

# CS5222 Project 2

## Custom Acceleration with FPGAs

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### Abstract

In this project, I'm going to port the lab to **PYNQ 2.7** and **Vivado/Vitis 2020.2**. The experiment is done on ASUS RS500-E8-PS4 V2, with operating system Ubuntu 20.04.4 LTS (GNU/Linux 5.4.0-100-generic x86\_64).

## 1 Matrix Multiplication Pipeline Optimization in HLS

### 1.1 Understanding the baseline matrix multiply (background)

For Vitis 2020.2, the command used should be

```
$ vitis_hls -f hls.tcl
```

The loop details report generated by HLS (as in [Table 1a](#)) shows that some pipelining has already been done automatically by Vitis HLS. After inspecting the migration guide, I added two lines in the `hls.tcl`:

```
config_compile -pipeline_loops 0  
set_clock_uncertainty 12.5%
```

The performance and utilization estimates of the two profiles, together with those for the following profiles, are reported in [Table 6](#). The new loop details is as [Table 1b](#). It turns out that the overall performance is a little bit worse than documented. This is because every iteration in L3 loop takes 11 cycles and thus 2816 cycles in total to perform a single inner product.

The overall latency of the baseline is 228022 cycles. Since it only predicts on a batch of 8 inputs, the normalized latency is 28502.75 cycles.

### 1.2 Pipelining in HLS (8 marks)

The work in this section is done with auto pipelining disabled.

#### 1.2.1 Pipelining the L3 (innermost) loop

The code is modified as [Figure 1](#). As reported in [Table 3](#), pipelining L3 reduces its latency from 2816 cycles to 1031 cycles. The L1 is flattened, but L2 cannot be flattened because L2 is not a perfect loop. Thus the result has 2-layer loops where the outer layer has 80 iterations, and the inner layer has 256 iterations. This design utilizes slightly more resources but no more floating-point adders or multipliers. The overall latency is 85286 cycles, which is about 2.67x speedup. Other statistics in detail can be found in [Table 6](#).

#### 1.2.2 Pipelining the L2 loop

The code is modified as [Figure 2a](#). As reported in [Table 4a](#), pipelining the loop body of L2 unrolls L3 and flattens L1. The design introduced parallelism, which uses 16 adders and 16 multipliers. The overall latency is reduced to 7341 cycles, which is about 31.1x speedup relative to the baseline. The initiation interval has increased to 128 cycles, which is pretty heavy. Other statistics in detail can be found in [Table 6](#).

Table 1: Loop details for baseline

(a) Baseline with automatic pipelining

| Loop Name             | Latency (cycles) |       | Iteration<br>Latency | Initiation Interval |        | Trip<br>Count | Pipelined |
|-----------------------|------------------|-------|----------------------|---------------------|--------|---------------|-----------|
|                       | min              | max   |                      | achieved            | target |               |           |
| - LOAD_OFF_1          | 5                | 5     | 1                    | 1                   | 1      | 5             | yes       |
| - LOAD_W_1_LOAD_W_2   | 1280             | 1280  | 1                    | 1                   | 1      | 1280          | yes       |
| - LOAD_I_1_LOAD_I_2   | 1024             | 1024  | 1                    | 1                   | 1      | 1024          | yes       |
| - L1_L2               | 82800            | 82800 | 1035                 | -                   | -      | 80            | no        |
| + L3                  | 1031             | 1031  | 12                   | 4                   | 1      | 256           | yes       |
| - STORE_O_1_STORE_O_2 | 42               | 42    | 4                    | 1                   | 1      | 40            | yes       |

(b) Baseline without automatic pipelining

| Loop Name    | Latency (cycles) |        | Iteration<br>Latency | Initiation Interval |        | Trip<br>Count | Pipelined |
|--------------|------------------|--------|----------------------|---------------------|--------|---------------|-----------|
|              | min              | max    |                      | achieved            | target |               |           |
| - LOAD_OFF_1 | 5                | 5      | 1                    | -                   | -      | 5             | no        |
| - LOAD_W_1   | 1300             | 1300   | 130                  | -                   | -      | 10            | no        |
| + LOAD_W_2   | 128              | 128    | 1                    | -                   | -      | 128           | no        |
| - LOAD_I_1   | 1040             | 1040   | 130                  | -                   | -      | 8             | no        |
| + LOAD_I_2   | 128              | 128    | 1                    | -                   | -      | 128           | no        |
| - L1         | 225536           | 225536 | 28192                | -                   | -      | 8             | no        |
| + L2         | 28190            | 28190  | 2819                 | -                   | -      | 10            | no        |
| ++ L3        | 2816             | 2816   | 11                   | -                   | -      | 256           | no        |
| - STORE_O_1  | 136              | 136    | 17                   | -                   | -      | 8             | no        |
| + STORE_O_2  | 15               | 15     | 3                    | -                   | -      | 5             | no        |

