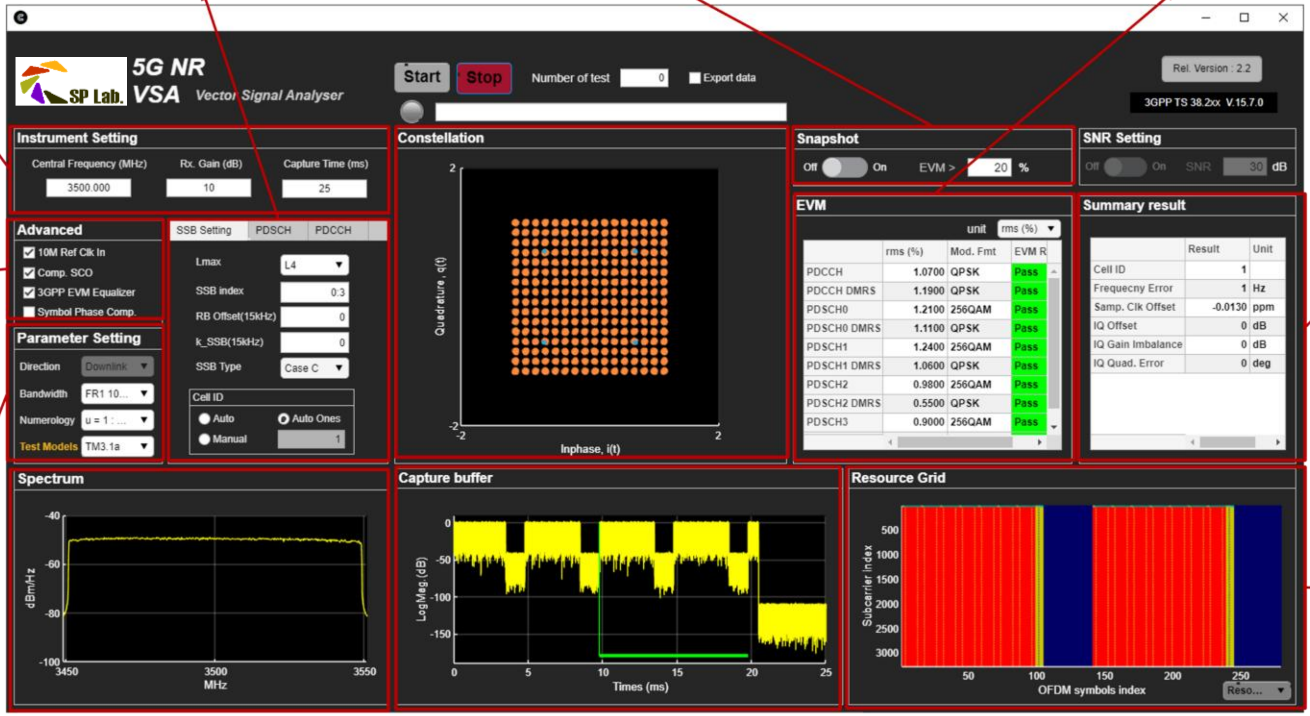
Advanced
10M Ref Clk
Comp. SCO (Samp. Clk. Offset)
Comp. CPE (Comm. Phase Error)
Symbol Phase Comp.

Parameter Setting
Direction :
Downlink/Uplink
Bandwidth (FR1/FR2):
5 - 400 MHz
Numerology (FR1/FR2):
0 - 3 (15/30/60/120 kHz)
Test Models (DL)
TM1.1, TM1.2, TM2.0, TM2.0a, TM3.1, TM3.1a, TM3.2, TM3.3
Fixed Reference Channel (UL)
G-FR1-A1-x, G-FR2-A1-x, G-FR1-A2-x, …

Channel Setting
DL : SSB/PDCCH/PDSCH/PT-RS
UL : PUCCH/PUSCH/PT-RS
BWP SC/RB offset
Flexible allocation (Symbol/RB/Slot)
Modulation order (Up to 256QAM)
Auto detection Cell Id

Snapshot :
Snapshot of failed EVM measurement

EVM :
EVM for rms (%) & Mod. format
DL :
PSS/SSS/PBCH/DMRS/PDCCH/PDSCH/PTRS
UL :
DMRS/PUCCH/PUSCH/PTRS



Summary Result :
Cell ID
Frequency error
IQ offset
IQ imbalance
SCO

Plot Result :
Constellation
Spectrum
Power vs. Time
Resource Grid
Power vs. Symbol & Carrier

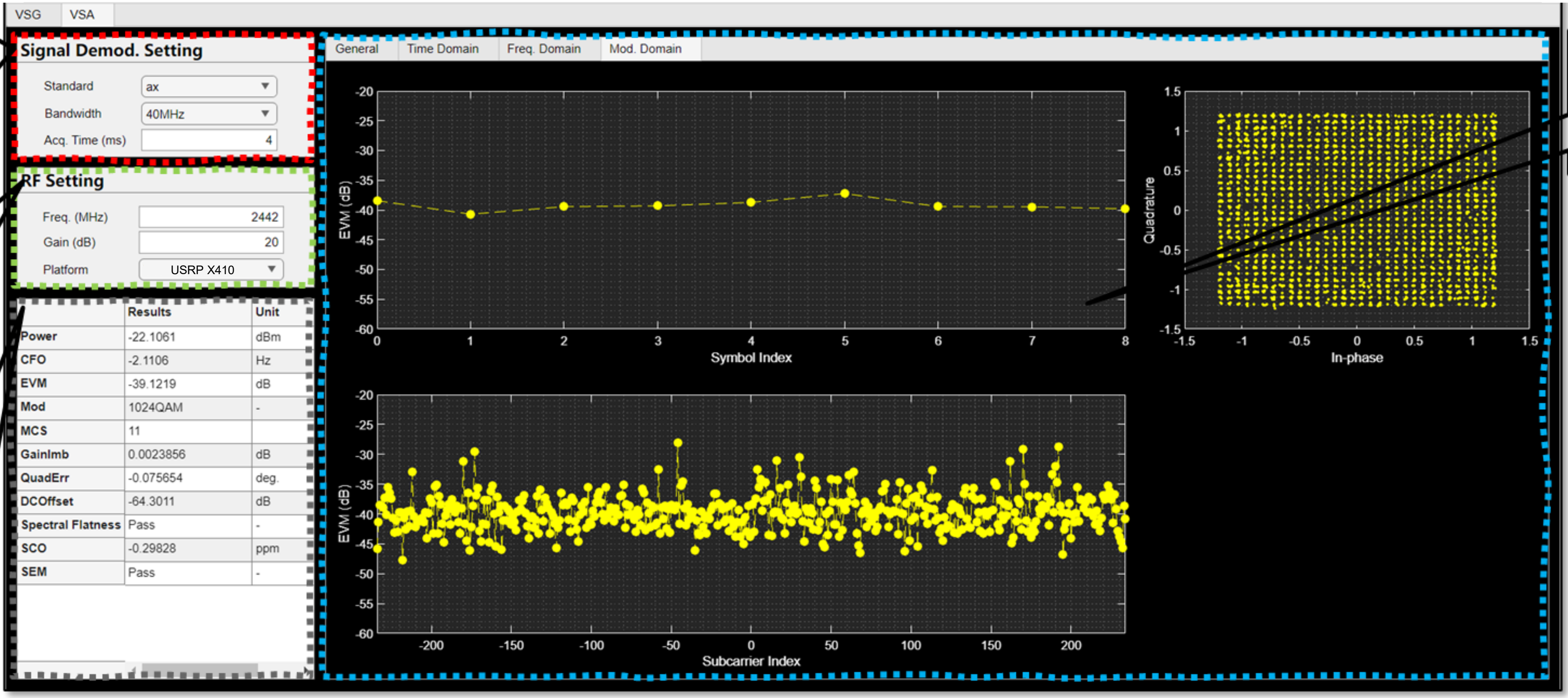
CSP Wi-Fi VSG/VSA

CSPLab Wi-Fi VSG and VSA

Signal Demod Setting
- Standard
- Bandwidth (MHz) or Rate (Mbps)
- Acq. Time (ms)

