# Intel® FPGA with Integrated ADC/DACs



## **REW All Digital Beamforming Transformation**

- All digital beam forming required for future threats including swarm of drones
- Reduction in SWAP\* requirements drive need for heterogeneous integration
- Thousands of array elements in a given system with data converter at each element will radically change market dynamics









#### EMIB embedded multi-die interconnect bridge



https://www.intel.com/content/www/us/en/architecture-and-technology/programmable/analog-rf-fpga.html https://www.intel.com/content/www/us/en/architecture-and-technology/programmable/fpga-integrated-data-converter-solution-br ief.html

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## EMIB technology



- Allows integration of high-performance analog converter chiplets regardless of process node, foundry, or IP provider with Intel® FPGA
- Provide lower latency versus JESD204c
- Provide lower power per bit versus JESD204c

## Chiplets



https://www.intel.com/content/www/us/en/products/docs/programmable/direct-rf-series-fpga-white-paper.html

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## **AIB** Overview

- Support peer-to-peer high bandwidth parallel communication
- Open to download from Intel Website
- Versatile per-channel clocking in both directions
- Streaming or transactional protocols can be implemented on top of AIB
- AIB's flexible IO cell permits arbitrary TX, RX, clock and control mapped by the protocol layer above



## Why Direct RF?







#### **Direct RF Architecture**

Least analog circuitry required Highest performance Smallest form-factor Fastest time-to-market, lowest risk ~32GHz of BW

#### **Direct IF Architecture**

Moderate analog circuitry required Modest performance Large form-factor Slow time-to-market, medium risk ~1 to 2GHz of BW

#### Superheterodyne Architecture

Most analog circuitry required Lowest performance Largest form-factor Slowest time-to-market, most risk ~100 to 200MHz of BW

#### https://www.intel.com/content/www/us/en/architecture-and-technology/programmable/analog-rf-fpga. html



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## Direct RF Sampling Advantages

- Eliminates analog tuner circuitry
- Provides real-time frequency agility
  - Multi-mode radar / EW
- Provides wider bandwidths
  - EW countermeasures

Advantage in Size, Weight, Power, Cost, and Capability

Up to 90+% Savings in Size



#### Integration



#### Intel® Stratix® 10 AX and Intel Agilex® 9 FPGA Direct RF-Series



Intel® Stratix® 10 AX FPGA

Intel® Stratix® 10 FPGA 2.8 MLE + 8-Channels ADC/DAC



#### Intel Agilex® 9 FPGA Direct RF-Series

Intel Agilex® FPGA 1.4 MLE + 4-Channels ADC/DAC



#### Intel Agilex<sup>®</sup> 9 FPGA Direct RF-Series

Intel Agilex® FPGA 2.7 MLE + 8-Channels ADC/DAC

Intel<sup>®</sup> Programmable Solution Group

## **Devices familly**

• Agilex based



| Product Name  | Logic Elements<br>(LE) | 18x19<br>Multipliers | # of<br>ADC/DAC | Sample Rate<br>(Gsps) | # of Bits<br>Resolution | Embedded<br>Memory (Mb) | Quad Core<br>ARM | XCVR's                | PCIe | Package   |
|---|------------------------|----------------------|-----------------|-----------------------|-------------------------|-------------------------|------------------|-----------------------|------|-----------|
| Intel® Agilex™ Direct RF-Series<br>SoC FPGA AGRW014 | 1437                   | 9020                 | 4/4             | 64/64                 | 10/10                   | 190                     | Yes              | 58G PAM-4, 32G<br>NRZ | 4.0  | 45x32     |
| Intel® Agilex™ Direct RF-Series<br>SoC FPGA AGRW027 | 2693                   | 17056                | 8/8             | 64/64                 | 10/10                   | 287                     | Yes              | 58G PAM-4, 32G<br>NRZ | 4.0  | 52.5x42.5 |
| Intel® Agilex™ Direct RF-Series<br>SoC FPGA AGRM027 | 2693                   | 17056                | 20/16           | 4/12                  | 14/14                   | 287                     | Yes              | 58G PAM-4, 32G<br>NRZ | 4.0  | 56x45     |

