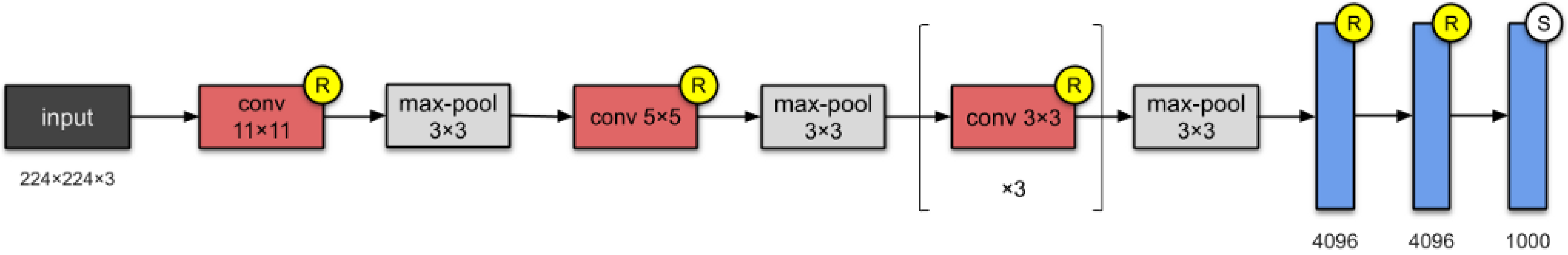
Acceleration of AlexNet for ImageNet Classification



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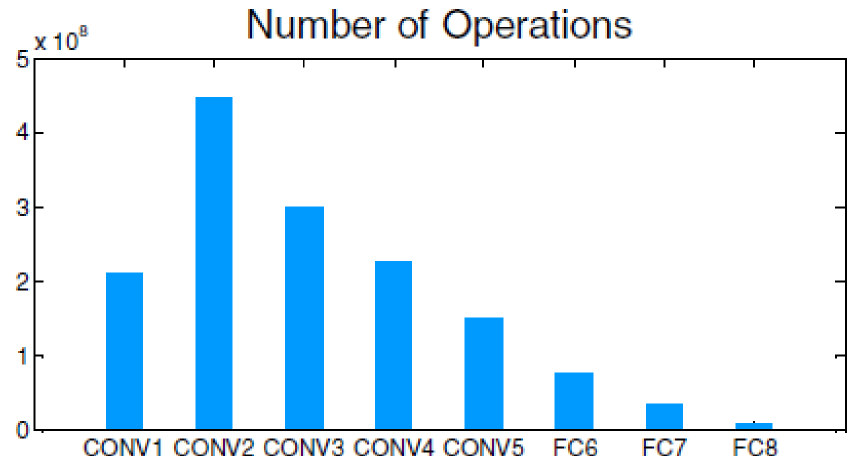
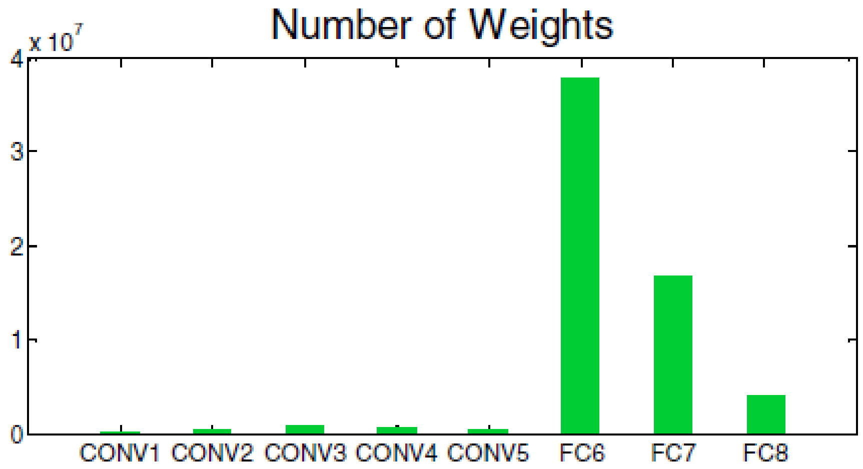
Problem statement



Number of Operations



Number of Weights

- AlexNet Architecture has 14 layers
- Convolution layers are computation intensive (large number of operations)
  - Higher parallelism degree
  - More resources used
- Fully connected layers are memory intensive (large data accesses from memory for weights)
  - Reduce memory bandwidth
- Limited by resources available on board, primary focus was to first bring down resource utilization followed by latency optimization

Workflow

Python Implementation – golden output and layer parameters

C++ Implementation – Individual Layers

C++ Implementation – Binding and logic verification

HLS – Unoptimized individual layers

Binding all unoptimized layers

HLS – Optimized individual layers

Binding all optimized layers

CONV1 deployment on FPGA board

Logic Implementation

Python Implementation

- Model - Tensorflow & Keras
- Dataset- CIFAR-10 (created by Alex Krizhevsky)
- Successfully trained model with 90% accuracy.
- Golden output, weights and bias for each layer generated were stored and used for C implementation

C++ Implementation

- Separate executable for each layer.
- Separate testbench for logic verification of each layer. (MSE (conv1) – 4.83 x 10^(-14))
- Weights and biases generated from Python were used.
- Wrapper testbench for binding all layers.
- Logic verified by accurate class prediction.

Optimization Techniques

Array Partitioning

Tiling

Unrolling and Pipelining

Data quantization – Accuracy, Speedup and Utilization

Loop Reordering

Efficient data reading and writing – Optimizing DRAM access

Dataflow – memory streaming

CONV1 (3X227X227)

Product family: zynquplus
Target device: xczu3eg-sbva484-1-e

			BRAM_18K	DSP	FF	LUT	LATENCY (ms)
		AVAILABLE	432	360	141120	70560	
FXT <32, 8>	UNOPTIMIZED	TOTAL	798	30	4542	7331	8441
		UTILIZATION	**184%**	8%	3%	10%	
	OPTIMIZED	TOTAL	280	43	5699	11444	373 (**22.63x**)
		UTILIZATION	**64%**	11%	4%	16%	
FXT <16, 4> Underflow issue	UNOPTIMIZED	TOTAL	414	16	4012	7001	8441
		UTILIZATION	**95%**	4%	2%	9%	
	OPTIMIZED	TOTAL	159	21	5136	10308	1244 (**6.78x**)
		UTILIZATION	**36%**	5%	3%	14%	

- Output dimensions – 96x55x55
- OUT_BUF size – 32x11x11

			BRAM_18K	DSP	FF	LUT	LATENCY (ms)
		AVAILABLE	432	360	141120	70560	
Conv2 (96X27x27)	UNOPTIMIZED	TOTAL	828	12	3835	6805	8969
		UTILIZATION	**191%**	3%	2%	9%	
	OPTIMIZED	TOTAL	27	11	10637	10855	**47.66 (188.2x)**
		UTILIZATION	**6%**	3%	7%	15%	
Conv3 (256x13x13)	UNOPTIMIZED	TOTAL	973	12	3499	7174	3001
		UTILIZATION	**225%**	3%	2%	10%	
	OPTIMIZED	TOTAL	47	20	11217	17091	**11.57 (259.4x)**
		UTILIZATION	**10%**	5%	7%	24%	
Conv4 (384x13x13)	UNOPTIMIZED	TOTAL	260	5	2727	4863	252
		UTILIZATION	**60%**	1%	1%	6%	
	OPTIMIZED	TOTAL	223	200	9146	15378	**5.252 (47.98X)**
		UTILIZATION	**51%**	55	6	21	
Conv5 (384x13x13)	UNOPTIMIZED	TOTAL	197	5	2722	4834	168
		UTILIZATION	**45%**	1	1	6	
	OPTIMIZED	TOTAL	172	69	5634	12260	4.362 **(38.51x)**
		UTILIZATION	**39%**	19	3	17	

Fully Connected - 1

		BRAM_18K	DSP	FF	LUT	LATENCY (ms)
	AVAILABLE	432	360	141120	70560	
UNOPTIMIZED	TOTAL	34581	2	2761	4151	1133
	UTILIZATION	**8004%**	~0%	1%	5%	
OPTIMIZED	TOTAL	44	32	3925	5441	**379 (3x)**
	UTILIZATION	**10%**	8%	2%	7%	

- FC1 dimensions = 9216 x 4096
- Tiling buffer dimension = 32 x 256 (input depth x output depth)
- Pipelining on input depth.
- Further tried to optimize latency by incorporating array partitioning in the weights and output array. But saw no improvement in latency, with an increase in resource utilization.

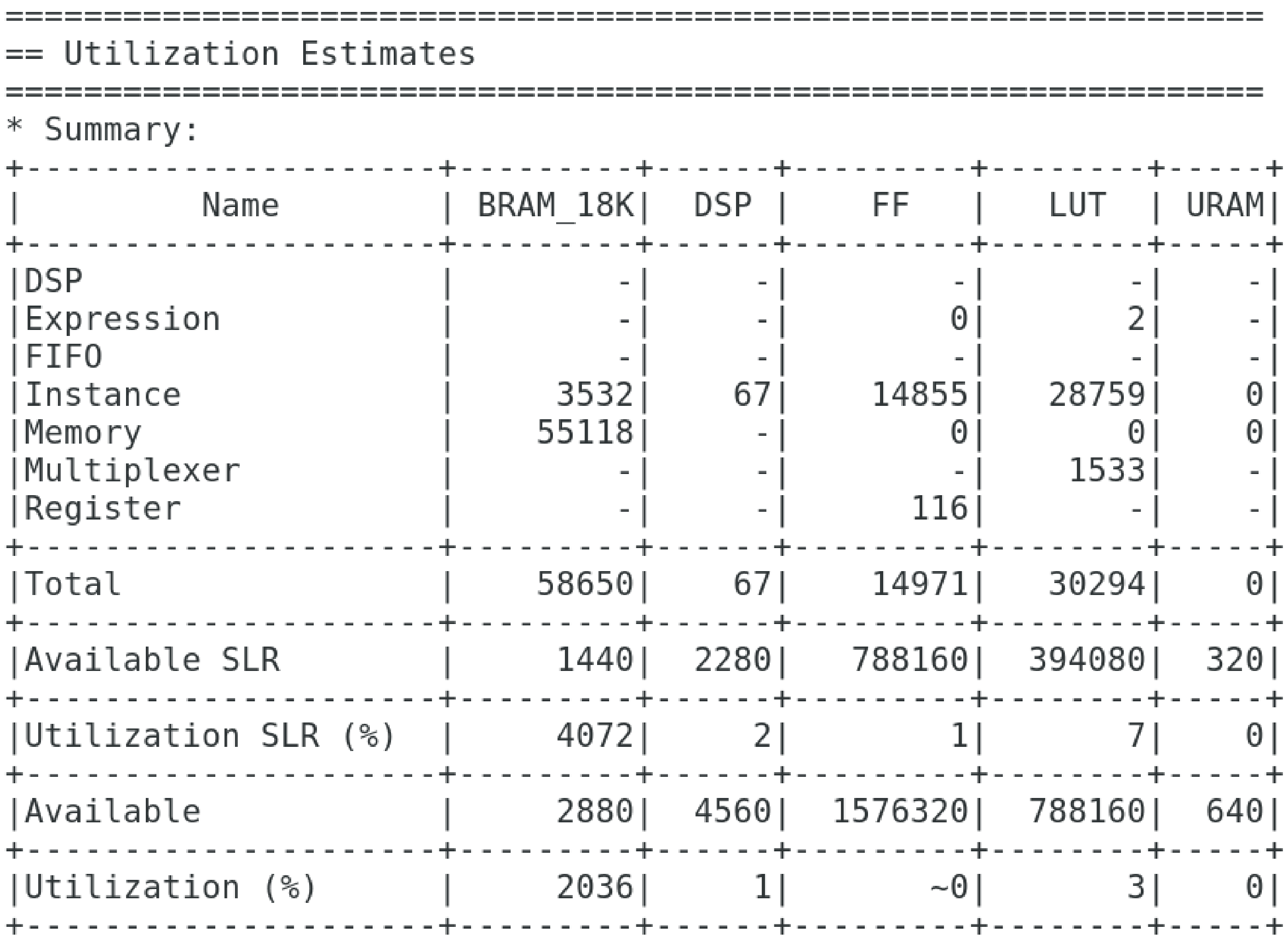
			BRAM_18K	DSP	FF	LUT	LATENCY (ms)
		AVAILABLE	432	360	141120	70560	
FC2 4096 x 4096	UNOPTIMIZED	TOTAL	29720	6	2124	3374	336
		UTILIZATION	**6879%**	1%	1%	4%	
	OPTIMIZED	TOTAL	27	16	3892	5255	**167 (2x)**
		UTILIZATION	**6%**	4%	2%	7%	
FC3 4096 x 10	UNOPTIMIZED	TOTAL	51	18	4319	5257	1.23
		UTILIZATION	11%	5%	3%	5%	
	OPTIMIZED	TOTAL	8	16	4376	5104	**0.459 (2.7x)**
		UTILIZATION	**1%**	4%	3%	7%	
FLAT 9216	UNOPTIMIZED	TOTAL	24	0	1017	2167	0.277
		UTILIZATION	5%	~0%	~0%	3%	
	OPTIMIZED	TOTAL	4	0	1126	3230	**0.092 (3x)**
		UTILIZATION	~0%	~0%	~0%	4%	