RF Setting
- Freq. (MHz)
- Gain (dB)
- Platform

Analysis Results
- Power (dBm)
- CFO (Hz)
- EVM (dB)
- Mod
- MCS
- Gain Imb. (dB)
- Quad. Err. (deg.)
- DC Offset (dB)
- Spectral. Flatness
- SCO (ppm)
- SEM



Plot
- EVM vs. Symbol
- EVM vs. Subcarrier
- Constellation

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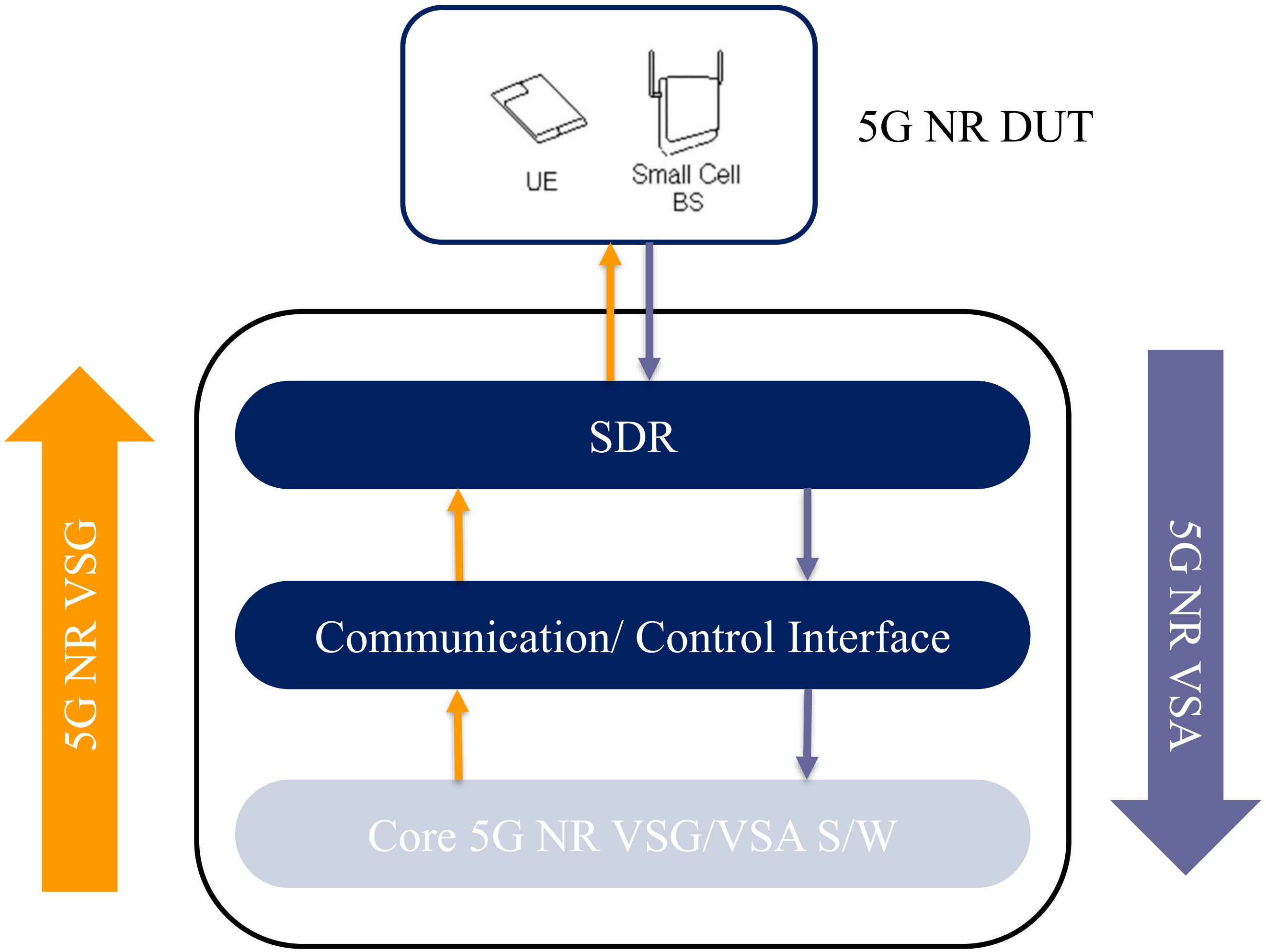
Detachable 3-layer Architecture of an SDR-based Signal Tester



SDR: NI/Ettus USRP X410

Wi-Fi 6/7 System Parameters

IEEE 802.11		802.11ax	802.11be
Transmission Vector Format		HE (High Efficiency)	EHT (Extreme High Throughput)
Definition		2021	Planned in 2024
Freq.	2.4 GHz	√	√
	5 GHz	√	√
	6 GHz	√	√
Bandwidth [MHz]		20/40/80/160/80+80	20/40/80/160/320
Maximum throughput rate [bps]		9.6G	30G or more
Modulation scheme		BPSK QPSK 16QAM 64QAM 256QAM 1024QAM	BPSK QPSK 16QAM 64QAM 256QAM 1024QAM 4096QAM
Stream		8 Stream OFDMA	16 Stream OFDMA
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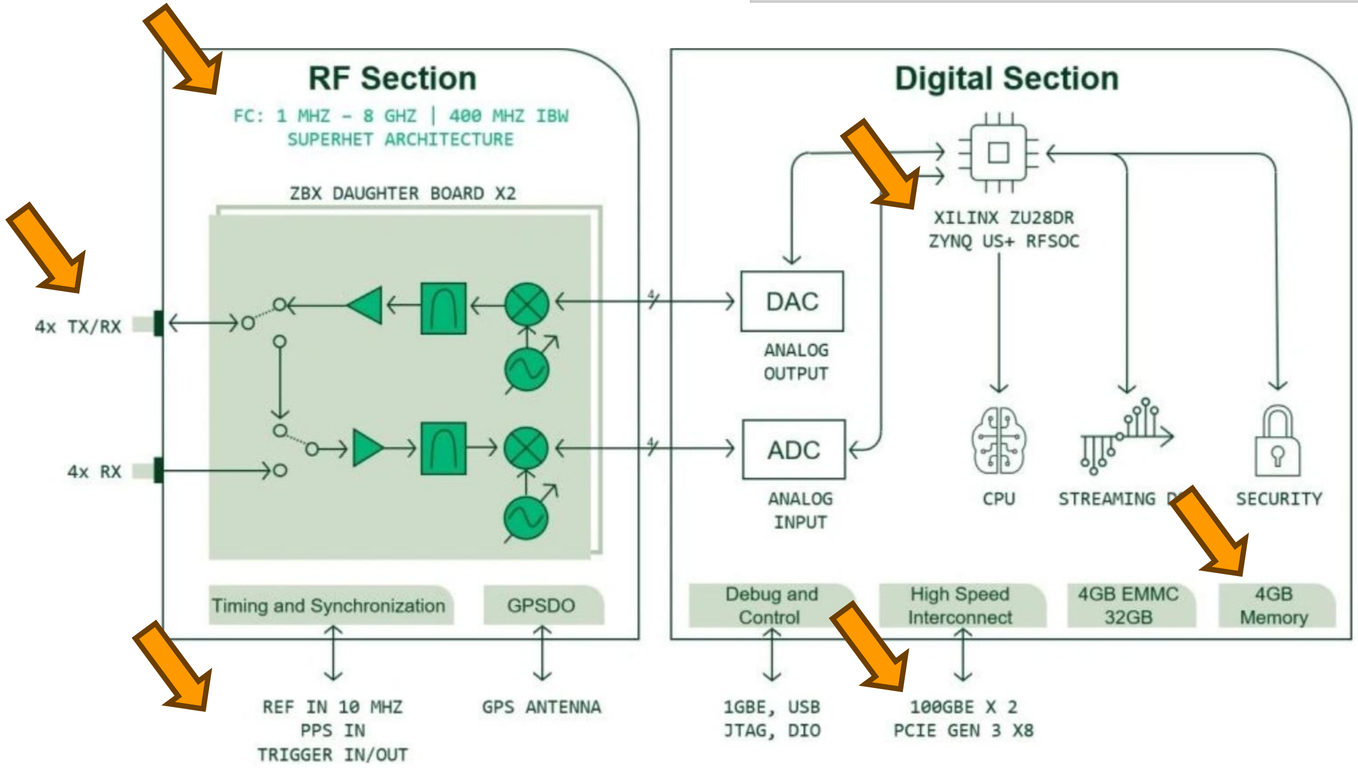
60	66	132	264	N.A
120	32	66	132	264

RF capabilities

- 4 TX, 4 RX, independently tunable
- Superheterodyne architecture
- 1 MHz to 7.2 GHz, tunable up to 8 GHz
- Up to 400 MHz bandwidth per channel



Sampling Rate and Bandwidth Issue

- The sampling rate of a 5G NR FR2 400MHz bandwidth signal is 491.52MSps.
- To enable 4 TX and 4 RX channels on a USRP X410 operating at a sampling rate of 491.52MSps, the interface must sustain a data rate of **125.82912 Gbps**.