#### Intel® FPGA with Integrated ADC/DACs



- up to 64GSPS sample rate
- EMIB technology
- AIB physical layer protocol

#### Overview

Logic # of Sample Rate # of Bits Embedded Product 18x19 Elements Multipliers ADC/DAC (Gsps) Resolution Memory Name (LE) Intel<sup>®</sup> Stratix<sup>®</sup> 10 AX SOC 2 A tiles 2753 11520 8/8 64/64 10/10 244 Stratix 10 FPGA 1SA28 Intel<sup>®</sup> Agilex™ Direct RF-Wide Series SoC 4/4 64/64 10/10 1437 9020 190 1 A tile FPGA Band AGRW014 Intel<sup>®</sup> Agilex<sup>™</sup> Direct RF-Agilex 2 A tiles Series SoC 2693 17056 8/8 64/64 10/10 287 FPGA AGRW027 Intel<sup>®</sup> Agilex™ Mid Direct RF-20/16 14/14 Series SoC 4/12 2693 17056 287 FPGA Band AGRM027

https://www.intel.com/content/www/us/en/architecture-and-technology/programmable/analog-rf-fpga.html

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#### Schematic Representation



#### 8 ADC and 8 DAC per device

## running 64GSPS per ADC or DAC



## **Block diagram**

Coarse DDC Coarse DUC Fine DDC Fine DUC NCOs



https://www.intel.com/content/www/us/en/architecture-and-technolog y/programmable/fpga-integrated-data-converter-solution-brief.html



Analog performance: 25GHz of instantaneous bandwidth with a 65 dBc SNR



Intel® Programmable Solution Group

#### Intel® FPGA with Integrated ADC/DACs board



## RF performance sweeps

#### ADC NSD Sweep



Intel<sup>®</sup> Programmable Solution Group

#### intel.<sup>19</sup>

#### ADC NSD Performance Summary



# ADC Spurious Demo

Fs = 51.2 Gsps Decimate by 16 RF input level = -1 dBFS Sweep (16 GHz, 19 GHz)