*Flat is the connecting layer b/w CNN and ANN layers to flatten data from 3 dimension to 1 dimension

Results – Maxpool/ LRN

		BRAM_18K	DSP	FF	LUT	LATENCY (ms)
AVAILABLE		432	360	141120	70560	
Maxpool1	UNOPTIMIZED	**510%**	1%	1%	5%	4.304
	OPTIMIZED	**44%**	1%	9%	27%	2.968 **(1.45x)**
Maxpool2	UNOPTIMIZED	**330%**	0%	1%	4%	2.732
	OPTIMIZED	**~0%**	0%	27%	**81%**	1.885 **(1.45x)**
Maxpool5	UNOPTIMIZED	**80%**	0%	0%	4%	0.617
	OPTIMIZED	**~0%**	0%	6%	21%	0.441 **(1.4x)**
LRN1	UNOPTIMIZED	**124%**	0%	2%	5%	8.713
	OPTIMIZED	**~0%**	0%	1%	3%	2.9 **(3x)**
LRN2	UNOPTIMIZED	40%	1%	0%	3%	11.213
	OPTIMIZED	~0%	0%	0%	2%	1.866 **(6x)**

Unoptimized Binding Results



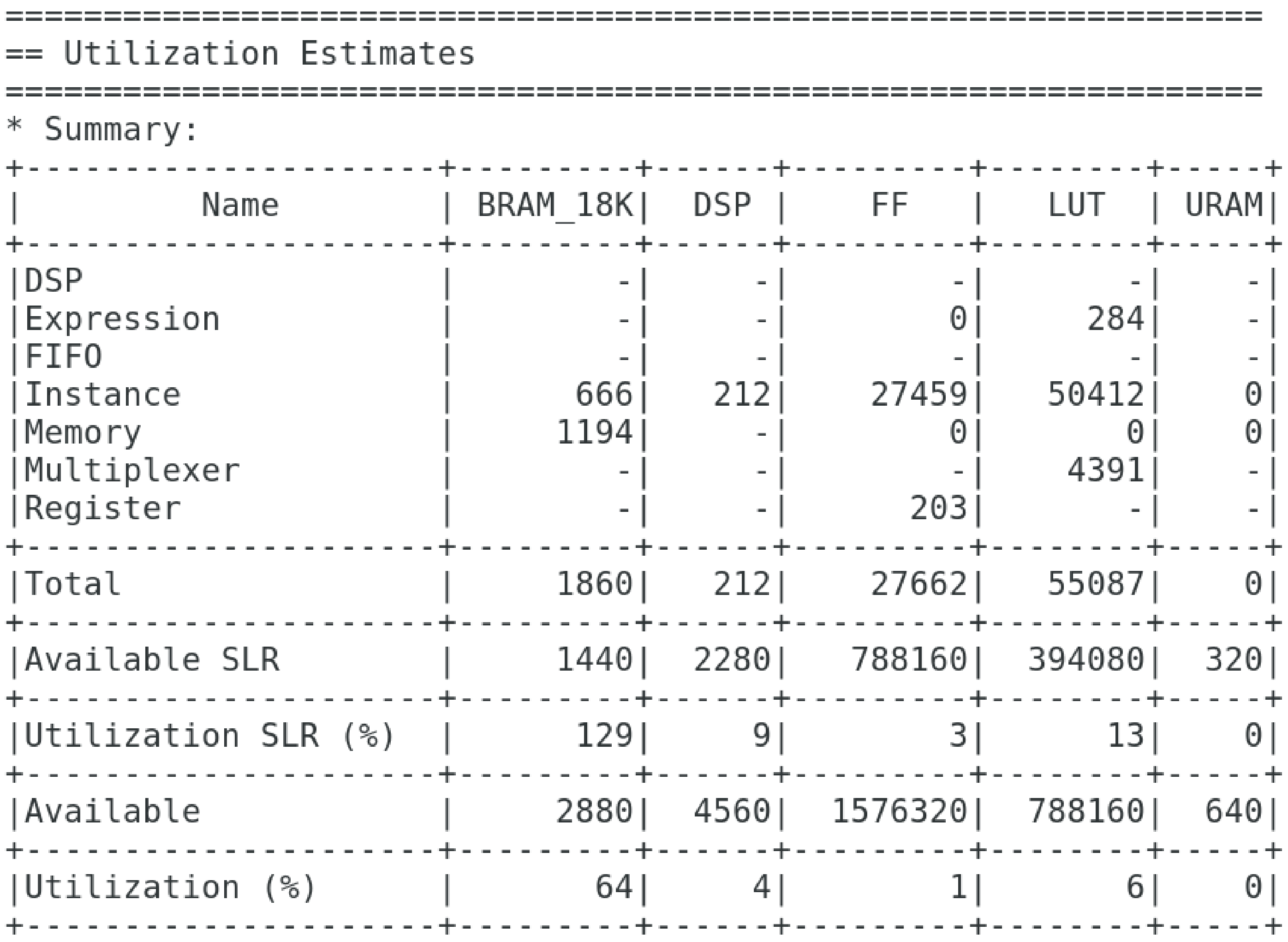
```
================================================================
== Utilization Estimates
================================================================
* Summary:
+----------------------+---------+------+---------+--------+-----+
|         Name         | BRAM_18K|  DSP |    FF   |   LUT  | URAM|
+----------------------+---------+------+---------+--------+-----+
|DSP                   |        -|     -|        -|       -|    -|
|Expression            |        -|     -|        0|       2|    -|
|FIFO                  |        -|     -|        -|       -|    -|
|Instance              |     3532|    67|    14855|   28759|    0|
|Memory                |    55118|     -|        0|       0|    0|
|Multiplexer           |        -|     -|        -|    1533|    -|
|Register              |        -|     -|      116|       -|    -|
+----------------------+---------+------+---------+--------+-----+
|Total                 |    58650|    67|    14971|   30294|    0|
+----------------------+---------+------+---------+--------+-----+
|Available SLR         |     1440|  2280|   788160|  394080|  320|
+----------------------+---------+------+---------+--------+-----+
|Utilization SLR (%)   |     4072|     2|        1|       7|    0|
+----------------------+---------+------+---------+--------+-----+
|Available             |     2880|  4560|  1576320|  788160|  640|
+----------------------+---------+------+---------+--------+-----+
|Utilization (%)       |     2036|     1|       ~0|       3|    0|
+----------------------+---------+------+---------+--------+-----+
```

Product family: virtexuplus
Target device: xqvu7p-flra2104-1-I

Unoptimized Latency = 15.6 sec

<16, 4> fixed type data used

Optimized Binding Results



```
================================================================
== Utilization Estimates
================================================================
* Summary:
+---------------------+---------+------+---------+--------+-----+
|         Name        | BRAM_18K| DSP  |    FF   |   LUT  | URAM|
+---------------------+---------+------+---------+--------+-----+
|DSP                  |        -|     -|        -|       -|    -|
|Expression           |        -|     -|        0|     284|    -|
|FIFO                 |        -|     -|        -|       -|    -|
|Instance             |      666|   212|    27459|   50412|    0|
|Memory               |     1194|     -|        0|       0|    0|
|Multiplexer          |        -|     -|        -|    4391|    -|
|Register             |        -|     -|      203|       -|    -|
+---------------------+---------+------+---------+--------+-----+
|Total                |     1860|   212|    27662|   55087|    0|
+---------------------+---------+------+---------+--------+-----+
|Available SLR        |     1440|  2280|   788160|  394080|  320|
+---------------------+---------+------+---------+--------+-----+
|Utilization SLR (%)  |      129|     9|        3|      13|    0|
+---------------------+---------+------+---------+--------+-----+
|Available            |     2880|  4560|  1576320|  788160|  640|
+---------------------+---------+------+---------+--------+-----+
|Utilization (%)      |       64|     4|        1|       6|    0|
+---------------------+---------+------+---------+--------+-----+
```