Table 2: Loop details for baseline of array partition

| Loop Name             | Latency (cycles) |       | Iteration<br>Latency | Initiation Interval |        | Trip<br>Count | Pipelined |
|-----------------------|------------------|-------|----------------------|---------------------|--------|---------------|-----------|
|                       | min              | max   |                      | achieved            | target |               |           |
| - LOAD_OFF_1          | 5                | 5     | 1                    | 1                   | 1      | 5             | yes       |
| - LOAD_W_1_LOAD_W_2   | 1280             | 1280  | 1                    | 1                   | 1      | 1280          | yes       |
| - LOAD_I_1_LOAD_I_2   | 1024             | 1024  | 1                    | 1                   | 1      | 1024          | yes       |
| - L1_L2               | 11398            | 11398 | 1287                 | 128                 | 1      | 80            | yes       |
| - STORE_O_1_STORE_O_2 | 42               | 42    | 4                    | 1                   | 1      | 40            | yes       |

```

@@ -78,6 +78,7 @@
    T tmp = offset_buf[j];
    L3:
      for (int k = 0; k < FEAT; k++) {
+#pragma HLS PIPELINE II = 1
        tmp += in_buf[i][k] * weight_buf[j][k];
      }
    out_buf[i][j] = tmp;

```

Figure 1: Inserting HLS directive for L3 Pipelining

An important observation is that the design can utilise 16 adders and 16 multipliers instead of being limited by the dual-port RAMs. The reason for that is Vitis HLS infers the RAM type as 1WnR, which is Multi-Ported Memory using Replication, and this type of memory has a single write port and multiple concurrent read ports.

Table 3: Loop details for L3 Pipelining

| Loop Name    | Latency (cycles) |       | Iteration Latency | Initiation Interval |        | Trip Count | Pipelined |
|--------------|------------------|-------|-------------------|---------------------|--------|------------|-----------|
|              | min              | max   |                   | achieved            | target |            |           |
| - LOAD_OFF_1 | 5                | 5     | 1                 | -                   | -      | 5          | no        |
| - LOAD_W_1   | 1300             | 1300  | 130               | -                   | -      | 10         | no        |
| + LOAD_W_2   | 128              | 128   | 1                 | -                   | -      | 128        | no        |
| - LOAD_I_1   | 1040             | 1040  | 130               | -                   | -      | 8          | no        |
| + LOAD_I_2   | 128              | 128   | 1                 | -                   | -      | 128        | no        |
| - L1_L2      | 82800            | 82800 | 1035              | -                   | -      | 80         | no        |
| + L3         | 1031             | 1031  | 12                | 4                   | 1      | 256        | yes       |
| - STORE_O_1  | 136              | 136   | 17                | -                   | -      | 8          | no        |
| + STORE_O_2  | 15               | 15    | 3                 | -                   | -      | 5          | no        |

Table 4: Loop details for L2 pipelining

(a) L2 pipelining with 1WnR memory

| Loop Name    | Latency (cycles) |      | Iteration Latency | Initiation Interval |        | Trip Count | Pipelined |
|--------------|------------------|------|-------------------|---------------------|--------|------------|-----------|
|              | min              | max  |                   | achieved            | target |            |           |
| - LOAD_OFF_1 | 5                | 5    | 1                 | -                   | -      | 5          | no        |
| - LOAD_W_1   | 2580             | 2580 | 258               | -                   | -      | 10         | no        |
| + LOAD_W_2   | 256              | 256  | 2                 | -                   | -      | 128        | no        |
| - LOAD_I_1   | 2064             | 2064 | 258               | -                   | -      | 8          | no        |
| + LOAD_I_2   | 256              | 256  | 2                 | -                   | -      | 128        | no        |
| - L1_L2      | 2550             | 2550 | 1287              | 16                  | 1      | 80         | yes       |
| - STORE_O_1  | 136              | 136  | 17                | -                   | -      | 8          | no        |
| + STORE_O_2  | 15               | 15   | 3                 | -                   | -      | 5          | no        |

(b) L2 Pipelining with T2P memory

| Loop Name    | Latency (cycles) |       | Iteration Latency | Initiation Interval |        | Trip Count | Pipelined |
|--------------|------------------|-------|-------------------|---------------------|--------|------------|-----------|
|              | min              | max   |                   | achieved            | target |            |           |
| - LOAD_OFF_1 | 5                | 5     | 1                 | -                   | -      | 5          | no        |
| - LOAD_W_1   | 1300             | 1300  | 130               | -                   | -      | 10         | no        |
| + LOAD_W_2   | 128              | 128   | 1                 | -                   | -      | 128        | no        |
| - LOAD_I_1   | 1040             | 1040  | 130               | -                   | -      | 8          | no        |
| + LOAD_I_2   | 128              | 128   | 1                 | -                   | -      | 128        | no        |
| - L1_L2      | 11398            | 11398 | 1287              | 128                 | 1      | 80         | yes       |
| - STORE_O_1  | 136              | 136   | 17                | -                   | -      | 8          | no        |
| + STORE_O_2  | 15               | 15    | 3                 | -                   | -      | 5          | no        |

INFO: [HLS 200-1457] Automatically inferring 1WnR RAM type for array 'weight\_buf'. Use bind\_storage pragma to overwrite if needed.