- Approach
  - DPDK
  - RFNoC: Replay block

DPDK
DATA PLANE DEVELOPMENT KIT

Configuration	Channels and Sampling Rates
Dual Port DPDK	4 Rx + 4 Tx @ 491.52 MS/s 4 Rx @ 491.52 MS/s 4 Tx @ 491.52 MS/s

*Port: 100GBE
*100GbE Streaming only supports Linux Hosts

https://kb.ettus.com/X410#100_Gigabit_Ethernet


RFNoC Replay Block
Ch0: Record Offset: 0
Ch0: Record Size: 122.88M
Ch0: Play Offset: 0
Ch0: Play Size: 122.88M
Ch1: Record Offset: 0
Ch1: Record Size: 122.88M
Ch1: Play Offset: 0
Ch1: Play Size: 122.88M
Ch2: Record Offset: 0
Ch2: Record Size: 122.88M
Ch2: Play Offset: 0
Ch2: Play Size: 122.88M
Ch3: Record Offset: 0
Ch3: Record Size: 122.88M
Ch3: Play Offset: 0
Ch3: Play Size: 122.88M

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USRP X410 FPGA Image Flavor: X4_400

- X4_400:
  400 MHz analog bandwidth per channel
  streaming to/from on-board DRAM
  using the RFNoC Record/Replay block.
- x410_X4_400_rfnoc_image_core.yml

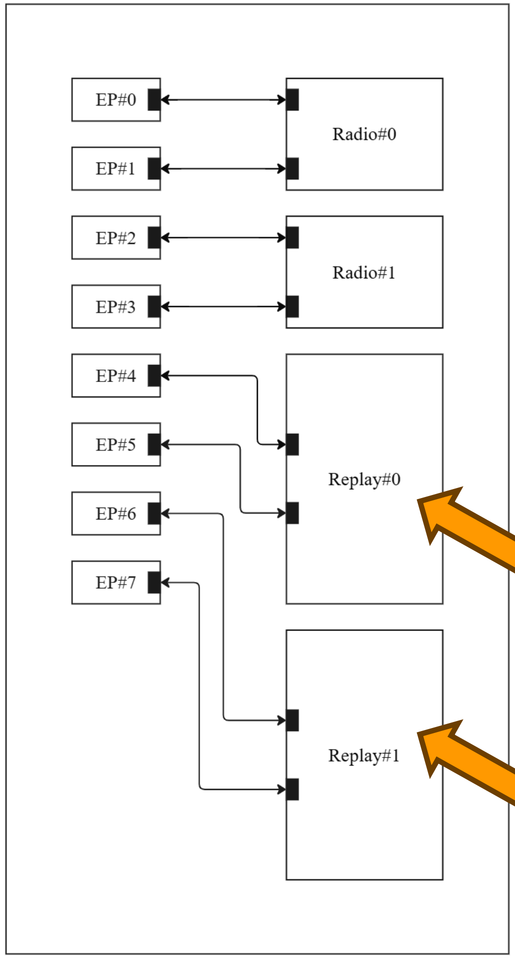
```
replay0:
  block_desc: 'replay.yml'
  parameters:
    NUM_PORTS: 2
    MEM_DATA_W: 128
    MEM_ADDR_W: 32

replay1:
  block_desc: 'replay.yml'
  parameters:
    NUM_PORTS: 2
    MEM_DATA_W: 128
    MEM_ADDR_W: 32

# Replay Connections
- { srcblk: ep4,     srcport: out0,   dstblk: replay0, dstport: in_0 }
- { srcblk: replay0, srcport: out_0,  dstblk: ep4,     dstport: in0  }
- { srcblk: ep5,     srcport: out0,   dstblk: replay0, dstport: in_1 }
- { srcblk: replay0, srcport: out_1,  dstblk: ep5,     dstport: in0  }
- { srcblk: ep6,     srcport: out0,   dstblk: replay1, dstport: in_0 }
- { srcblk: replay1, srcport: out_0,  dstblk: ep6,     dstport: in0  }
- { srcblk: ep7,     srcport: out0,   dstblk: replay1, dstport: in_1 }
- { srcblk: replay1, srcport: out_1,  dstblk: ep7,     dstport: in0  }
```

https://github.com/EttusResearch/uhd/blob/master/fpga/usrp3/top/x400/x410_X4_400_rfnoc_image_core.yml

FPGA image flavor: X4_400



Static connections in design

uhd_usrp_probe result

```
|     /
|    |       RFNoC blocks on this device:
|    |
|    |   * 0/Radio#0
|    |   * 0/Radio#1
|    |   * 0/Replay#0
|    |   * 0/Replay#1
|
|     /
|    |       Static connections on this device:
|    |
|    |   * 0/SEP#0:0==>0/Radio#0:0
|    |   * 0/Radio#0:0==>0/SEP#0:0
|    |   * 0/SEP#1:0==>0/Radio#0:1
|    |   * 0/Radio#0:1==>0/SEP#1:0
|    |   * 0/SEP#2:0==>0/Radio#1:0
|    |   * 0/Radio#1:0==>0/SEP#2:0
|    |   * 0/SEP#3:0==>0/Radio#1:1
|    |   * 0/Radio#1:1==>0/SEP#3:0
|    |   * 0/SEP#4:0==>0/Replay#0:0
|    |   * 0/Replay#0:0==>0/SEP#4:0
|    |   * 0/SEP#5:0==>0/Replay#0:1
|    |   * 0/Replay#0:1==>0/SEP#5:0
|    |   * 0/SEP#6:0==>0/Replay#1:0
|    |   * 0/Replay#1:0==>0/SEP#6:0
|    |   * 0/SEP#7:0==>0/Replay#1:1
|    |   * 0/Replay#1:1==>0/SEP#7:0
```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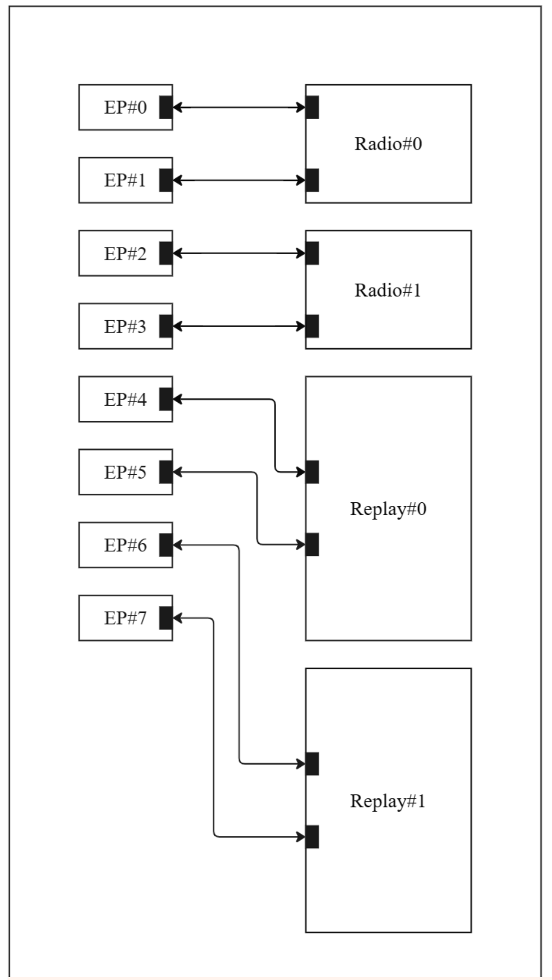
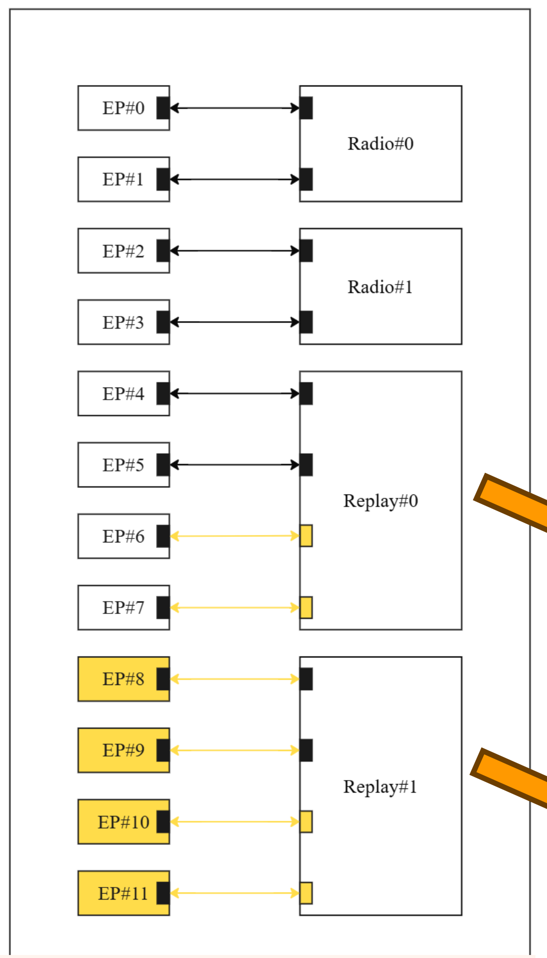
Extend X4_400 to Support 4TX and 4RX