Product family: virtexuplus
Target device: xqvu7p-flra2104-1-I

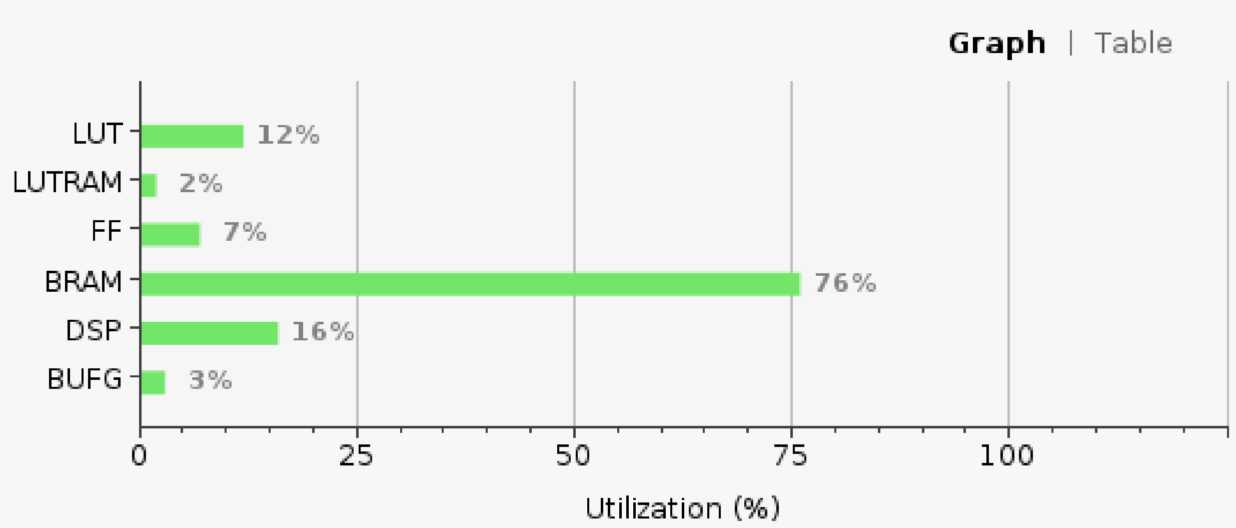
Optimized Latency =1.877 sec

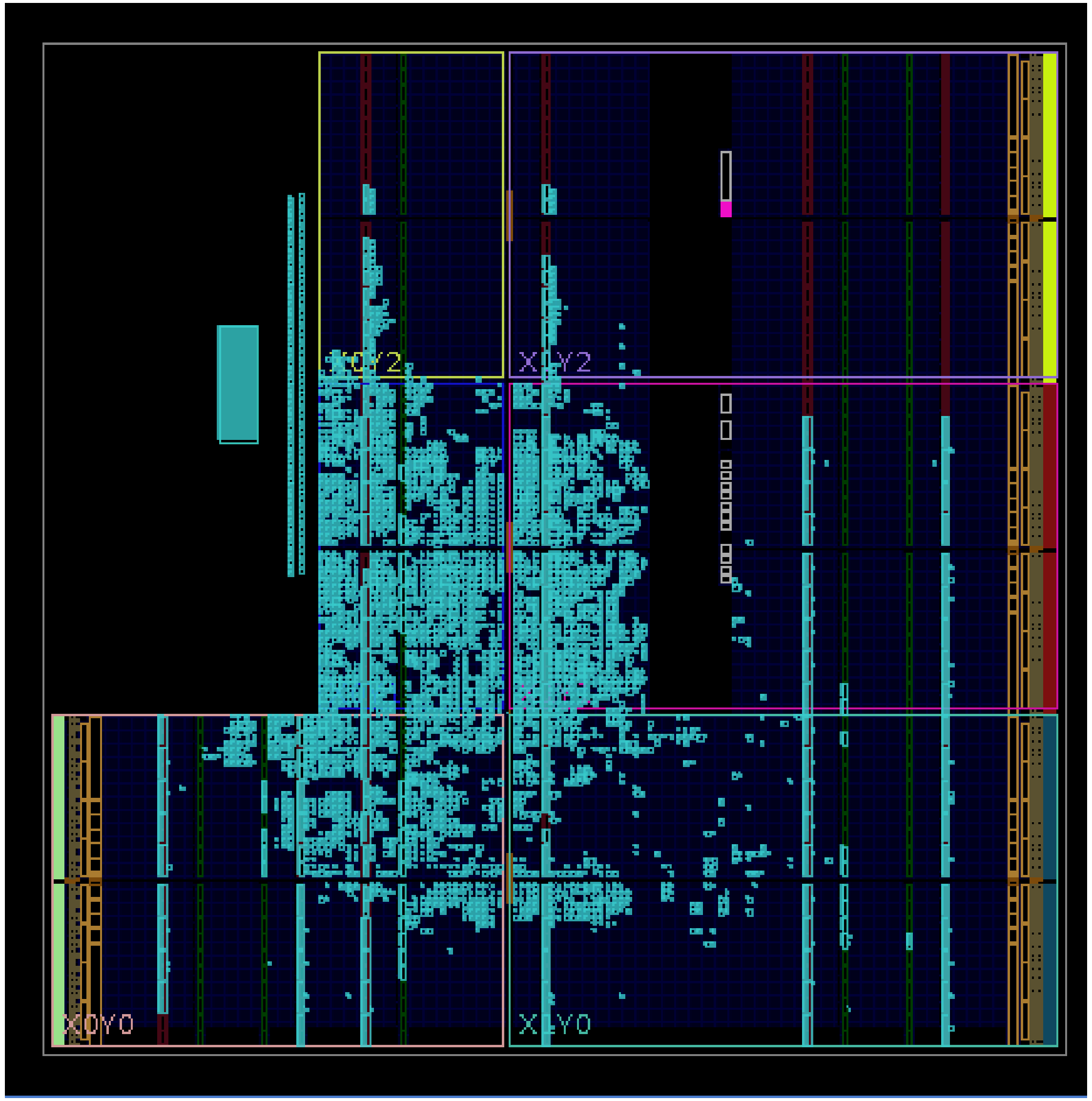
Speedup = 15.6/ 1.877
= 8.3x

<16, 4> fixed type data used

Deployment

Successfully deployed CONV1 on Pynq-Z2 (xc7z020clg400-1)





DSE and Learnings

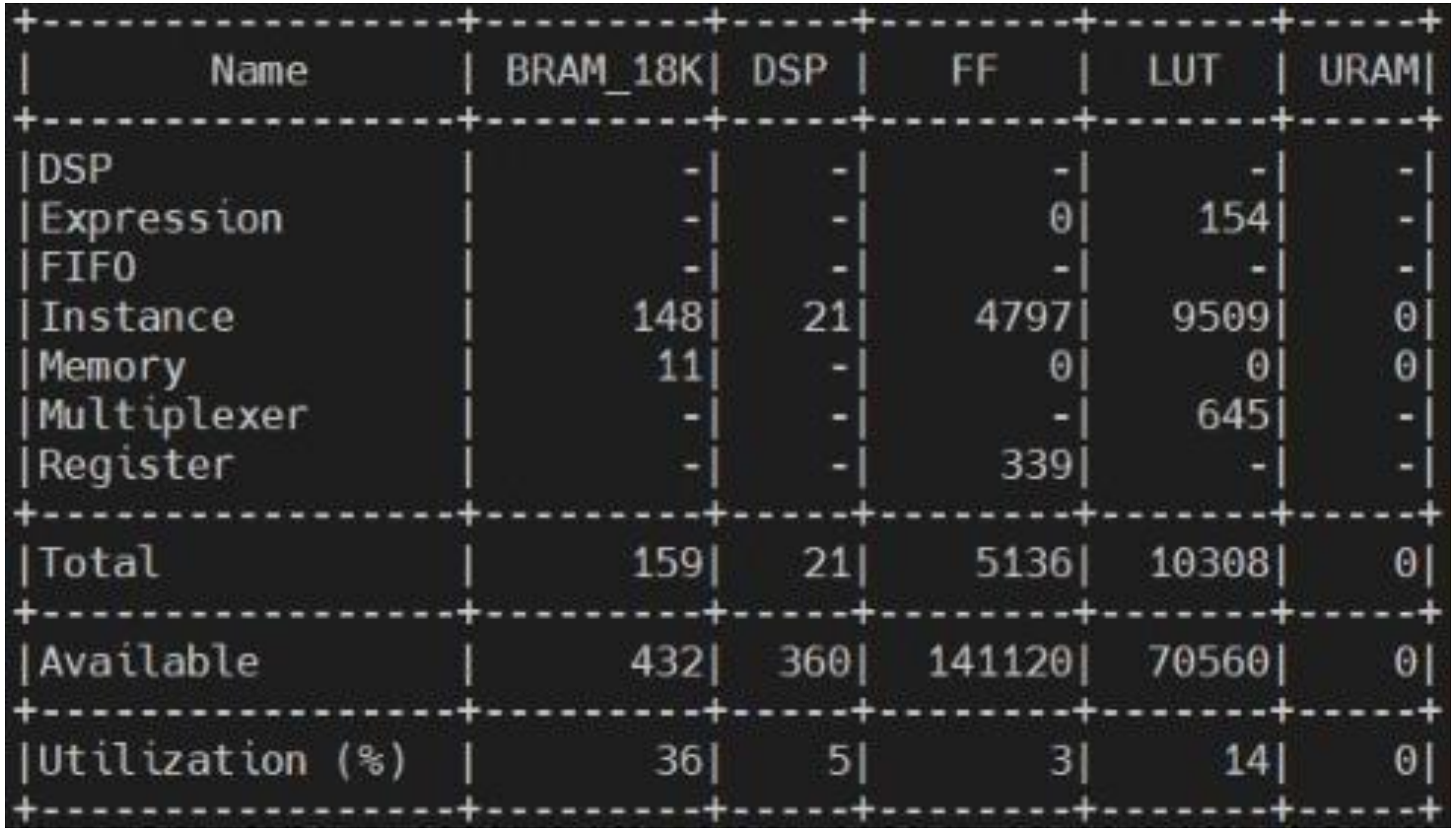
- Data Quantization
  - Tested different fixed type dimensions <16,x>, <32,x>
  - Checked the latency, utilization, accuracy
  - Used <16,4> for binding layers.

- On board storage
  - FPGA resources limited
  - During binding, could not store intermediate outputs on board (sacrificed latency)

- Used "hls_math.h" library for synthesis of LRN and FC3 layer on the Vitis HLS tool.