INFO: [HLS 200-1457] Automatically inferring 1WnR RAM type for array 'in\_buf'. Use bind\_storage pragma to overwrite if needed.

In order to prepare for the following memory partition optimization, the memory type should be forced to the dual-port (T2P) RAM as [Figure 2b](#). The result shows that the L2 pipelining with T2P RAM uses only two adders and two multipliers. The overall latency is 13885 cycles, which is a 16.4x improvement, which has already achieved the goal for this section. As the loop details in [Table 4b](#), the initiation interval is 128 cycles, which is slightly heavy.

```

@@ -74,6 +74,7 @@
    // Iterate over output classes
    L2:
        for (int j = 0; j < CLASSES; j++) {
+##pragma HLS PIPELINE II = 1
            // Perform the dot product
            T tmp = offset_buf[j];
        L3:

```

(a) Using 1WnR RAM

```

@@ -32,6 +32,11 @@
    T in_buf[BATCH][FEAT];
    T out_buf[BATCH][CLASSES];

+##pragma HLS bind_storage variable = offset_buf type = RAM_T2P
+##pragma HLS bind_storage variable = weight_buf type = RAM_T2P
+##pragma HLS bind_storage variable = in_buf type = RAM_T2P
+##pragma HLS bind_storage variable = out_buf type = RAM_T2P
+
    // Input and output AXI stream indices
    int is_idx = 0;
    int os_idx = 0;
@@ -74,6 +79,7 @@
    // Iterate over output classes
    L2:
        for (int j = 0; j < CLASSES; j++) {
+##pragma HLS PIPELINE II = 1
            // Perform the dot product
            T tmp = offset_buf[j];
        L3:

```

(b) Using T2P RAM

Figure 2: Inserting HLS directive for L2 Pipelining

### 1.2.3 Pipelining the L1 (outermost) loop

The code is modified as [Figure 3a](#). The loop details are in [Table 5a](#). Pipelining L1 makes both L2 and L3 completely unrolled, which makes there only one loop with 8 iterations. The unrolled loop body is heavily paralleled **with 1WnR memory used**, which make use of 160 floating-point adders and 160 floating-point multipliers. The parallelism reduces the latency for one equivalent iteration from 28192 cycles to 1291 cycles. The pipelining further reduce the latency for L1 to 1402 cycles, although there are eight iterations. The overall latency is 6193 cycles, about 36.82x speedup relative to L3 pipelining and 2.22x speedup compared to L2 pipelining. Other statistics in detail can be found in [Table 6](#).

Although L1 pipelining with 1WnR memory achieves some speedup compared to L2 pipelining, it takes 299.1 seconds to complete the whole building process, while the time used for L2 pipelining is only 62.5 seconds. At the same time, the hardware resource usage has exceeded those available on board.

As we did in [Section 1.2.2](#), we try using dual-port memory as well. The code is modified as [Figure 3b](#). The result shows that both overall latency and resource usage are lower than using 1WnR. That is good, but the usage of FF and LUT still exceeds the resource budget. That might be due to the 20 adders and 20 multipliers, but I failed to figure out how the computation units are used since dual-port memory is used. As in [Table 5b](#), the initiation interval is 128 cycles.

## 1.3 Increasing Pipeline Parallelism by Repartitioning Memories (8 marks)

The work in this section is based on L2 pipelining with auto pipelining enabled using T2P memory. The loop details for this baseline is in [Table 2](#).

### 1.3.1 Understanding the dim parameter

Instead of diving into the factor, which is of interest in this project, we try to choose an appropriate dim. The dim option is used to specify which dimension is partitioned. [Figure 4](#) is a figure coming from *Vitis HLS User Guide (ug1399)*, which clearly

Table 5: Loop details for L1 pipelining

(a) L1 pipelining with 1WnR memory

| Loop Name    | Latency (cycles) |      | Iteration Latency | Initiation Interval |        | Trip Count | Pipelined |
|--------------|------------------|------|-------------------|---------------------|--------|------------|-----------|
|              | min              | max  |                   | achieved            | target |            |           |
| - LOAD_OFF_1 | 5                | 5    | 1                 | -                   | -      | 5          | no        |
| - LOAD_W_1   | 1300             | 1300 | 130               | -                   | -      | 10         | no        |
| + LOAD_W_2   | 128              | 128  | 1                 | -                   | -      | 128        | no        |
| - LOAD_I_1   | 2064             | 2064 | 258               | -                   | -      | 8          | no        |
| + LOAD_I_2   | 256              | 256  | 2                 | -                   | -      | 128        | no        |
| - L1         | 1402             | 1402 | 1291              | 16                  | 1      | 8          | yes       |
| - STORE_O_1  | 136              | 136  | 17                | -                   | -      | 8          | no        |
| + STORE_O_2  | 15               | 15   | 3                 | -                   | -      | 5          | no        |