FPGA image flavor: X4_400



Static connections in design

FPGA:X4_400_2RB4CH



Static connections in design

uhd_usrp_probe result

```
|     /
|    |       RFNoC blocks on this device:
|    |
|    |   * 0/Radio#0
|    |   * 0/Radio#1
|    |   * 0/Replay#0
|    |   * 0/Replay#1
|
|     /
|    |       Static connections on this device:
|    |
|    |   * 0/SEP#0:0==>0/Radio#0:0
|    |   * 0/Radio#0:0==>0/SEP#0:0
|    |   * 0/SEP#1:0==>0/Radio#0:1
|    |   * 0/Radio#0:1==>0/SEP#1:0
|    |   * 0/SEP#2:0==>0/Radio#1:0
|    |   * 0/Radio#1:0==>0/SEP#2:0
|    |   * 0/SEP#3:0==>0/Radio#1:1
|    |   * 0/Radio#1:1==>0/SEP#3:0
|    |   * 0/SEP#4:0==>0/Replay#0:0
|    |   * 0/Replay#0:0==>0/SEP#4:0
|    |   * 0/SEP#5:0==>0/Replay#0:1
|    |   * 0/Replay#0:1==>0/SEP#5:0
|    |   * 0/SEP#6:0==>0/Replay#0:2
|    |   * 0/Replay#0:2==>0/SEP#6:0
|    |   * 0/SEP#7:0==>0/Replay#0:3
|    |   * 0/Replay#0:3==>0/SEP#7:0
|    |   * 0/SEP#8:0==>0/Replay#1:0
|    |   * 0/Replay#1:0==>0/SEP#8:0
|    |   * 0/SEP#9:0==>0/Replay#1:1
|    |   * 0/Replay#1:1==>0/SEP#9:0
|    |   * 0/SEP#10:0==>0/Replay#1:2
|    |   * 0/Replay#1:2==>0/SEP#10:0
|    |   * 0/SEP#11:0==>0/Replay#1:3
|    |   * 0/Replay#1:3==>0/SEP#11:0
```