Thank You

Appendix – conv1 <16,4>



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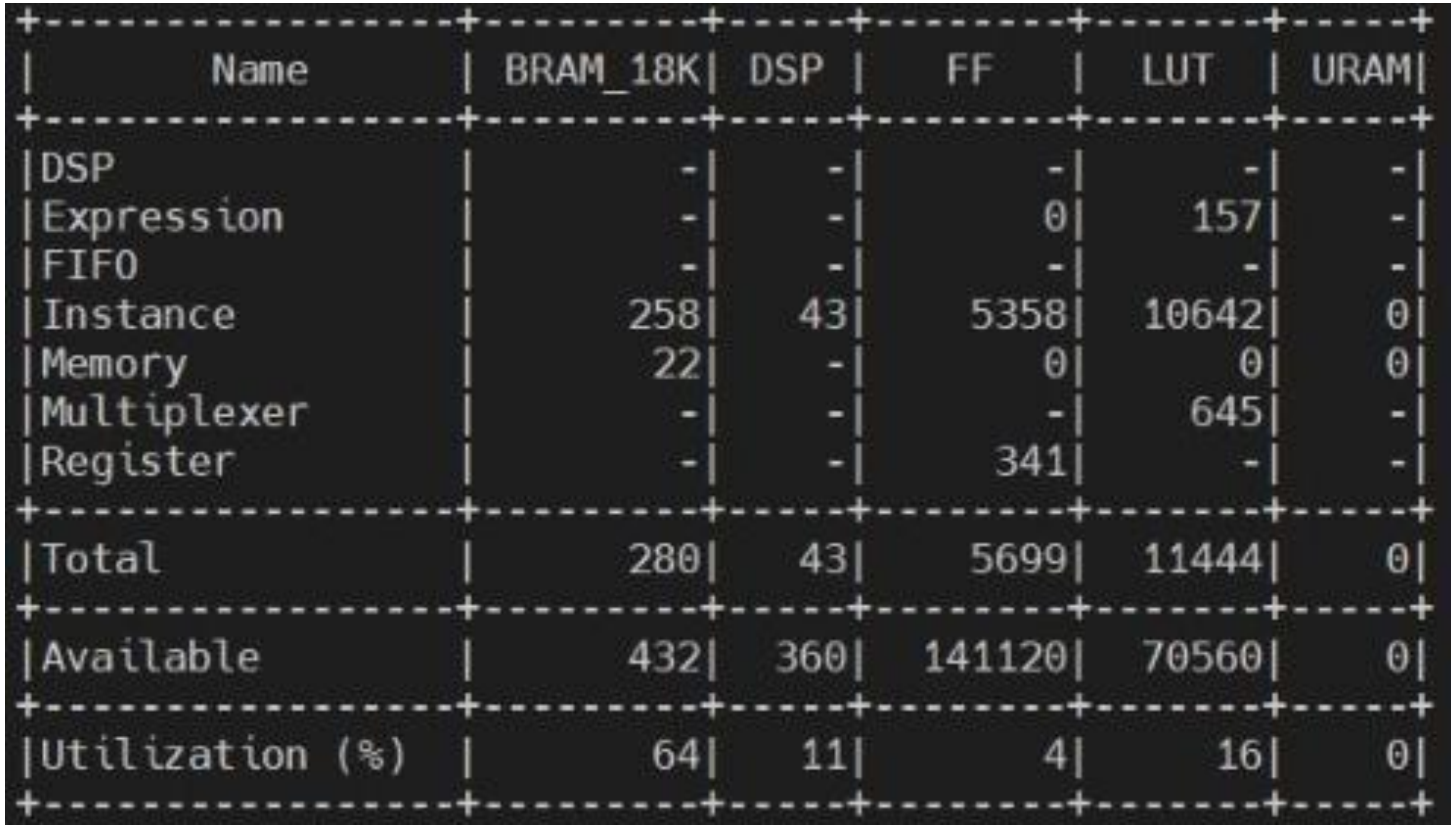
+-----------------+---------+-----+--------+-------+-----+
|       Name      | BRAM_18K| DSP |   FF   |  LUT  | URAM|
+-----------------+---------+-----+--------+-------+-----+
|DSP              |        -|    -|       -|      -|    -|
|Expression       |        -|    -|       0|    154|    -|
|FIFO             |        -|    -|       -|      -|    -|
|Instance         |      148|   21|    4797|   9509|    0|
|Memory           |       11|    -|       0|      0|    0|
|Multiplexer      |        -|    -|       -|    645|    -|
|Register         |        -|    -|     339|      -|    -|
+-----------------+---------+-----+--------+-------+-----+
|Total            |      159|   21|    5136|  10308|    0|
+-----------------+---------+-----+--------+-------+-----+
|Available        |      432|  360|  141120|  70560|    0|
+-----------------+---------+-----+--------+-------+-----+
|Utilization (%)  |       36|    5|       3|     14|    0|
+-----------------+---------+-----+--------+-------+-----+
```

Appendix – conv1 <32,8>



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+-----------------+---------+-----+--------+-------+-----+
|       Name      | BRAM_18K| DSP |   FF   |  LUT  | URAM|
+-----------------+---------+-----+--------+-------+-----+
|DSP              |        -|    -|       -|      -|    -|
|Expression       |        -|    -|       0|    157|    -|
|FIFO             |        -|    -|       -|      -|    -|
|Instance         |      258|   43|    5358|  10642|    0|
|Memory           |       22|    -|       0|      0|    0|
|Multiplexer      |        -|    -|       -|    645|    -|
|Register         |        -|    -|     341|      -|    -|
+-----------------+---------+-----+--------+-------+-----+
|Total            |      280|   43|    5699|  11444|    0|
+-----------------+---------+-----+--------+-------+-----+
|Available        |      432|  360|  141120|  70560|    0|
+-----------------+---------+-----+--------+-------+-----+
|Utilization (%)  |       64|   11|       4|     16|    0|
+-----------------+---------+-----+--------+-------+-----+
```
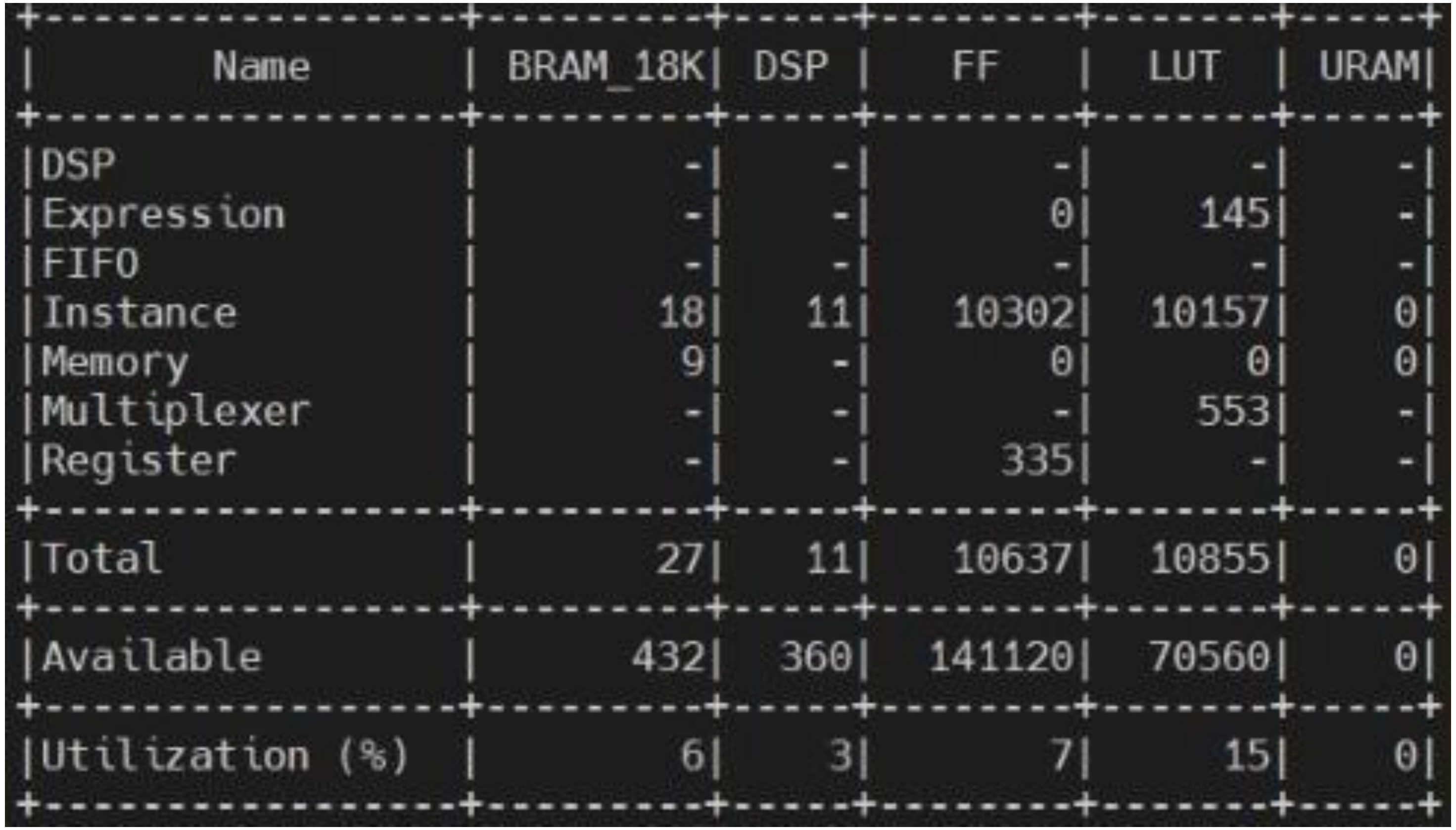