#### Intel Agilex<sup>®</sup> 9 FPGA Direct RF-Series Spurious Frequency Calculator

| Intel A-tile ADC Sp             | ur Calculato                       | r   |  |  |  |              |                     |
|---------------------------------|------------------------------------|---|--|--|--|--------------|---------------------|
| Note: predicted spur la         | cations in this e                  | alculator are base  | d on the ADC a   | architectu   | are. Only spur loc   | ations, not  | maanitude           |
| are shown. Spurs at se          | me locations m                     | ay have a very low  | magnitude and  | d not be w   | isible above the n   | toise floor. |                     |
| User should fill out boxes in ( | Drange.                            |   |  |  |  |              |                     |
| Parameter                       | Value                              | Unit Allowed ent  | ries   |  |  |              |                     |
| Fs                              | 64                                 | Gsps (40, 64)   | 1. Enter the   | sample rate  | P  |              |                     |
| Fundamental                     | 12,58496                           | GHz (0,1.36)  | 2. Enter fun   | damental P   | Finput frequency.  |              |                     |
| NCO entry option                | frequency                          | Idron down  | 1 3 Select to  | enter NCO  | hu werwerden of the  | anne oten Fi | Lout 3a or 3b, acco |
| NCO frequency entry             | 12                                 | GHz   | 3a Enterth   | e MOThe  | Wearbour   |              |                     |
| Coarse NCO step entru           | 22                                 | sten (-64.63)   | 3b Enter /2  | nanna MOT  | ahan   | _            |                     |
| Decimation factor               | 16                                 | [drop down  | 4. Select de   | ecimation fa   | actor.   |              |                     |
| NCO frequency                   | 12                                 | GHz   | NCO freque   | enourequity  | calculated from User   | inputs       |                     |
| BV                              | 4                                  | GHz   | IBW/result o   | alculated fr   | rom User inputs  | - group.     | /                   |
|                                 |                                    | 5-7 TE  | ID W lesuit C  | Jacouateun   | ioni oser inputs.  |              | /                   |
|                                 |                                    |   |  | -  | -  |              | 1                   |
| Highlighted any log stores a    | a measure in side sh               | - IPU   |  |  |  |              | /                   |
| r lignlighted spur locations ar | e present inside th                | elow.   |  |  |  |              | / /                 |
|                                 |                                    |   |  |  |  | Sample       | er Spur/            |
| Harmonic Calculator             |                                    | Interleavin   | g Spur Calcul  | ator   |  | Calcula      | ator /              |
|                                 | Harmonies                          |   | Gain an  | d Phase  | Offset Source  | Sour         | Source              |
| Vamo                            | (GHz)                              | Index   | Server   | (GHz)  | (GHz)  | Inder        | (GH-)               |
| lame                            | (GHZ)                              | index   | 0 EPE  |  | 12 000   | Index        | (Gnz)               |
| unuallientai                    | 12 170                             | 0   | 0.305  | 1 505  | -12.000  | 2            | -0.000              |
| 102                             | 10.170                             | 0   | -0.415   | 1.505  | 10.000   | 2            | -4.000              |
| 10.3                            | 14.245                             | 1   | -1.415   | 2.585  | -10.000  | 3 /          | 0.000               |
| 104                             | 1.660                              | 2   | -2.415   | 3.565  | -9.000   | 4            | 4.000               |
| 105                             | -10.925                            | 3   | -3.415   | 4.585  | -8.000   | 5            | 8.000               |
| НОБ                             | -0.490                             | 4   | -4.415   | 5.585  | -7.000   | 6            | 12.000              |
| HU7                             | 12.095                             | 5   | -5.415   | 6.585  | -6.000   | 7/           | 16.000              |
| HD8                             | 15.320                             | 6   | -6.415   | 7.585  | -5.000   | /            |                     |
| HD9                             | 2.735                              | 7   | -7.415   | 8.585  | -4.000   | 1            |                     |
| HD10                            | -9.850                             | 8   | -8.415   | 9.585  | -3.000   | /            |                     |
| HD11                            | -1.565                             | 9   | -9.415   | 10.585   | -2.000 /   |              |                     |
| HD12                            | 11.020                             | 10  | -10.415  | 11.585   | -1.000 🟒   |              |                     |
| HD13                            | 16.396                             | 11  | -11.415  | 12.585   | 0.000  |              |                     |
| HD14                            | 3.811                              | 12  | -11.585  | 13.585   | 1.000  |              |                     |
| HD15                            | -8.774                             | 13  | -10.585  | 14.585   | 2.000  |              |                     |
| HD16                            | -2.641                             | 14  | -9.585   | 15.585   | 3.000  |              |                     |
| HD17                            |                                    | and the second se |  |  | 4.000  |              |                     |
| HD18                            | 9.944                              | 15  | -8.585   | 16.585   | 4.000  |              |                     |
| HD19                            | 9.944                              | 15  | -8.585   | 16.585   | 5.000  |              |                     |
| 020                             | 9.944<br>17.471<br>4.886           | 15<br>16<br>17  | -8.585<br>-7.585<br>-6.585   | 16.585<br>17.585<br>18.585   | 5.000  | _            |                     |
| 1020                            | 9.944<br>17.471<br>4.886<br>-7.699 | 15<br>16<br>17<br>18  | -8.585<br>-7.585<br>-6.585<br>-5.585   | 16.585<br>17.585<br>18.585<br>19.585   | 5.000<br>6.000<br>7.000  |              |                     |
| 1020                            | 9.944<br>17.471<br>4.886<br>-7.699 | 15<br>16<br>17<br>18<br>19  | -8.585<br>-7.585<br>-6.585<br>-5.585<br>-4.585   | 16.585<br>17.585<br>18.585<br>19.585<br>19.415   | 4,000<br>5,000<br>6,000<br>7,000<br>8,000  |              |                     |
| 1020                            | 9.944<br>17.471<br>4.886<br>-7.699 | 15<br>16<br>17<br>18<br>19<br>20  | -8.585<br>-7.585<br>-6.585<br>-5.585<br>-4.585<br>-3.585   | 16.585<br>17.585<br>18.585<br>19.585<br>19.415<br>18.415                               | 4.000<br>5.000<br>6.000<br>7.000<br>8.000<br>9.000                               |              |                     |
| nD20                            | 9.944<br>17.471<br>4.886<br>-7.699 | 15<br>16<br>17<br>18<br>19<br>20<br>21  | -8.585<br>-7.585<br>-6.585<br>-5.585<br>-4.585<br>-3.585<br>-2.585                               | 16.585<br>17.585<br>18.585<br>19.585<br>19.415<br>18.415<br>18.415                     | 4.000<br>5.000<br>6.000<br>7.000<br>8.000<br>9.000                               |              |                     |
| 1020                            | 9.944<br>17.471<br>4.886<br>-7.699 | 15<br>16<br>17<br>18<br>19<br>20<br>21<br>22  | -8.585<br>-7.585<br>-6.585<br>-5.585<br>-4.585<br>-3.585<br>-2.585<br>-1.585                     | 16.585<br>17.585<br>18.585<br>19.585<br>19.415<br>18.415<br>18.415<br>17.415<br>16.415 | 4,000<br>5,000<br>6,000<br>7,000<br>8,000<br>9,000<br>10,000<br>11,000           |              |                     |
| 1020                            | 9.944<br>17.471<br>4.886<br>-7.699 | 15<br>16<br>17<br>18<br>19<br>20<br>21<br>22<br>22<br>23  | -8,585<br>-7,585<br>-6,585<br>-5,585<br>-4,585<br>-3,585<br>-2,585<br>-2,585<br>-1,585<br>-0,585 | 16.585<br>17.585<br>18.585<br>19.415<br>19.415<br>18.415<br>17.415<br>16.415<br>15.415 | 4,000<br>5,000<br>6,000<br>7,000<br>8,000<br>9,000<br>10,000<br>11,000<br>12,000 |              |                     |