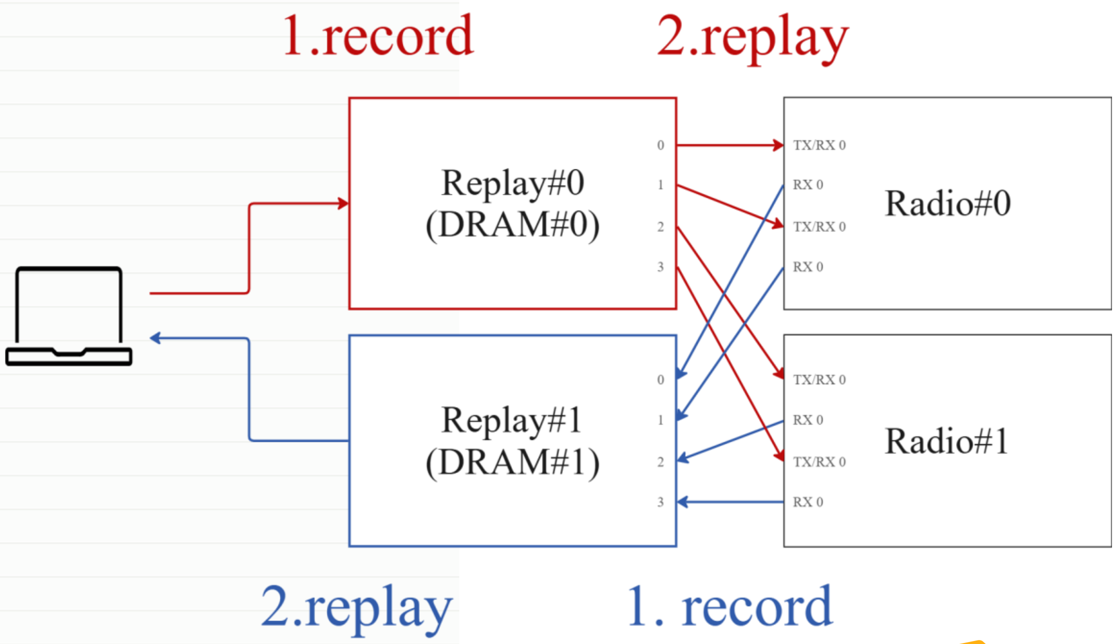
For TX 4-channel

For RX 4-channel

Public Member Functions of Replay Block

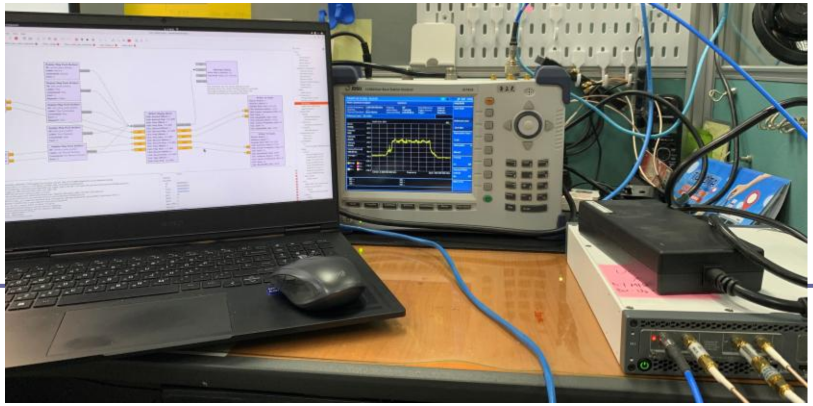
Public Member Functions

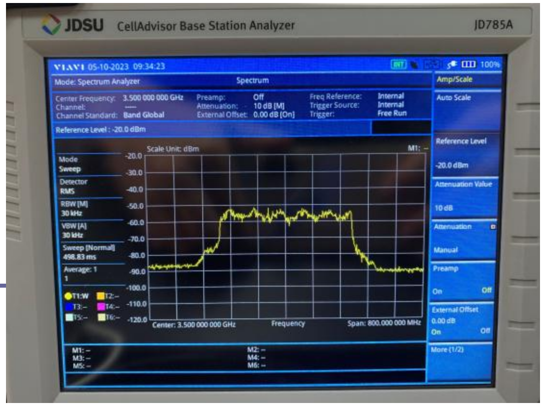
virtual void	record (const uint64_t offset, const uint64_t size, const size_t port=0)=0
virtual void	record_restart (const size_t port=0)=0
virtual void	play (const uint64_t offset, const uint64_t size, const size_t port=0, const uhd::time_spec_t time_spec=uhd::time_spec_t(0.0), const bool repeat=false)=0
virtual void	stop (const size_t port=0)=0
virtual uint64_t	get_mem_size () const =0
virtual uint64_t	get_word_size () const =0
virtual uint64_t	get_record_offset (const size_t port=0) const =0
virtual uint64_t	get_record_size (const size_t port=0) const =0
virtual uint64_t	get_record_fullness (const size_t port=0)=0
virtual uint64_t	get_record_position (const size_t port=0)=0
virtual io_type_t	get_record_type (const size_t port=0) const =0
virtual size_t	get_record_item_size (const size_t port=0) const =0
virtual bool	get_record_async_metadata (uhd::rx_metadata_t &metadata, const double timeout=0.1)=0
virtual uint64_t	get_play_offset (const size_t port=0) const =0
virtual uint64_t	get_play_size (const size_t port=0) const =0
virtual uint64_t	get_play_position (const size_t port=0)=0
virtual uint32_t	get_max_items_per_packet (const size_t port=0) const =0
virtual uint32_t	get_max_packet_size (const size_t port=0) const =0
virtual io_type_t	get_play_type (const size_t port=0) const =0
virtual size_t	get_play_item_size (const size_t port=0) const =0
virtual bool	get_play_async_metadata (uhd::async_metadata_t &metadata, const double timeout=0.1)=0
virtual void	set_record_type (const io_type_t type, const size_t port=0)=0
virtual void	config_play (const uint64_t offset, const uint64_t size, const size_t port=0)=0
virtual void	set_play_type (const io_type_t type, const size_t port=0)=0
virtual void	set_max_items_per_packet (const uint32_t ipp, const size_t port=0)=0
virtual void	set_max_packet_size (const uint32_t size, const size_t port=0)=0
virtual void	issue_stream_cmd (const uhd::stream_cmd_t &stream_cmd, const size_t port=0)=0
virtual void	post_input_action (const std::shared_ptr< uhd::rfnoc::action_info > &action, const size_t port)=0
virtual void	post_output_action (const std::shared_ptr< uhd::rfnoc::action_info > &action, const size_t port)=0

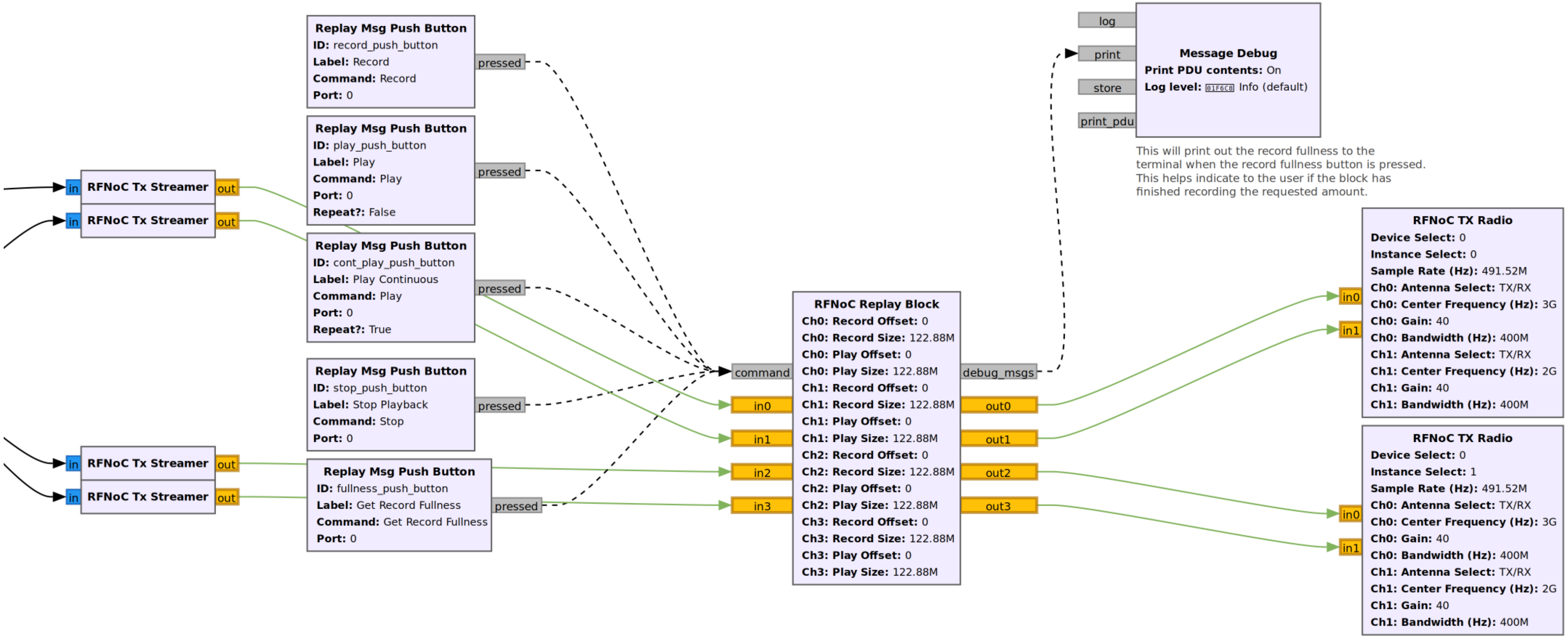


Control of Replay Block

Load file: 5gnr_fr2_400MHz_tm3p1a.sigmf-data







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SDR-Based VSG/VSA Integration and Verification