Appendix – conv2



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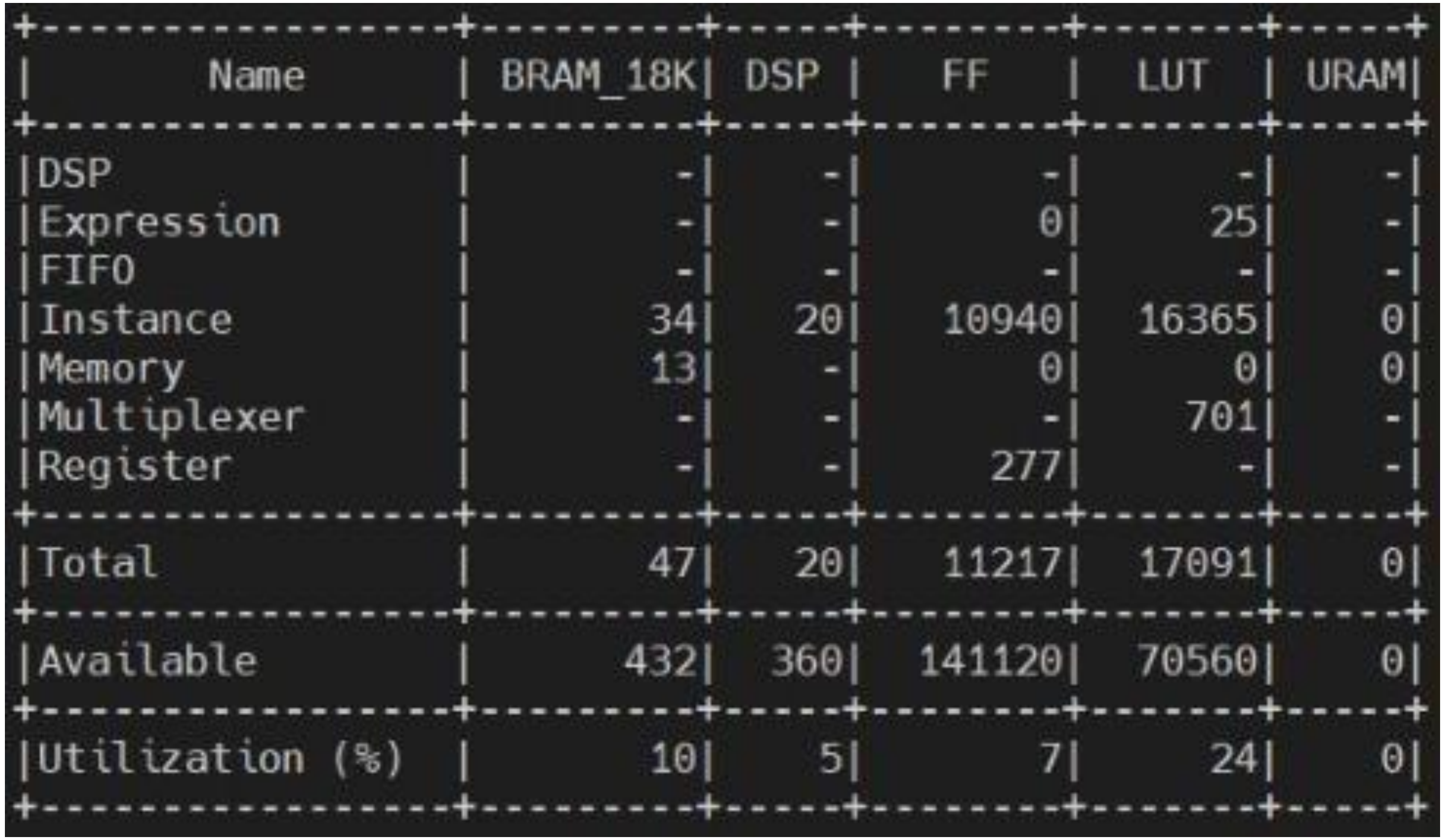
+-----------------+---------+-----+--------+-------+-----+
|       Name      | BRAM_18K| DSP |   FF   |  LUT  | URAM|
+-----------------+---------+-----+--------+-------+-----+
|DSP              |        -|    -|       -|      -|    -|
|Expression       |        -|    -|       0|    145|    -|
|FIFO             |        -|    -|       -|      -|    -|
|Instance         |       18|   11|   10302|  10157|    0|
|Memory           |        9|    -|       0|      0|    0|
|Multiplexer      |        -|    -|       -|    553|    -|
|Register         |        -|    -|     335|      -|    -|
+-----------------+---------+-----+--------+-------+-----+
|Total            |       27|   11|   10637|  10855|    0|
+-----------------+---------+-----+--------+-------+-----+
|Available        |      432|  360|  141120|  70560|    0|
+-----------------+---------+-----+--------+-------+-----+
|Utilization (%)  |        6|    3|       7|     15|    0|
+-----------------+---------+-----+--------+-------+-----+
```

Appendix – conv3



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+-----------------+---------+-----+--------+-------+-----+
|       Name      | BRAM_18K| DSP |   FF   |  LUT  | URAM|
+-----------------+---------+-----+--------+-------+-----+
|DSP              |        -|    -|       -|      -|    -|
|Expression       |        -|    -|       0|     25|    -|
|FIFO             |        -|    -|       -|      -|    -|
|Instance         |       34|   20|   10940|  16365|    0|
|Memory           |       13|    -|       0|      0|    0|
|Multiplexer      |        -|    -|       -|    701|    -|
|Register         |        -|    -|     277|      -|    -|
+-----------------+---------+-----+--------+-------+-----+
|Total            |       47|   20|   11217|  17091|    0|
+-----------------+---------+-----+--------+-------+-----+
|Available        |      432|  360|  141120|  70560|    0|
+-----------------+---------+-----+--------+-------+-----+
|Utilization (%)  |       10|    5|       7|     24|    0|
+-----------------+---------+-----+--------+-------+-----+
```
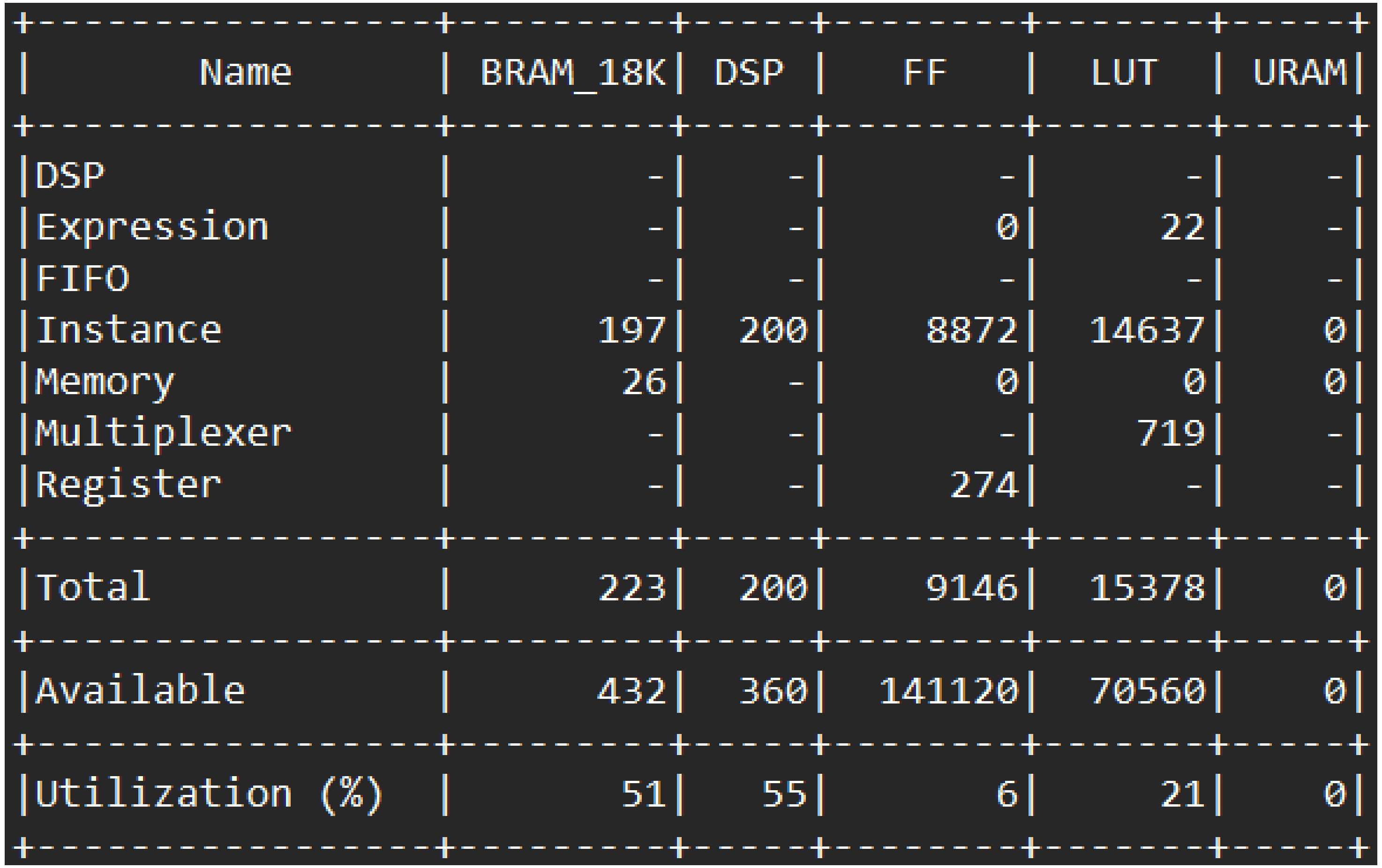
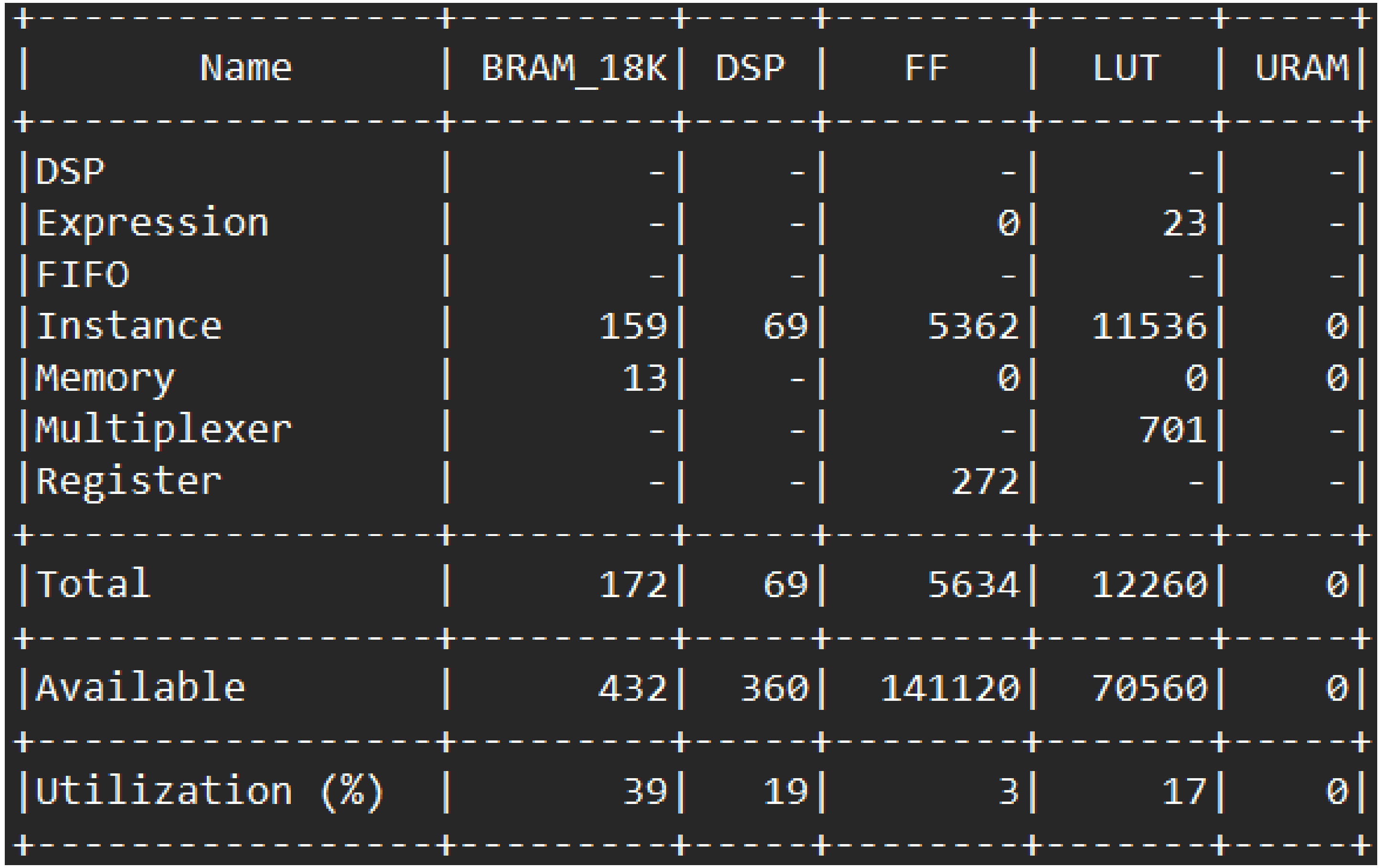

Appendix – conv4



```
+-----------------+---------+-----+--------+-------+-----+
|       Name      | BRAM_18K| DSP |   FF   |  LUT  | URAM|
+-----------------+---------+-----+--------+-------+-----+
|DSP              |        -|    -|       -|      -|    -|
|Expression       |        -|    -|       0|     22|    -|
|FIFO             |        -|    -|       -|      -|    -|
|Instance         |      197|  200|    8872|  14637|    0|
|Memory           |       26|    -|       0|      0|    0|
|Multiplexer      |        -|    -|       -|    719|    -|
|Register         |        -|    -|     274|      -|    -|
+-----------------+---------+-----+--------+-------+-----+
|Total            |      223|  200|    9146|  15378|    0|
+-----------------+---------+-----+--------+-------+-----+
|Available        |      432|  360|  141120|  70560|    0|
+-----------------+---------+-----+--------+-------+-----+
|Utilization (%)  |       51|   55|       6|     21|    0|
+-----------------+---------+-----+--------+-------+-----+
```