(b) L1 pipelining with T2P memory

| Loop Name    | Latency (cycles) |      | Iteration Latency | Initiation Interval |        | Trip Count | Pipelined |
|--------------|------------------|------|-------------------|---------------------|--------|------------|-----------|
|              | min              | max  |                   | achieved            | target |            |           |
| - LOAD_OFF_1 | 5                | 5    | 1                 | -                   | -      | 5          | no        |
| - LOAD_W_1   | 1300             | 1300 | 130               | -                   | -      | 10         | no        |
| + LOAD_W_2   | 128              | 128  | 1                 | -                   | -      | 128        | no        |
| - LOAD_I_1   | 1040             | 1040 | 130               | -                   | -      | 8          | no        |
| + LOAD_I_2   | 128              | 128  | 1                 | -                   | -      | 128        | no        |
| - L1         | 2186             | 2186 | 1291              | 128                 | 1      | 8          | yes       |
| - STORE_O_1  | 136              | 136  | 17                | -                   | -      | 8          | no        |
| + STORE_O_2  | 15               | 15   | 3                 | -                   | -      | 5          | no        |

shows the idea of dim. In our application, the loop body of L2 is pipelined, which reads 256 elements from in\_buf and 256 elements from weight\_buf. In order to improve parallelism, it is obvious that we should distribute the one vector of 256 elements to several blocks of memory. That is, we need to set dim to 2.

I have also experimented on this, where the code is modified as Figure 5. The HLS summary (Table 6) shows setting dim to 1 introduces more resource usage but the latency is worse. On the contrary, setting dim to 2 leads to introducing more floating-point adders and multipliers and achieves a lower latency. The result also supports our conclusion above.

### 1.3.2 Trying different factors

As shown in Table 6, adding the factor to 32 makes the utilization of DSP and LUT exceeds the resource budget.

When factor=8, the latency is reduced to 4911, which means 46.4x improvement, where 16 floating-point adders and 16 floating-point multipliers are used. When factor=16, the latency is reduced to 4279, which means 53.3x improvement, where 32 floating-point adders and 32 floating-point multipliers are used. That is exactly 16 times of that when array partition is not used. From Table 7 and Table 8, it can be seen that the initiation interval is 16 cycles when factor=8 and 8 cycles when factor=16.

## 1.4 Amortizing Iteration Latency with Batching (8 marks)

The result is reported in Table 6 as well as Figure 6. The usage of BRAM\_18K exceeds 100% when the batch size comes to 512. When the batch size is 256, the BRAM\_18K usage is 60%, which achieves the goal of 55%. The corresponding latency is 57103 cycles.

In order to evaluate its efficiency, an additional baseline with the batch size 256 and without any optimization is conducted. The result shows the baseline took 29020446 cycles, which is 508x longer than the optimized one.

It can also be evaluated by calculating the average latency per input. In baseline<sup>1</sup>, the batch size is 8 and the latency per

<sup>1</sup>Partition (dim=2, factor=16)

Table 6: Performance and utilization estimates for mmult\_float

| Profile |                               | Latency (cycles) |          | Latency (ms) |         | Interval (cycles) |          | Pipeline Type |
|---------|-------------------------------|------------------|----------|--------------|---------|-------------------|----------|---------------|
|         |                               | min              | max      | min          | max     | min               | max      |               |
| 1.1     | Baseline (AutoPipe)           | 85160            | 85160    | 1.236        | 1.236   | 85161             | 85161    | none          |
| 1.1     | Baseline (NoPipe)             | 228022           | 228022   | 2.280        | 2.280   | 228023            | 228023   | none          |
| 1.2.1   | L3 Pipelining                 | 85286            | 85286    | 1.238        | 1.238   | 85287             | 85287    | none          |
| 1.2.2   | L2 Pipelining (1WnR)          | 7341             | 7341     | 0.073        | 0.073   | 7342              | 7342     | none          |
| 1.2.2   | L2 Pipelining (T2P)           | 13885            | 13885    | 0.139        | 0.139   | 13886             | 13886    | none          |
| 1.2.3   | L1 Pipelining (1WnR)          | 6193             | 6193     | 0.062        | 0.062   | 6194              | 6194     | none          |
| 1.2.3   | L1 Pipelining (T2P)           | 5953             | 5953     | 0.060        | 0.060   | 5954              | 5954     | none          |
| 1.3     | Baseline (L2, AutoPipe, T2P)  | 13759            | 13759    | 0.138        | 0.138   | 13760             | 13760    | none          |
| 1.3.1   | Partition (dim=1, factor=2)   | 13772            | 13772    | 0.138        | 0.138   | 13773             | 13773    | none          |
| 1.3.1   | Partition (dim=2, factor=2)   | 8703             | 8703     | 0.087        | 0.087   | 8704              | 8704     | none          |
| 1.3.2   | Partition (dim=2, factor=4)   | 6175             | 6175     | 0.062        | 0.062   | 6176              | 6176     | none          |
| 1.3.2   | Partition (dim=2, factor=8)   | 4911             | 4911     | 0.049        | 0.049   | 4912              | 4912     | none          |
| 1.3.2   | Partition (dim=2, factor=16)  | 4279             | 4279     | 0.043        | 0.043   | 4280              | 4280     | none          |
| 1.3.2   | Partition (dim=2, factor=32)  | 3963             | 3963     | 0.040        | 0.040   | 3964              | 3964     | none          |
| 1.4     | Amortizing (batch=16)         | 5983             | 5983     | 0.060        | 0.060   | 5984              | 5984     | none          |
| 1.4     | Amortizing (batch=32)         | 9391             | 9391     | 0.094        | 0.094   | 9392              | 9392     | none          |
| 1.4     | Amortizing (batch=64)         | 16207            | 16207    | 0.162        | 0.162   | 16208             | 16208    | none          |
| 1.4     | Amortizing (batch=128)        | 29839            | 29839    | 0.298        | 0.298   | 29840             | 29840    | none          |
| 1.4     | Amortizing (batch=256)        | 57103            | 57103    | 0.571        | 0.571   | 57104             | 57104    | none          |
| 1.4     | Amortizing (batch=512)        | 111631           | 111631   | 1.116        | 1.116   | 111632            | 111632   | none          |
| 1.4     | Baseline (NoPipe, batch=256)  | 29020446         | 29020446 | 290.000      | 290.000 | 29020447          | 29020447 | none          |
| 1.5     | Tiling (batch=2048, tile=128) | 458106           | 458106   | 4.581        | 4.581   | 458107            | 458107   | none          |
| 1.6     | Hardware Compilation          | 949242           | 949242   | 9.492        | 9.492   | 949243            | 949243   | none          |