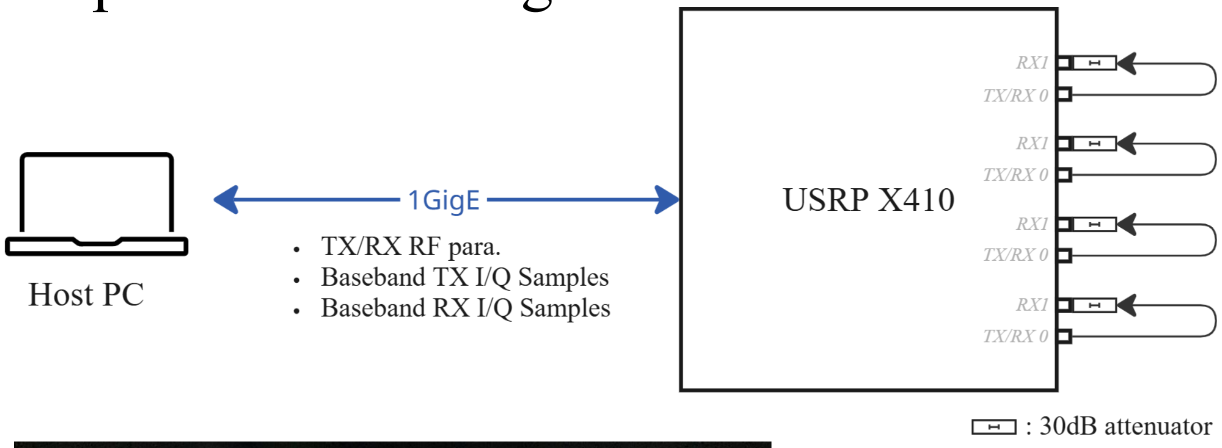
Parameter setting

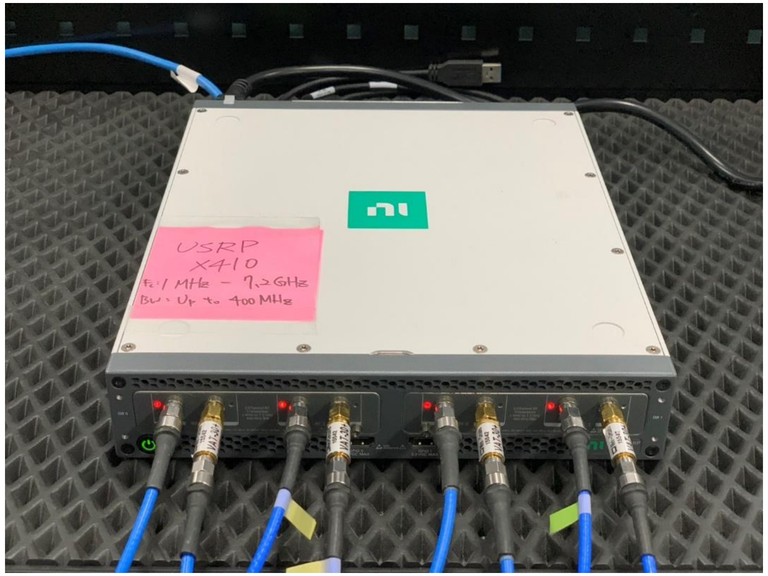
5G NR FR2 TM3.1a

Parameter	Value	Unit
FR	2	-
μ	3	-
SC Spacing	120	kHz
Cyclic Prefix	Normal	
Bandwidth	400	MHz
FFT Size	4096	-
No. of RB	264	-
No. Slot per Subframe	8	-
No. Users	2	-
n_{RNTI}	2: PRBs located in PRB#0-2; 0: 0 for remaining PRBs	-
Sample Rate	491.52	MSps
Modulation	256 QAM	-
Center Frequency	3.5	GHz

Experimental setting

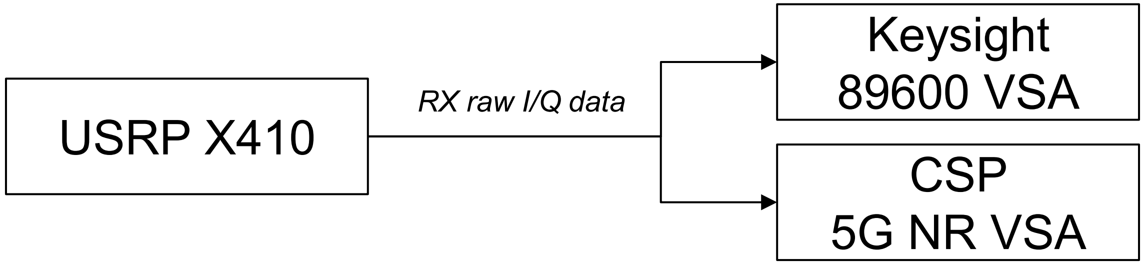
Power calibrated

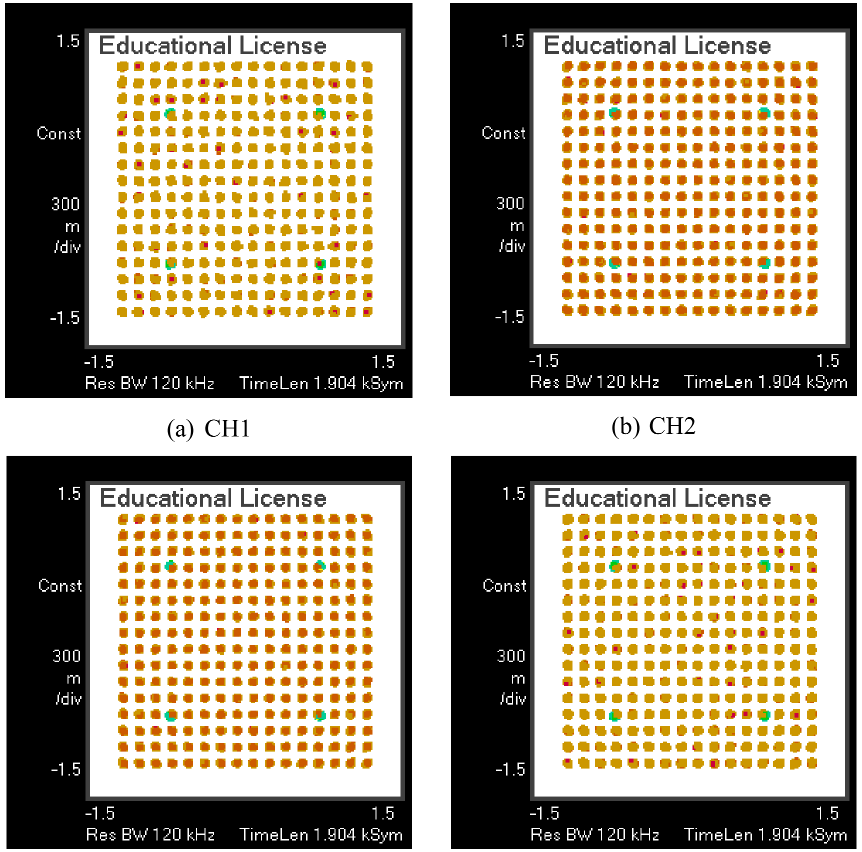




EVM Comparison

Keysight 89600VSA and CSP 5G NR VSA

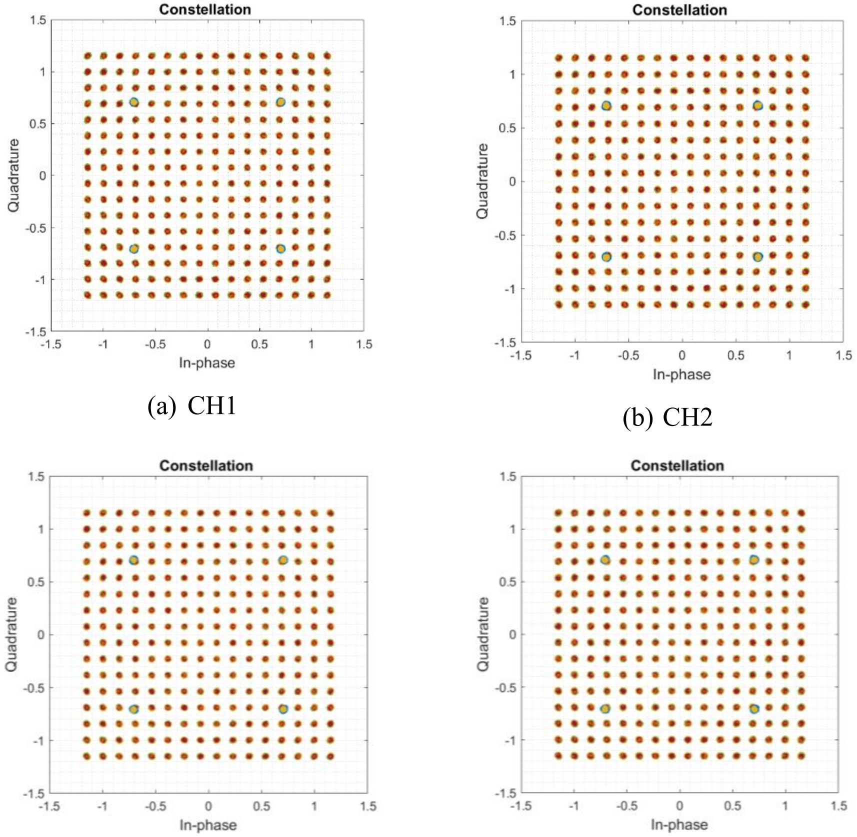




(a) CH1 (b) CH2

(c) CH3 (d) CH4

Figure. Equalized constellation diagrams on four independent channels using Keysight 89600 VSA



(a) CH1 (b) CH2

(c) CH3 (d) CH4

Figure. Equalized constellation diagrams on four independent channels using CSP 5G NR VSA