Appendix – conv5



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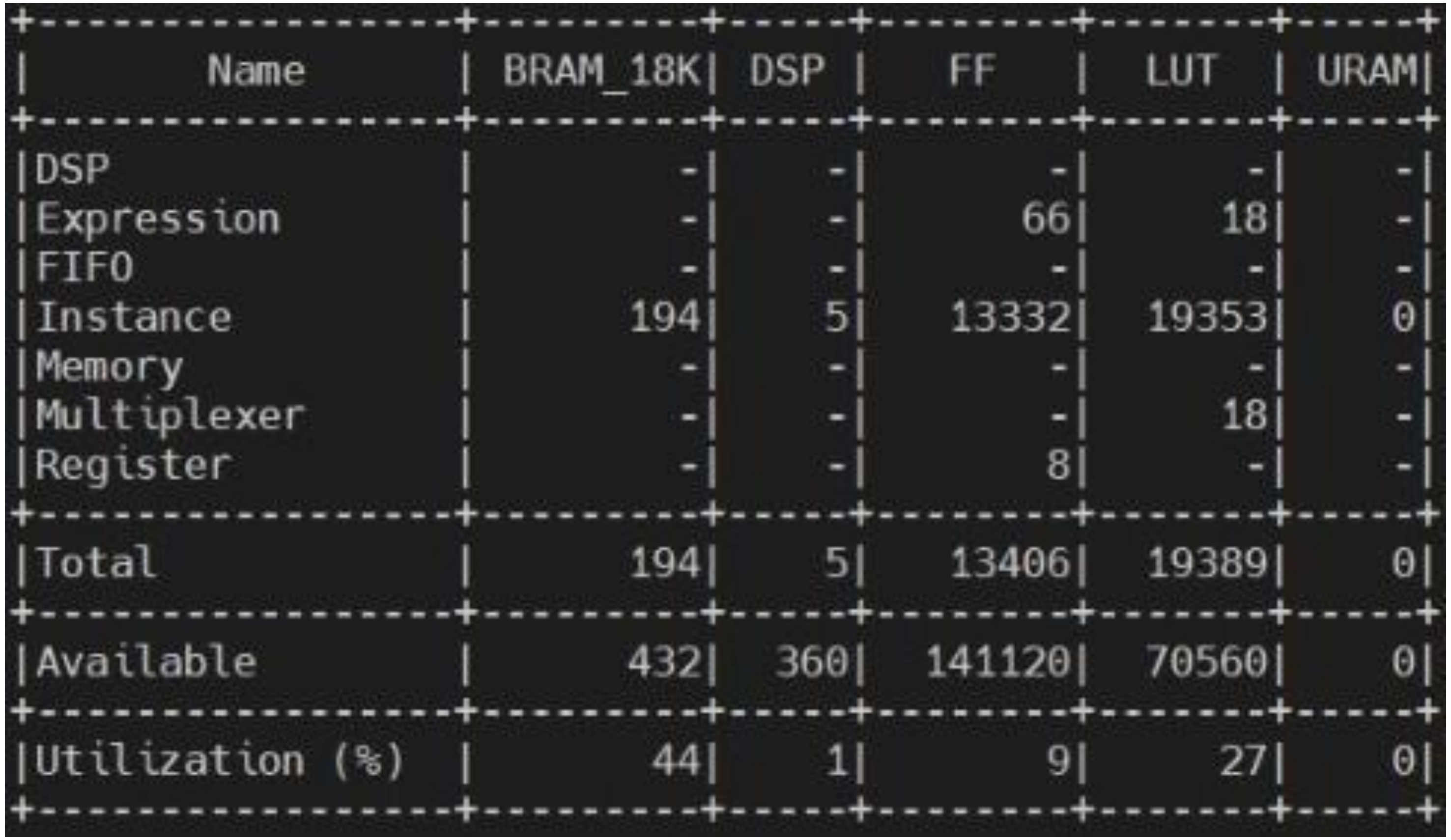
+-----------------+---------+-----+--------+-------+-----+
|       Name      | BRAM_18K| DSP |   FF   |  LUT  | URAM|
+-----------------+---------+-----+--------+-------+-----+
|DSP              |        -|    -|       -|      -|    -|
|Expression       |        -|    -|       0|     23|    -|
|FIFO             |        -|    -|       -|      -|    -|
|Instance         |      159|   69|    5362|  11536|    0|
|Memory           |       13|    -|       0|      0|    0|
|Multiplexer      |        -|    -|       -|    701|    -|
|Register         |        -|    -|     272|      -|    -|
+-----------------+---------+-----+--------+-------+-----+
|Total            |      172|   69|    5634|  12260|    0|
+-----------------+---------+-----+--------+-------+-----+
|Available        |      432|  360|  141120|  70560|    0|
+-----------------+---------+-----+--------+-------+-----+
|Utilization (%)  |       39|   19|       3|     17|    0|
+-----------------+---------+-----+--------+-------+-----+
```

Appendix – maxpool1



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+-----------------+---------+-----+--------+-------+-----+
|       Name      | BRAM_18K| DSP |   FF   |  LUT  | URAM|
+-----------------+---------+-----+--------+-------+-----+
|DSP              |        -|    -|       -|      -|    -|
|Expression       |        -|    -|      66|     18|    -|
|FIFO             |        -|    -|       -|      -|    -|
|Instance         |      194|    5|   13332|  19353|    0|
|Memory           |        -|    -|       -|      -|    -|
|Multiplexer      |        -|    -|       -|     18|    -|
|Register         |        -|    -|       8|      -|    -|
+-----------------+---------+-----+--------+-------+-----+
|Total            |      194|    5|   13406|  19389|    0|
+-----------------+---------+-----+--------+-------+-----+
|Available        |      432|  360|  141120|  70560|    0|
+-----------------+---------+-----+--------+-------+-----+
|Utilization (%)  |       44|    1|       9|     27|    0|
+-----------------+---------+-----+--------+-------+-----+
```
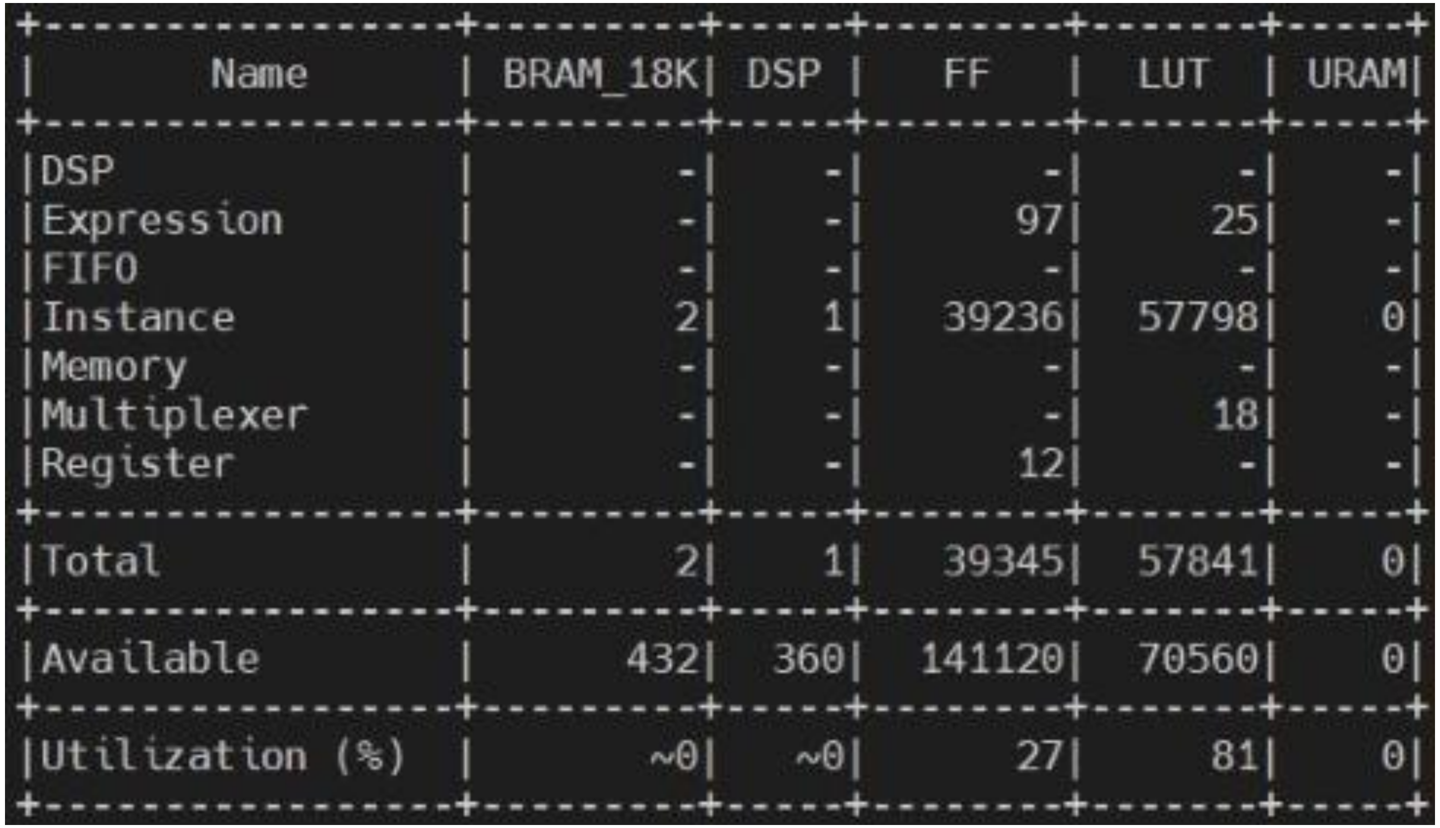