| Profile |                               | Utilization Summary |            |               |               |        | Instance |      |
|---------|-------------------------------|---------------------|------------|---------------|---------------|--------|----------|------|
|         |                               | BRAM_18K            | DSP        | FF            | LUT           | URAM   | fadd     | fmul |
| 1.1     | Baseline (AutoPipe)           | 13 (4%)             | 5 (2%)     | 1050 (~0%)    | 2000 (3%)     | 0 (0%) | 1        | 1    |
| 1.1     | Baseline (NoPipe)             | 14 (5%)             | 5 (2%)     | 817 (~0%)     | 1635 (3%)     | 0 (0%) | 1        | 1    |
| 1.2.1   | L3 Pipelining                 | 14 (5%)             | 5 (2%)     | 921 (~0%)     | 1713 (3%)     | 0 (0%) | 1        | 1    |
| 1.2.2   | L2 Pipelining (1WnR)          | 182 (65%)           | 80 (36%)   | 38357 (36%)   | 34359 (64%)   | 0 (0%) | 16       | 16   |
| 1.2.2   | L2 Pipelining (T2P)           | 16 (5%)             | 10 (4%)    | 24710 (23%)   | 22359 (42%)   | 0 (0%) | 2        | 2    |
| 1.2.3   | L1 Pipelining (1WnR)          | 70 (25%)            | 800 (363%) | 415044 (390%) | 243128 (457%) | 0 (0%) | 160      | 160  |
| 1.2.3   | L1 Pipelining (T2P)           | 16 (5%)             | 100 (45%)  | 312992 (294%) | 120185 (225%) | 0 (0%) | 20       | 20   |
| 1.3     | Baseline (L2, AutoPipe, T2P)  | 16 (5%)             | 10 (4%)    | 24776 (23%)   | 22615 (42%)   | 0 (0%) | 2        | 2    |
| 1.3.1   | Partition (dim=1, factor=2)   | 16 (5%)             | 10 (4%)    | 32491 (30%)   | 45788 (86%)   | 0 (0%) | 2        | 2    |
| 1.3.1   | Partition (dim=2, factor=2)   | 16 (5%)             | 20 (9%)    | 27306 (25%)   | 19326 (36%)   | 0 (0%) | 4        | 4    |
| 1.3.2   | Partition (dim=2, factor=4)   | 20 (7%)             | 40 (18%)   | 31022 (29%)   | 20786 (39%)   | 0 (0%) | 8        | 8    |
| 1.3.2   | Partition (dim=2, factor=8)   | 36 (12%)            | 80 (36%)   | 37606 (35%)   | 26782 (50%)   | 0 (0%) | 16       | 16   |
| 1.3.2   | Partition (dim=2, factor=16)  | 68 (24%)            | 160 (72%)  | 52606 (49%)   | 40402 (75%)   | 0 (0%) | 32       | 32   |
| 1.3.2   | Partition (dim=2, factor=32)  | 132 (47%)           | 320 (145%) | 72201 (67%)   | 65294 (122%)  | 0 (0%) | 64       | 64   |
| 1.4     | Amortizing (batch=16)         | 68 (24%)            | 160 (72%)  | 52634 (49%)   | 40446 (76%)   | 0 (0%) | 32       | 32   |
| 1.4     | Amortizing (batch=32)         | 68 (24%)            | 160 (72%)  | 52675 (49%)   | 40501 (76%)   | 0 (0%) | 32       | 32   |
| 1.4     | Amortizing (batch=64)         | 68 (24%)            | 160 (72%)  | 52708 (49%)   | 40547 (76%)   | 0 (0%) | 32       | 32   |
| 1.4     | Amortizing (batch=128)        | 102 (36%)           | 160 (72%)  | 52741 (49%)   | 40597 (76%)   | 0 (0%) | 32       | 32   |
| 1.4     | Amortizing (batch=256)        | 170 (60%)           | 160 (72%)  | 52774 (49%)   | 40646 (76%)   | 0 (0%) | 32       | 32   |
| 1.4     | Amortizing (batch=512)        | 306 (109%)          | 160 (72%)  | 52807 (49%)   | 40699 (76%)   | 0 (0%) | 32       | 32   |
| 1.4     | Baseline (NoPipe, batch=256)  | 552 (197%)          | 5 (2%)     | 940 (~0%)     | 1724 (3%)     | 0 (0%) | 1        | 1    |
| 1.5     | Tiling (batch=2048, tile=128) | 102 (36%)           | 160 (72%)  | 52864 (49%)   | 40805 (76%)   | 0 (0%) | 32       | 32   |
| 1.6     | Hardware Compilation          | 78 (27%)            | 40 (18%)   | 31458 (29%)   | 21570 (40%)   | 0 (0%) | 8        | 8    |

```

@@ -71,6 +71,7 @@
// Iterate over batch elements
L1:
    for (int i = 0; i < BATCH; i++) {
+##pragma HLS PIPELINE II = 1
// Iterate over output classes
L2:
    for (int j = 0; j < CLASSES; j++) {