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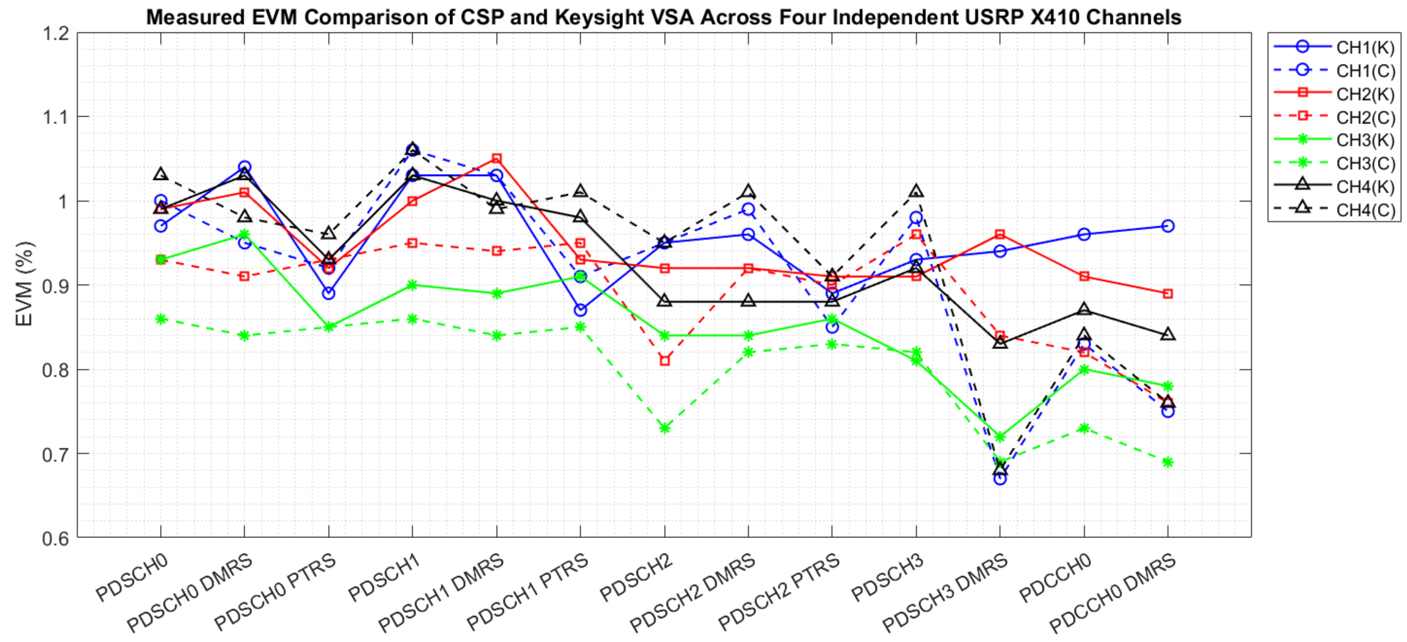
EVM Comparison

Keysight 89600VSA and CSP 5G NR VSA

- Test results

Physical Channel/ Physical Signal	EVM (%rms)							
	CH1		CH2		CH3		CH4	
	K	C	K	C	K	C	K	C
PDSCH0	0.97	1.00	0.99	0.93	0.93	0.86	0.99	1.03
PDSCH0 DMRS	1.04	0.95	1.01	0.91	0.96	0.84	1.03	0.98
PDSCH0 PTRS	0.89	0.92	0.92	0.93	0.85	0.85	0.93	0.96
PDSCH1	1.03	1.06	1.00	0.95	0.90	0.86	1.03	1.06
PDSCH1 DMRS	1.03	1.03	1.05	0.94	0.89	0.84	1.00	0.99
PDSCH1 PTRS	0.87	0.91	0.93	0.95	0.91	0.85	0.98	1.01
PDSCH2	0.95	0.95	0.92	0.81	0.84	0.73	0.88	0.95
PDSCH2 DMRS	0.96	0.99	0.92	0.92	0.84	0.82	0.88	1.01
PDSCH2 PTRS	0.89	0.85	0.91	0.90	0.86	0.83	0.88	0.91
PDSCH3	0.93	0.98	0.91	0.96	0.81	0.82	0.92	1.01
PDSCH3 DMRS	0.94	0.67	0.96	0.84	0.72	0.69	0.83	0.68
PDCCH0	0.96	0.83	0.91	0.82	0.80	0.73	0.87	0.84
PDCCH0 DMRS	0.97	0.75	0.89	0.76	0.78	0.69	0.84	0.76



EVM: -40dB=1%

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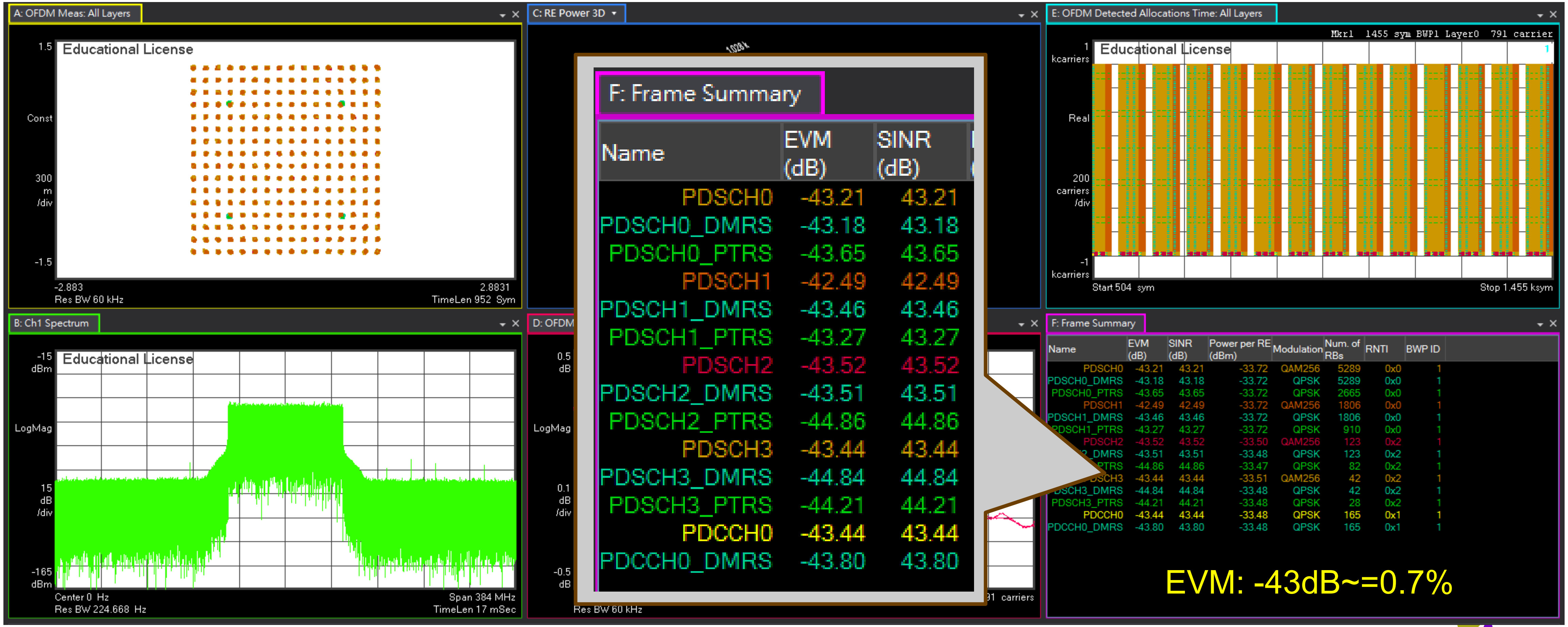
EVM for 5G NR 100 MHz BW Case in USRP X410 Loopback Test