Appendix – maxpool2



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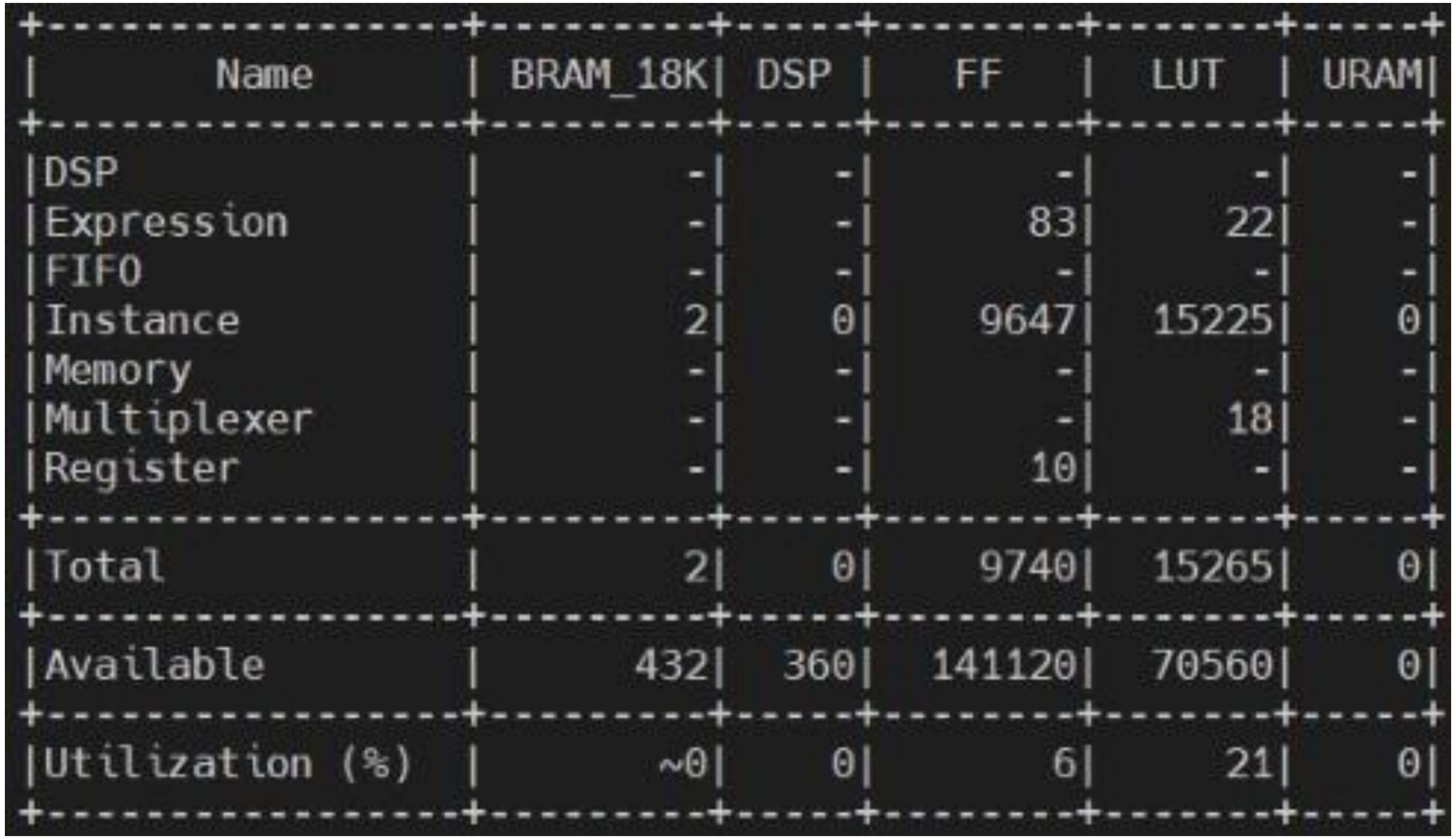
+-----------------+---------+-----+--------+-------+-----+
|       Name      | BRAM_18K| DSP |   FF   |  LUT  | URAM|
+-----------------+---------+-----+--------+-------+-----+
|DSP              |        -|    -|       -|      -|    -|
|Expression       |        -|    -|      97|     25|    -|
|FIFO             |        -|    -|       -|      -|    -|
|Instance         |        2|    1|   39236|  57798|    0|
|Memory           |        -|    -|       -|      -|    -|
|Multiplexer      |        -|    -|       -|     18|    -|
|Register         |        -|    -|      12|      -|    -|
+-----------------+---------+-----+--------+-------+-----+
|Total            |        2|    1|   39345|  57841|    0|
+-----------------+---------+-----+--------+-------+-----+
|Available        |      432|  360|  141120|  70560|    0|
+-----------------+---------+-----+--------+-------+-----+
|Utilization (%)  |       ~0|   ~0|      27|     81|    0|
+-----------------+---------+-----+--------+-------+-----+
```

Appendix – maxpool5



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+-----------------+---------+-----+--------+-------+-----+
|       Name      | BRAM_18K| DSP |   FF   |  LUT  | URAM|
+-----------------+---------+-----+--------+-------+-----+
|DSP              |        -|    -|       -|      -|    -|
|Expression       |        -|    -|      83|     22|    -|
|FIFO             |        -|    -|       -|      -|    -|
|Instance         |        2|    0|    9647|  15225|    0|
|Memory           |        -|    -|       -|      -|    -|
|Multiplexer      |        -|    -|       -|     18|    -|
|Register         |        -|    -|      10|      -|    -|
+-----------------+---------+-----+--------+-------+-----+
|Total            |        2|    0|    9740|  15265|    0|
+-----------------+---------+-----+--------+-------+-----+
|Available        |      432|  360|  141120|  70560|    0|
+-----------------+---------+-----+--------+-------+-----+
|Utilization (%)  |       ~0|    0|       6|     21|    0|
+-----------------+---------+-----+--------+-------+-----+
```
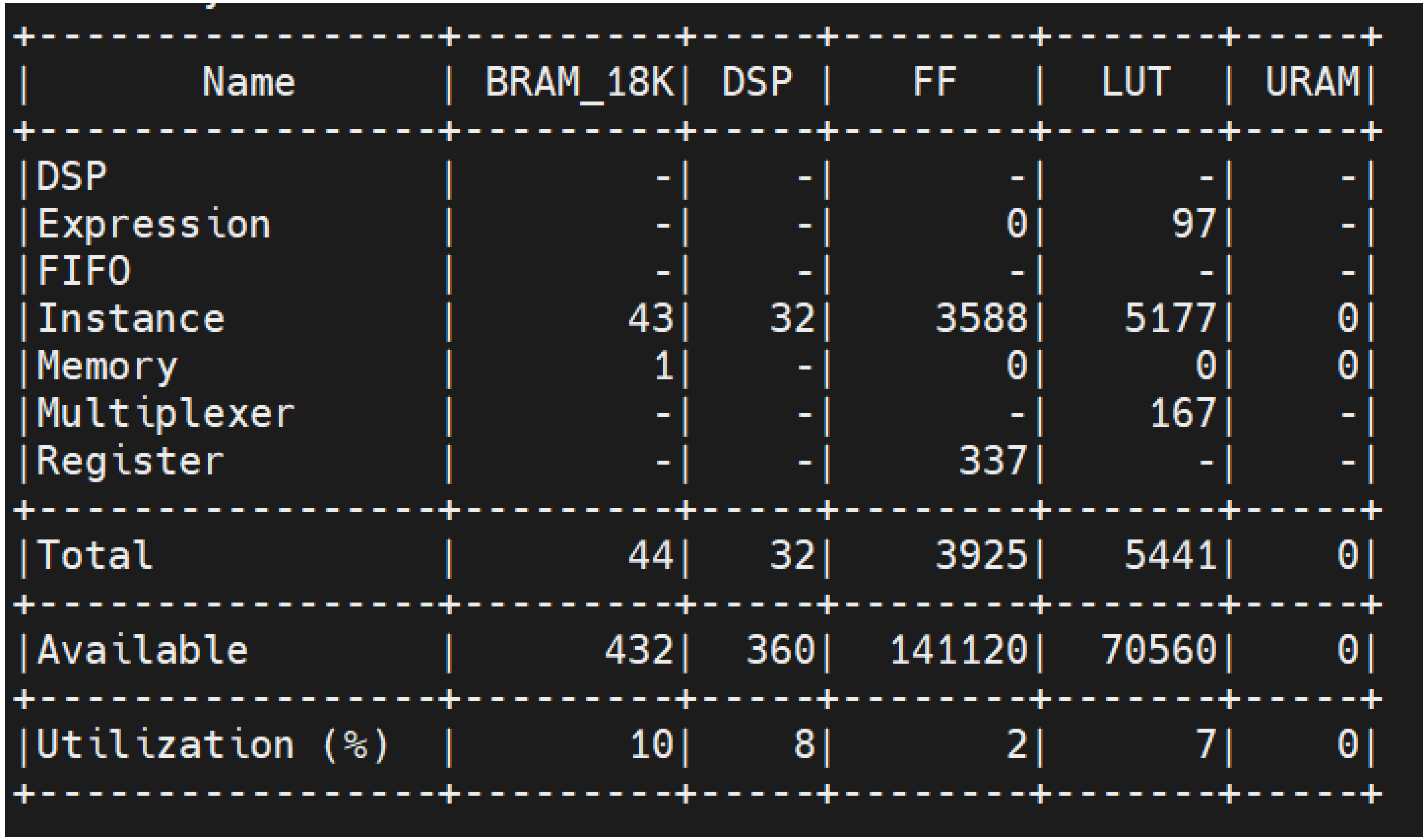
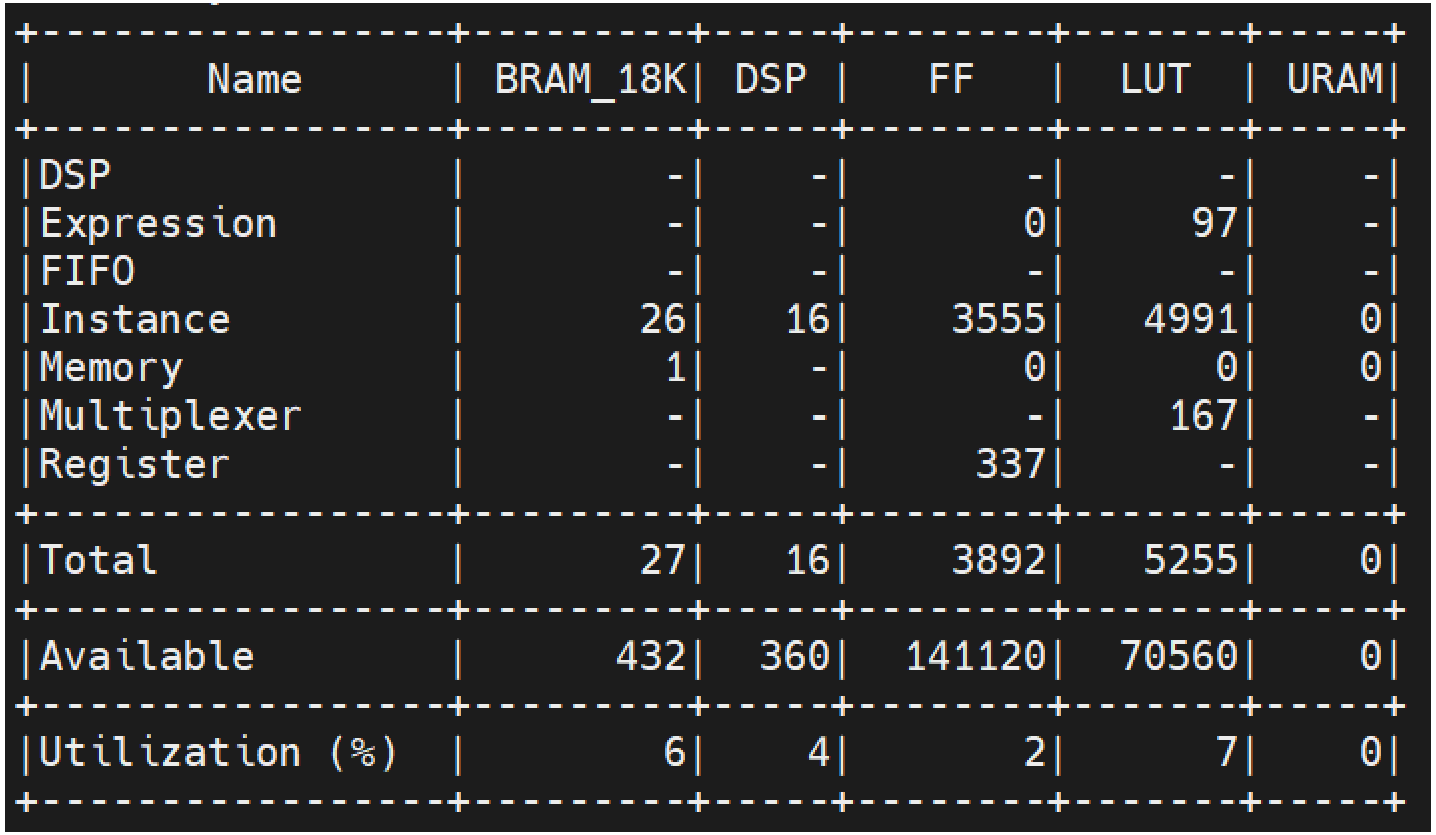

Appendix – fc1



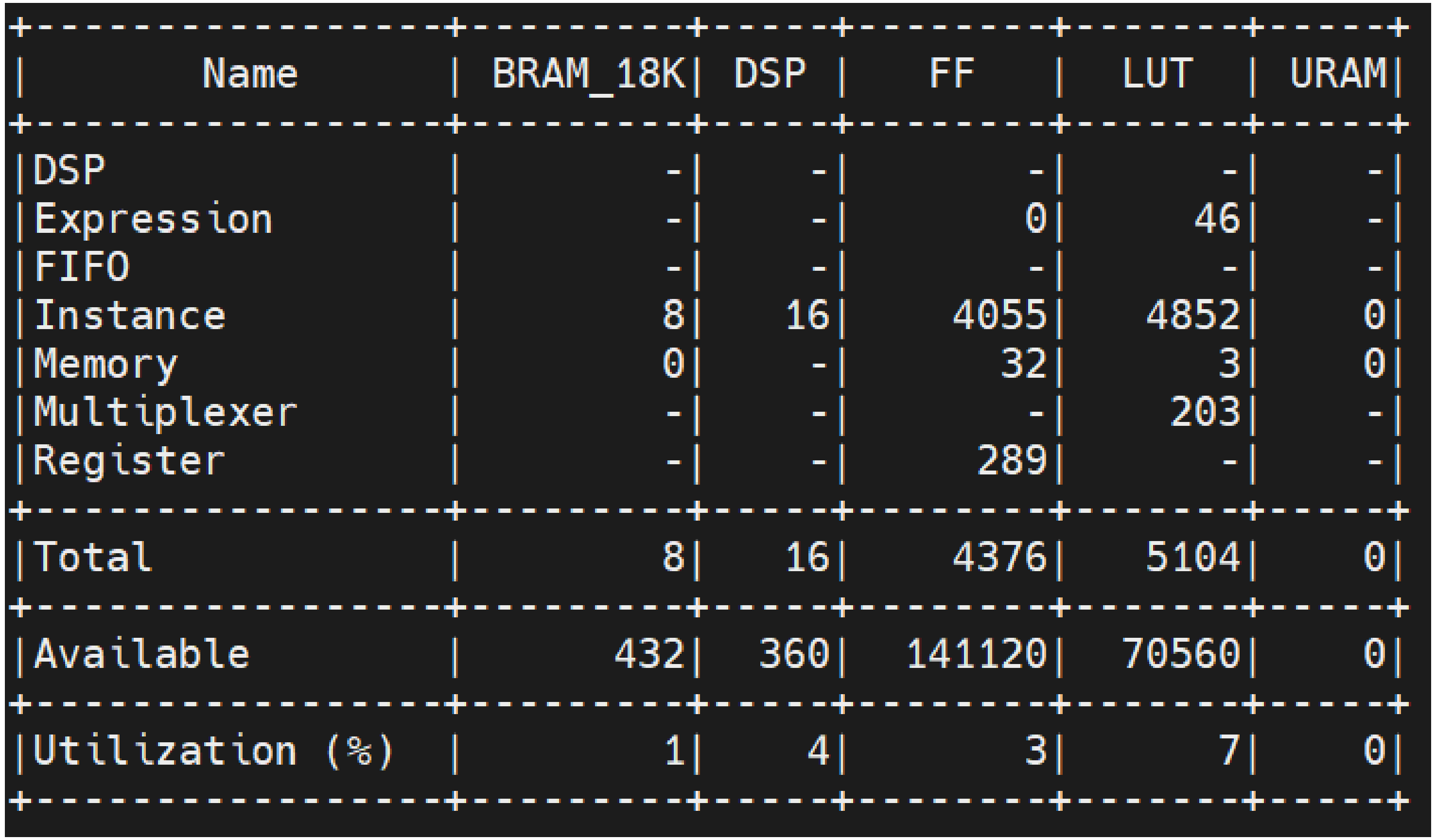
```
+-----------------+---------+-----+--------+-------+-----+
|       Name      | BRAM_18K| DSP |   FF   |  LUT  | URAM|
+-----------------+---------+-----+--------+-------+-----+
|DSP              |        -|    -|       -|      -|    -|
|Expression       |        -|    -|       0|     97|    -|
|FIFO             |        -|    -|       -|      -|    -|
|Instance         |       43|   32|    3588|   5177|    0|
|Memory           |        1|    -|       0|      0|    0|
|Multiplexer      |        -|    -|       -|    167|    -|
|Register         |        -|    -|     337|      -|    -|
+-----------------+---------+-----+--------+-------+-----+
|Total            |       44|   32|    3925|   5441|    0|
+-----------------+---------+-----+--------+-------+-----+
|Available        |      432|  360|  141120|  70560|    0|
+-----------------+---------+-----+--------+-------+-----+
|Utilization (%)  |       10|    8|       2|      7|    0|
+-----------------+---------+-----+--------+-------+-----+
```