```

(a) Using 1WnR RAM

```

@@ -32,6 +32,11 @@
    T in_buf[BATCH][FEAT];
    T out_buf[BATCH][CLASSES];

+##pragma HLS bind_storage variable = offset_buf type = RAM_T2P
+##pragma HLS bind_storage variable = weight_buf type = RAM_T2P
+##pragma HLS bind_storage variable = in_buf type = RAM_T2P
+##pragma HLS bind_storage variable = out_buf type = RAM_T2P
+
// Input and output AXI stream indices
int is_idx = 0;
int os_idx = 0;
@@ -71,6 +76,7 @@
// Iterate over batch elements
L1:
    for (int i = 0; i < BATCH; i++) {
+##pragma HLS PIPELINE II = 1
// Iterate over output classes
L2:
    for (int j = 0; j < CLASSES; j++) {

```

(b) Using T2P RAM

Figure 3: Inserting HLS directive for L1 Pipelining

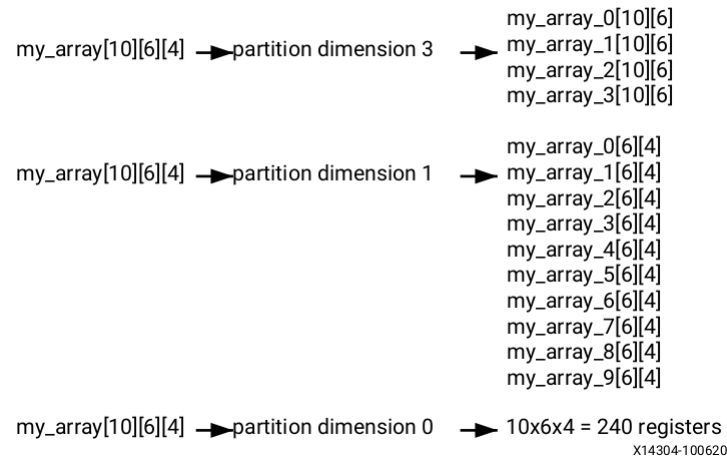


Figure 4: Partitioning Array Dimensions

input is 534.9 cycles. This design's latency per input is 223.1 cycles, a 2.4x improvement.

## 1.5 Extending Batch Size with Tiling (8 marks)

After tiling, the latency comes to 458106 cycles for 2048 batches, i.e., the latency per input is 223.7 cycles, which is almost the same as that in [Section 1.4](#). Without performance loss, the BRAM usage is reduced from 60% to 36%.

```

@@ -37,6 +37,9 @@
#pragma HLS bind_storage variable = in_buf type = RAM_T2P
#pragma HLS bind_storage variable = out_buf type = RAM_T2P

+#pragma HLS array_partition variable = weight_buf block factor = 2 dim = 1
+#pragma HLS array_partition variable = in_buf block factor = 2 dim = 1
+
// Input and output AXI stream indices
int is_idx = 0;
int os_idx = 0;

```

(a) Setting array partition with dim=1

```

@@ -37,6 +37,9 @@
#pragma HLS bind_storage variable = in_buf type = RAM_T2P
#pragma HLS bind_storage variable = out_buf type = RAM_T2P

+#pragma HLS array_partition variable = weight_buf block factor = 2 dim = 2
+#pragma HLS array_partition variable = in_buf block factor = 2 dim = 2
+
// Input and output AXI stream indices
int is_idx = 0;
int os_idx = 0;