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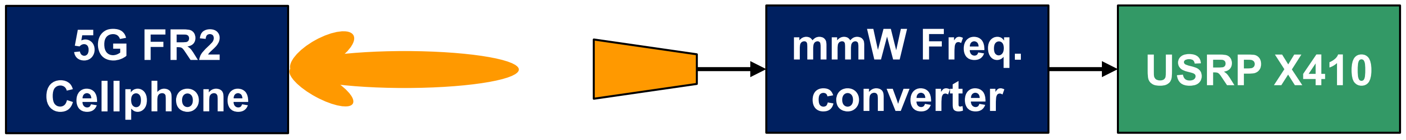
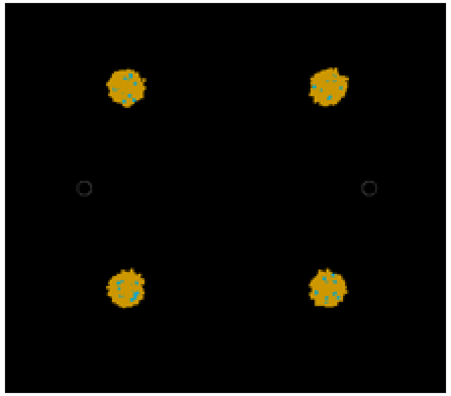
5G FR2
DUT OTA Testing



Parameters	Setting
Center Freq.	26.566 GHz
OFDM	CP-OFDM
BW (MHz)	100
SCS (kHz)	120
Mod.	QPSK
DMRS Config.	Type 1
Type A pos	2
DMRS Addpos.	2
CDM group	2

Means.	Keysight	CSP
PUSCH (%)	3.721	3.95
PUSCH DMRS (%)	2.971	2.96
Avg. EVM (%)	3.639	3.45
IQ offset (dB)	-30.037	N/A
Freq. error (Hz)	-5424	-5289
SCO (ppm)	-0.067	-0.03

Keysight 89600



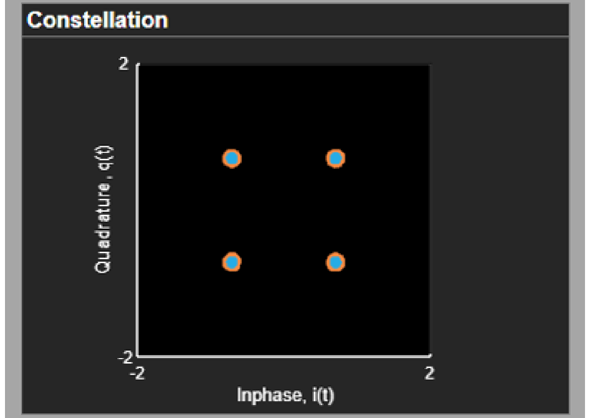
Name	EVM (%rms)	Power per RE (dBm)	Modulation	Num. of RBs	RNTI	BWP ID
PUSCH0	3.721	-33.70	QPSK	5280	0x1	0
PUSCH0_DMRS	2.971	-30.70	QPSK	5280	0x1	0

Analyzed Subframe	[Sf0,sym0] to [Sf9,sym111]	
Channel Power	-4.715	dBm
OFDMSym. Tx Power	-4.712	dBm
EVM	3.639	%rms
Frequency Error	-5.424	kHz
Symbol Clock Error	-0.067	ppm
IQ Offset	-30.037	dB
Time Offset	-500.00	us
Sync Correlation	99.693	%
Sync Source	PUSCH DMRS	
Cell ID	0	

In-Band Emissions Result = ***
Worst Case = *** at Slot *** RB ***
Average Result = ***
Average Worst Case = *** at RB ***

CSP

Constellation | Resource grid | CFR



	rms (%)	Mod. Fmt	EVM Req.
PUSCH	3.9500	QPSK	Pass
PUSCH DMRS	2.9600	QPSK	Pass

	Analysis Result	Unit
RMS EVM Mean	3.4550	%
RMS SCH EVM Mean (QPSK)	3.9500	%
Peak SCH EVM Max.	11.6700	%
RMS DMRS EVM Mean	2.9600	%
Peak DMRS EVM Max.	6.7140	%
Frequency Error	-5289	Hz
Sample Clock Offset	-0.0380	ppm
IQ Gain Imbalance	0	dB
IQ Phase	0	deg

Summary

- SDR-Based VSG/VSA
- Three-Detachable Layer Architecture
  - Designed and developed software for 5G NR and Wi-Fi ax VSG/VSA
  - Achieved 400MHz signal bandwidth transmission and reception across four channels on a USRP X410 through RFNoC replay blocks
  - Calibrated power to ensure consistent performance across all channels
- Results
  - Measured EVM values: -40dB for 400MHz bandwidth and -43dB for 100MHz bandwidth
  - Conducted over-the-air testing with a 5G FR2 mmWave cellphone
- Future Directions
  - Enhance VSA capture and analysis speed
  - Integrate AI-assisted measurement, diagnostics, and testing

Reference

- J. Malsbury and M. Ettus, “Simplifying FPGA Design with a Novel Network-on-Chip Architecture,” in *Proc. 2nd Workshop on software radio implementation forum (SRIF)*, Hong Kong, August 2013, pp. 45-52, doi: 10.1145/2491246.2491251.
- M. Braun and J. Pendlum, "A flexible data processing framework for heterogeneous processing environments: RF Network-on-Chip™," *2017 International Conference on FPGA Reconfiguration for General-Purpose Computing (FPGA4GPC)*, Hamburg, Germany, 2017, pp. 1-6, doi: 10.1109/FPGA4GPC.2017.8008958.
- *NR; User Equipment (UE) conformance specification; Radio transmission and reception; Part 1: Range 1 standalone Release 17*, 3GPP TS 38.521-1, V.17.11.0, 2024
- *NR; User Equipment (UE) conformance specification; Radio transmission and reception; Part 2: Range 2 standalone Release 17*, 3GPP TS 38.521-2, V.17.5.0, 2024
- *NR; Physical Channels and Modulation Release 17*, 3GPP TS 38.211, V.17.6.0, 2023.
- *NR; Multiplexing Channel Coding Release 17*, 3GPP TS 38.212, V.17.6.0, 2023.
- *NR; Physical Layer Procedures for Control Release 17*, 3GPP TS 38.213, V.17.6.0, 2023.
- M. Speth, S. A. Fechtel, G. Fock and H. Meyr, "Optimum receiver design for wireless broad-band systems using OFDM. I," *IEEE Transactions on Communications*, vol. 47, no. 11, pp. 1668-1677, Nov. 1999, doi: 10.1109/26.803501.
- S. Huang, Y. Su, Y. He and S. Tang, "Joint time and frequency offset estimation in LTE downlink," *7th International Conference on Communications and Networking in China*, Kunming, China, 2012, pp. 394-398, doi: 10.1109/ChinaCom.2012.6417514.
- J. J. van de Beek, M. Sandell and P. O. Borjesson, "ML estimation of time and frequency offset in OFDM systems," *IEEE Transactions on Signal Processing*, vol. 45, no. 7, pp. 1800-1805, July 1997, doi: 10.1109/78.599949.
- *IEEE Standard for Information Technology–Telecommunications and Information Exchange between Systems Local and Metropolitan Area Networks–Specific Requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 1: Enhancements for High-Efficiency WLAN, Standard 802.11ax-2021, 2021.*
- Ettus Research, "USRP Hardware Manual," [Online]. Available: https://files.ettus.com/manual/index.html. [Accessed: Jan. 2, 2025].
- Ettus Research, "X410 100 Gigabit Ethernet," [Online]. Available: https://kb.ettus.com/X410#100_Gigabit_Ethernet.[Accessed: Jan. 2, 2025].
- Ettus Research, *RFNoC Specification*, Revision 1.0, 2016. [Online]. Available: https://files.ettus.com/app_notes/RFNoC_Specification.pdf [Accessed: May 15, 2025].
- Ettus Research, "Getting Started with RFNoC in UHD 4.0," *Ettus Knowledge Base*, [Online]. Available: https://kb.ettus.com/Getting_Started_with_RFNoC_in_UHD_4.0#Available_RFNoC_Blocks [Accessed: Mar 15, 2025].

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USRP user community