#### **Excel-based Spur Calculator**

1.415

13.415

14.000

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#### EVP Spur Calculator analysis mode

#### ADC Spurious Performance Sweep



#### ADC Spurious Performance Summary



# DAC IMD Demo

Fs = 64 Gsps Interpolate by 8 Two tones: RF output level = -7 dBFS Sweep tone spacing, level, and  $f_c = (12 \text{ GHz}, 18 \text{ GHz})$ 



#### DAC IMD Sweep



#### DAC IMD Sweep

| MultiView      | Spectrum                       | × Ph   | ase Noise    | ×                        |                          |          |      |       | •                    |
|----------------|--------------------------------|--|--------------|--------------------------|--------------------------|----------|------|-------|----------------------|
| Ref Level 0.00 | 0 dBm                          | RBW 1 MI   | Hz           |                          |                          |          |      |       | SGL                  |
| Att            | 10 dB SWT 5.6                  | 6s <b>≎VBW</b> 1kł   | Hz Mode Auto | Sweep                    |                          |          |      |       | O LAD Clow           |
| 1 Frequency 5  | weep                           |  |              |                          |                          |          |      | M1[1] |                      |
|                |                                |  |              |                          |                          |          |      | MILII | 14 12600 GHz         |
|                |                                |  |              |                          |                          |          |      | M2[1] | -20.22 dBm           |
|                |                                |  |              |                          |                          |          |      | WZ[1] | 15.86310 GHz         |
|                |                                |  | 1 M I        |                          |                          | M2       |      |       | 15100510 012         |
|                |                                |  |              |                          |                          |          |      |       |                      |
|                |                                |  |              |                          |                          |          |      |       |                      |
|                |                                |  |              |                          |                          |          |      |       |                      |
|                |                                |  |              |                          |                          |          |      |       |                      |
|                |                                |  |              |                          |                          |          |      |       |                      |
|                |                                |  |              |                          |                          |          |      |       |                      |
|                |                                |  |              |                          |                          |          |      |       |                      |
|                |                                |  |              |                          |                          |          |      |       |                      |
|                |                                |  |              |                          |                          |          |      |       |                      |
|                |                                |  |              |                          |                          |          |      |       |                      |
|                |                                |  |              |                          |                          |          |      |       |                      |
| -70 dBm        | 7 1                            |  |              |                          |                          |          |      |       |                      |
|                |                                |  |              |                          |                          |          |      |       |                      |
| -80 d8m-       |                                |  |              |                          |                          |          | . La |       | introduction of the  |
|                | a far alablar have a far a far | the man and the second | ad land      | we make to a farmer have | مستقيرليه الالمحداقة محس | manipul  |      |       | - three and many and |
|                |                                |  |              |                          |                          |          |      |       |                      |
|                |                                |  |              |                          |                          |          |      |       |                      |
| -100 dBm       |                                |  |              |                          |                          |          |      |       |                      |
|                |                                |  |              |                          |                          |          |      |       |                      |
|                |                                |  |              |                          |                          |          |      |       |                      |
| -110 dBm-      |                                |  |              |                          |                          |          |      |       |                      |
|                |                                |  |              |                          |                          |          |      |       |                      |
| CE 15.0 GHz    |                                |  | 1001 nt      | s                        | 80                       | 0.0 MHz/ |      |       | Span 8.0 GHz         |