```

(b) Setting array partition with dim=2

Figure 5: Comparing different setting of dim

Table 7: Loop details for partition with dim=2 factor=8

| Loop Name             | Latency (cycles) |      | Iteration Latency | Initiation Interval |        | Trip Count | Pipelined |
|-----------------------|------------------|------|-------------------|---------------------|--------|------------|-----------|
|                       | min              | max  |                   | achieved            | target |            |           |
| - LOAD_OFF_1          | 5                | 5    | 1                 | 1                   | 1      | 5          | yes       |
| - LOAD_W_1_LOAD_W_2   | 1280             | 1280 | 1                 | 1                   | 1      | 1280       | yes       |
| - LOAD_I_1_LOAD_I_2   | 1024             | 1024 | 1                 | 1                   | 1      | 1024       | yes       |
| - L1_L2               | 2550             | 2550 | 1287              | 16                  | 1      | 80         | yes       |
| - STORE_O_1_STORE_O_2 | 42               | 42   | 4                 | 1                   | 1      | 40         | yes       |

Table 8: Loop details for partition with dim=2 factor=16

| Loop Name             | Latency (cycles) |      | Iteration Latency | Initiation Interval |        | Trip Count | Pipelined |
|-----------------------|------------------|------|-------------------|---------------------|--------|------------|-----------|
|                       | min              | max  |                   | achieved            | target |            |           |
| - LOAD_OFF_1          | 5                | 5    | 1                 | 1                   | 1      | 5          | yes       |
| - LOAD_W_1_LOAD_W_2   | 1280             | 1280 | 1                 | 1                   | 1      | 1280       | yes       |
| - LOAD_I_1_LOAD_I_2   | 1024             | 1024 | 1                 | 1                   | 1      | 1024       | yes       |
| - L1_L2               | 1918             | 1918 | 1287              | 8                   | 1      | 80         | yes       |
| - STORE_O_1_STORE_O_2 | 42               | 42   | 4                 | 1                   | 1      | 40         | yes       |

## 1.6 Hardware compilation and FPGA testing on the PYNQ (8 marks)

In this section, we met some problems.

The first problem that I met is when exporting the IP, which has been solved in: **Vivado fails to export IPs with the error message "Bad lexical cast: source type value could not be interpreted as target"**.

The second problem occurs when validating the system design, which reports a critical warning as **Figure 7**. As this signal shall be provided by Vitis HLS when implementing the AXI Stream interface, I changed the signature of the top function from C array to `hls::stream`. That fixes the problem.



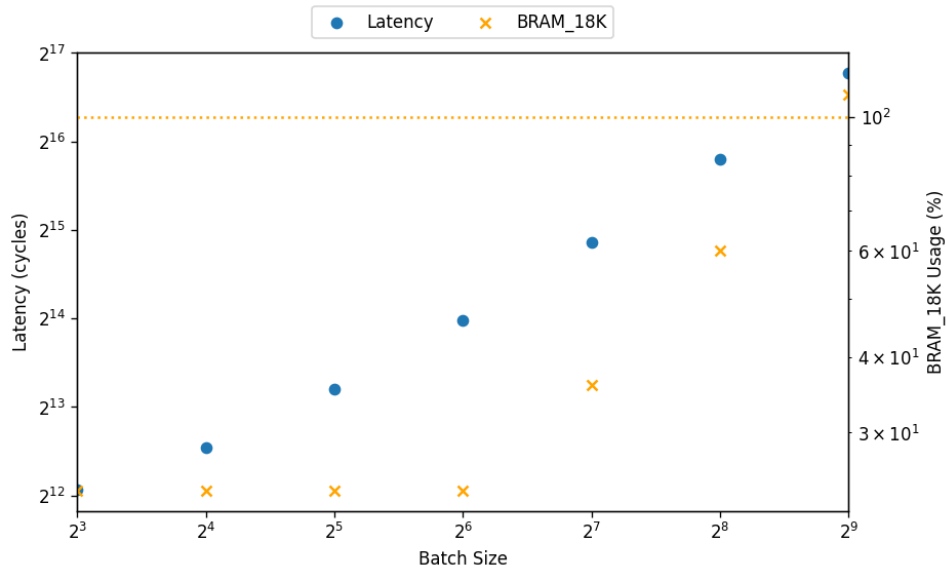


Figure 6: Latency and BRAM\_18K usage

```
[xilinx.com:ip:axi_dma:7.1-9] /axi_dma_1
#####
Interface connected to S_AXIS_S2MM does not have TLAST port
#####
```

Figure 7: Critical Warning from validating the design

After building, move the bitstream files to the board.

```
$ scp `find -name "*.bit"` xilinx@pynq-ip-addr:~/classifier.bit
$ scp `find -name "*.hwh"` xilinx@pynq-ip-addr:~/classifier.hwh
```

According to the different versions of PYNQ, I have to modify the notebook as well. The new version is attached in the submission.