Appendix – fc2



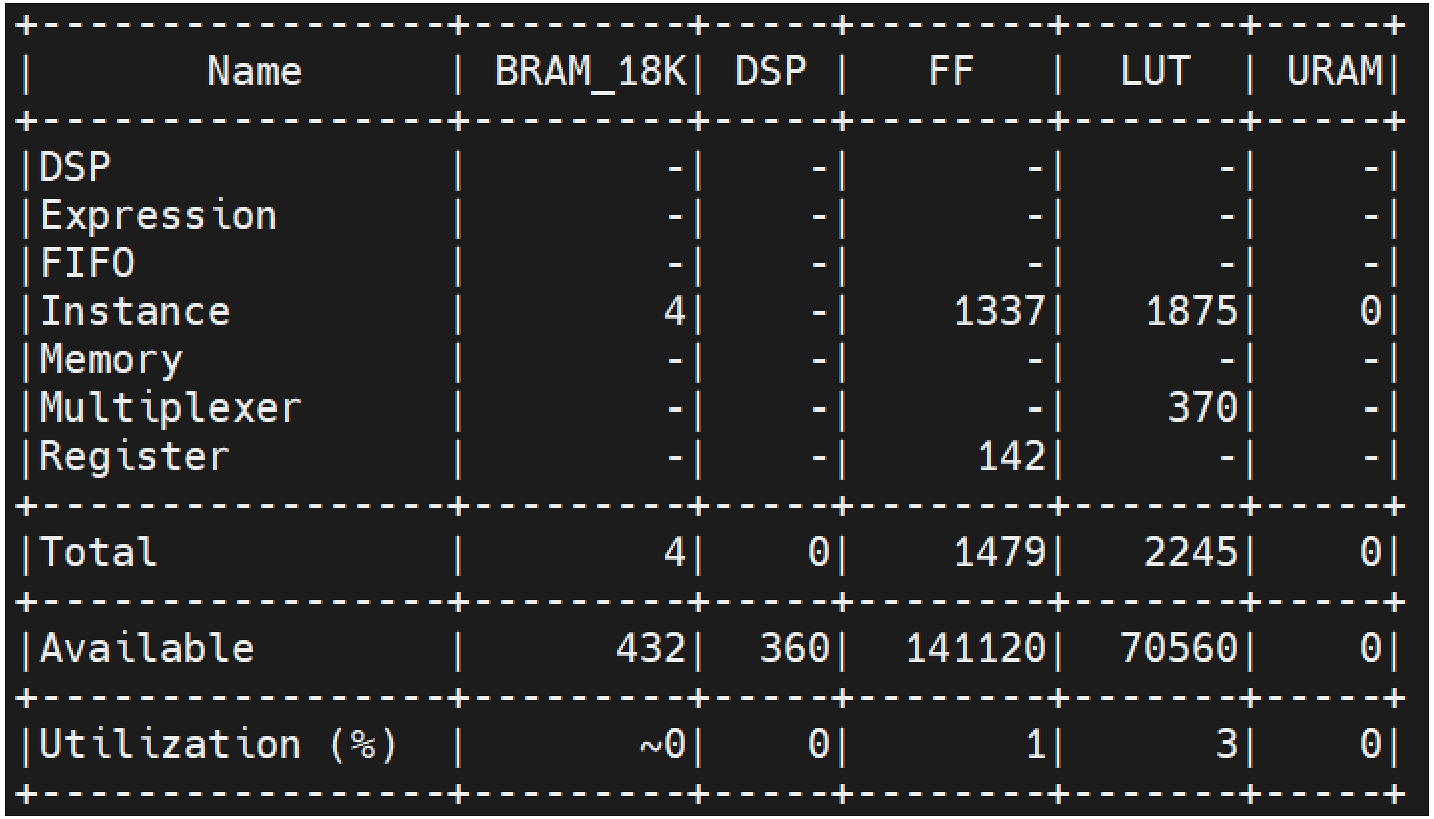
```
+-----------------+---------+-----+--------+-------+-----+
|       Name      | BRAM_18K| DSP |   FF   |  LUT  | URAM|
+-----------------+---------+-----+--------+-------+-----+
|DSP              |        -|    -|       -|      -|    -|
|Expression       |        -|    -|       0|     97|    -|
|FIFO             |        -|    -|       -|      -|    -|
|Instance         |       26|   16|    3555|   4991|    0|
|Memory           |        1|    -|       0|      0|    0|
|Multiplexer      |        -|    -|       -|    167|    -|
|Register         |        -|    -|     337|      -|    -|
+-----------------+---------+-----+--------+-------+-----+
|Total            |       27|   16|    3892|   5255|    0|
+-----------------+---------+-----+--------+-------+-----+
|Available        |      432|  360|  141120|  70560|    0|
+-----------------+---------+-----+--------+-------+-----+
|Utilization (%)  |        6|    4|       2|      7|    0|
+-----------------+---------+-----+--------+-------+-----+
```

Appendix – fc3



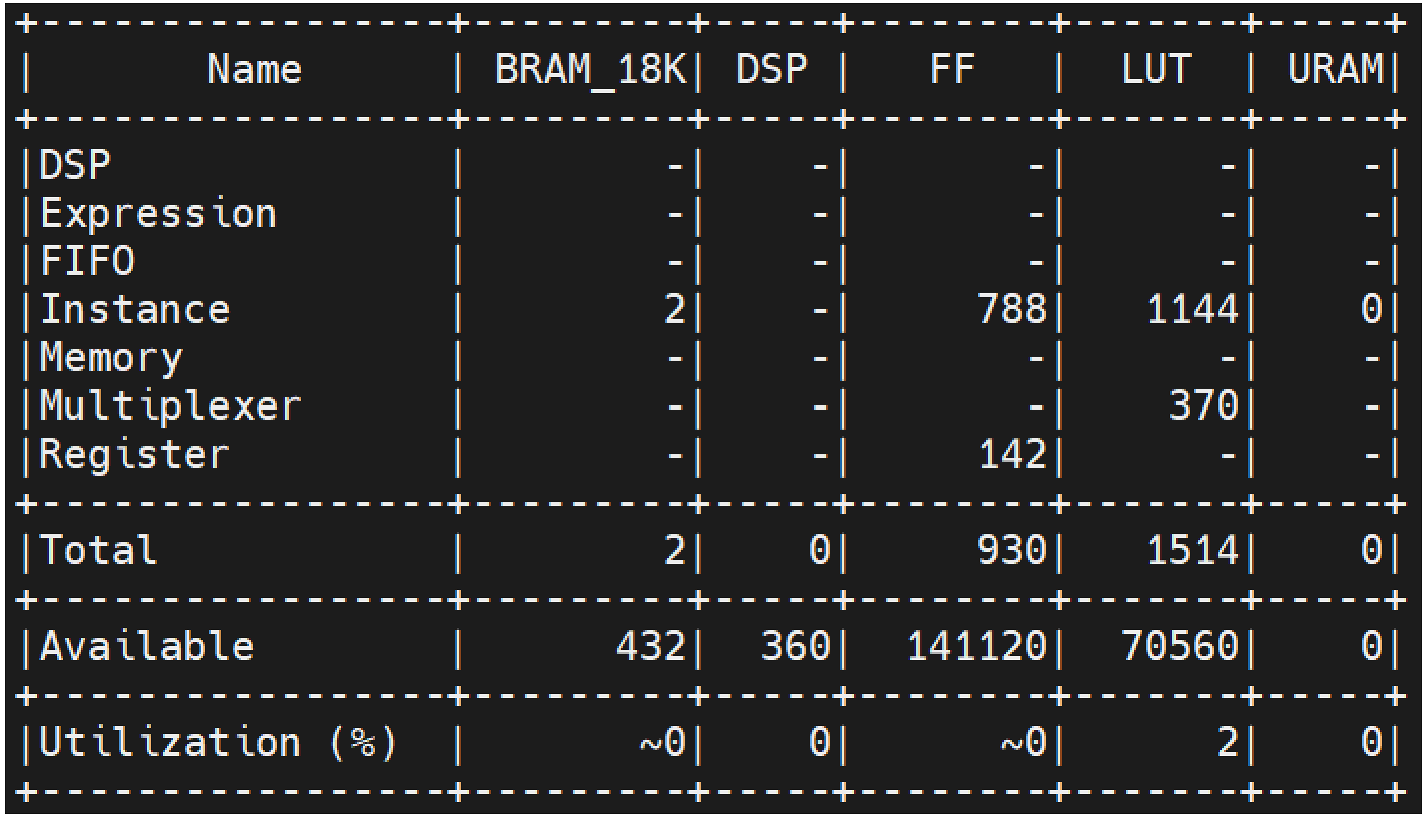
```
+-----------------+---------+-----+--------+-------+-----+
|       Name      | BRAM_18K| DSP |   FF   |  LUT  | URAM|
+-----------------+---------+-----+--------+-------+-----+
|DSP              |        -|    -|       -|      -|    -|
|Expression       |        -|    -|       0|     46|    -|
|FIFO             |        -|    -|       -|      -|    -|
|Instance         |        8|   16|    4055|   4852|    0|
|Memory           |        0|    -|      32|      3|    0|
|Multiplexer      |        -|    -|       -|    203|    -|
|Register         |        -|    -|     289|      -|    -|
+-----------------+---------+-----+--------+-------+-----+
|Total            |        8|   16|    4376|   5104|    0|
+-----------------+---------+-----+--------+-------+-----+
|Available        |      432|  360|  141120|  70560|    0|
+-----------------+---------+-----+--------+-------+-----+
|Utilization (%)  |        1|    4|       3|      7|    0|
+-----------------+---------+-----+--------+-------+-----+
```

Appendix – lrn1



```
+-----------------+---------+-----+--------+-------+-----+
|       Name      | BRAM_18K| DSP |   FF   |  LUT  | URAM|
+-----------------+---------+-----+--------+-------+-----+
|DSP              |        -|    -|       -|      -|    -|
|Expression       |        -|    -|       -|      -|    -|
|FIFO             |        -|    -|       -|      -|    -|
|Instance         |        4|    -|    1337|   1875|    0|
|Memory           |        -|    -|       -|      -|    -|
|Multiplexer      |        -|    -|       -|    370|    -|
|Register         |        -|    -|     142|      -|    -|
+-----------------+---------+-----+--------+-------+-----+
|Total            |        4|    0|    1479|   2245|    0|
+-----------------+---------+-----+--------+-------+-----+
|Available        |      432|  360|  141120|  70560|    0|
+-----------------+---------+-----+--------+-------+-----+
|Utilization (%)  |       ~0|    0|       1|      3|    0|
+-----------------+---------+-----+--------+-------+-----+
```

Appendix – lrn2



```
+-----------------+---------+-----+--------+-------+-----+
|       Name      | BRAM_18K| DSP |   FF   |  LUT  | URAM|
+-----------------+---------+-----+--------+-------+-----+
|DSP              |        -|    -|       -|      -|    -|
|Expression       |        -|    -|       -|      -|    -|
|FIFO             |        -|    -|       -|      -|    -|
|Instance         |        2|    -|     788|   1144|    0|
|Memory           |        -|    -|       -|      -|    -|
|Multiplexer      |        -|    -|       -|    370|    -|
|Register         |        -|    -|     142|      -|    -|
+-----------------+---------+-----+--------+-------+-----+
|Total            |        2|    0|     930|   1514|    0|
+-----------------+---------+-----+--------+-------+-----+
|Available        |      432|  360|  141120|  70560|    0|
+-----------------+---------+-----+--------+-------+-----+
|Utilization (%)  |       ~0|    0|      ~0|      2|    0|
+-----------------+---------+-----+--------+-------+-----+
```