#### DAC IMD Sweep

| Ref Level 0.00      | ) dBm Offset           | 1.00 dB . RBW         | 1 MHz                    | ~ ~                |   |                     |                       |                  | SGL          |
|---------------------|------------------------|-----------------------|--------------------------|--------------------|---|---------------------|-----------------------|------------------|--------------|
| Att                 | O dB SWT               | 5.6 s 🗢 VBW           | 1 kHz Mode               | Auto Sweep         |   |                     |                       |                  |              |
| Frequency Sv        | veep                   |                       |                          |                    |   |                     |                       |                  | •1AP Clrw    |
|                     |                        |                       |                          |                    |   |                     |                       | M1[1]            | -18.96 dBm   |
|                     |                        |                       |                          |                    |   |                     |                       |                  | 15.67930 GH  |
|                     |                        |                       |                          |                    |   |                     |                       | M2[1]            | -19.16 dBn   |
|                     |                        |                       |                          |                    | Mim                                       | 2                   |                       |                  | 15.76720 GH  |
|                     |                        |                       |                          |                    |   |                     |                       |                  |              |
|                     |                        |                       |                          |                    |   |                     |                       |                  |              |
| 30 dBm              |                        |                       |                          |                    |   |                     |                       |                  |              |
|                     |                        |                       |                          |                    |   |                     |                       |                  |              |
|                     |                        |                       |                          |                    |   |                     |                       |                  |              |
| i0 dBm              |                        |                       |                          |                    |   |                     |                       |                  |              |
|                     |                        |                       |                          |                    |   |                     |                       |                  |              |
|                     |                        |                       |                          |                    |   |                     |                       |                  |              |
|                     |                        |                       |                          |                    |   |                     |                       |                  |              |
|                     |                        |                       |                          |                    |   |                     |                       |                  |              |
|                     |                        |                       |                          |                    |   |                     |                       |                  |              |
|                     |                        |                       |                          |                    |   |                     | 11                    |                  |              |
|                     |                        |                       | 11                       |                    |   |                     |                       |                  |              |
|                     |                        |                       |                          |                    |   |                     |                       |                  |              |
|                     |                        |                       |                          |                    |   |                     |                       |                  |              |
|                     | . 1                    |                       |                          |                    |   |                     |                       |                  | 1            |
| rath marker and     | IL decline Ster Brown  | here a la secondardan | 1. Hold Halles Harry     |                    | le la | Whill have been and | Jul - la - la - la la | relifier and the | aband a find |
| An JELL an analytic | I offer and be descent |                       | where it is the first of | and the state hast |   |                     |                       |                  |              |
|                     |                        |                       |                          |                    |   |                     |                       |                  |              |
|                     |                        |                       |                          |                    |   |                     |                       |                  |              |
|                     |                        |                       |                          |                    |   |                     |                       |                  |              |
| 110 dBm             |                        |                       |                          |                    |   |                     |                       |                  |              |
|                     |                        |                       |                          |                    |   |                     |                       |                  |              |
|                     |                        |                       |                          |                    |   |                     |                       |                  |              |

#### DAC IMD Performance Summary





# ADC/DAC details: 64Gsps with 25GHz of instateneous bandwidth and with a 65 dBc SNR



Data converter chiplets include Numerically controlled Oscillators (NCOs) and integrated Digital Up Converters (DUCs) and Digital Down Converters (DDCs) that eleminate a substantial amount of analog circuitry

## Tile architecture

#### Clocking

- Clock Distribution Network
- External clocking
- Per channel CMU pll

#### AIB

- Data flexibility
- 1Tbit bandwidth



## **Differential inputs**

• A wideband balum is used to convert from common mode to differential inputs



# Intel Agilex<sup>®</sup> 9 FPGA Direct RF-Series Evaluation Platform (EVP)







Intel Agilex<sup>®</sup> 9 FPGA Direct RF-Series Development Kit





# ADC NSD Demo

Fs = 64 Gsps No decimation RF input level = -10 dBFS Sweep entire first Nyquist zone