The measured classification accuracy is 13.04% for both FPGA and CPU, which indicates that our implementation is correct. The running time on FPGA is around 16.16ms, while 78.04ms on CPU. That is, speedup on FPGA is 4.83x, a little bit smaller than required. This may due to the optimization between different versions of python and numpy.

## 2 Fixed-Point Optimizations

### 2.1 Dataset Preparation

I did some work to adapt `mnist.py` to Python 3. In order to get an appropriate scale, I did a search and got Figure 8, which shows the validation accuracy meets the requirement when the scale is around  $2^{16}$ . The fixed-point validation accuracy reported by `mnist.py` is as Figure 9, where the validation error with fixed-point number is 18.98%.

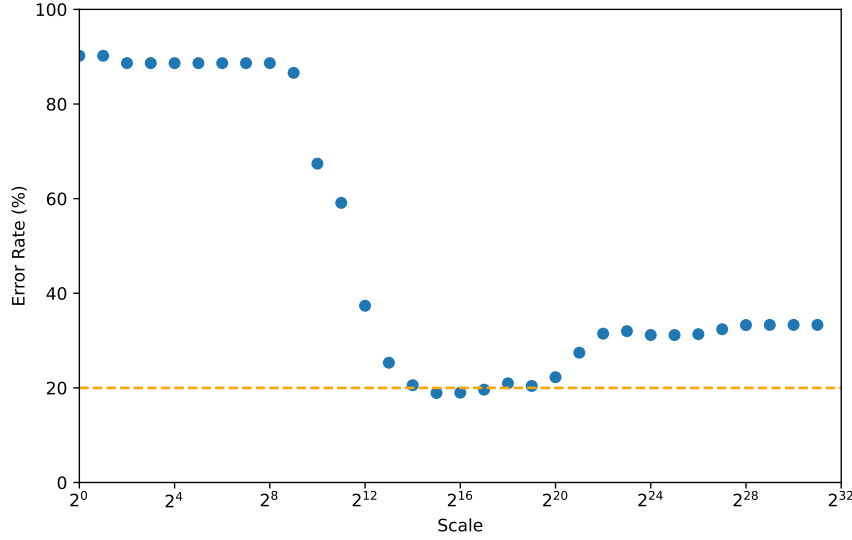


Figure 8: Misclassifications Rate with fixed point numbers under different scales

```
$ python3 mnist.py
Min/Max of coefficient values [-0.49227501415123354, 0.3931926418998524]
Min/Max of intersect values [-0.12369156945342877, 0.2528140743366973]
Misclassifications (float) = 14.05%
Misclassifications (fixed) = 18.98%
```

Figure 9: The output of `mnist.py`

### 2.2 Hardware Design

#### 2.2.1 Timing

The overall latency, as reported in Table 9, is 386378 cycles for 8192 batches, which means 47.17 cycles for each input on average. It is a 604.25x speedup over our baseline without auto pipelining. The pipelined loop has an initiation interval of 1 cycle achieved, as reported in Table 10.

Table 9: Performance Estimates

| Latency (cycles) |        | Latency (absolute) |          | Interval |        | Pipeline Type |
|------------------|--------|--------------------|----------|----------|--------|---------------|
| min              | max    | min                | max      | min      | max    |               |
| 386378           | 386378 | 3.864 ms           | 3.864 ms | 386379   | 386379 | none          |

Table 10: Loop detail of the pipelined loop

|                     |          | L1_L2 |
|---------------------|----------|-------|
| Latency (cycles)    | min      | 1287  |
| Latency (cycles)    | max      | 1287  |
| Iteration Latency   |          | 9     |
| Initiation Interval | achieved | 1     |
| Initiation Interval | target   | 1     |
| Trip Count          |          | 1280  |
| Trip Count          |          | 1280  |
| Pipelined           |          | yes   |

Table 11: Loop Latency of load, compute and store

| Loop Name                     | Latency (cycles) |      |
|-------------------------------|------------------|------|
|                               | min              | max  |
| LOAD_INPUT_VITIS_LOOP_73_4    | 4096             | 4096 |
| L1_L2                         | 1287             | 1287 |
| STORE_OUTPUT_VITIS_LOOP_106_6 | 642              | 642  |

### 2.2.2 Device Utilization

The overall device utilization is reported as [Table 12](#). We have 128 multipliers implemented by LUT and 129 multiply-accumulate operator implemented on DSP.

Table 12: Utilization Estimates Summary

| Name            | BRAM_18K | DSP | FF     | LUT   | URAM |
|-----------------|----------|-----|--------|-------|------|
| DSP             | -        | 129 | -      | -     | -    |
| Expression      | -        | -   | 0      | 3967  | -    |
| FIFO            | -        | -   | -      | -     | -    |
| Instance        | 0        | 0   | 36     | 5247  | -    |
| Memory          | 260      | -   | 4160   | 517   | -    |
| Multiplexer     | -        | -   | -      | 7513  | -    |
| Register        | -        | -   | 5633   | 128   | -    |
| Total           | 260      | 129 | 9829   | 17372 | 0    |
| Available       | 280      | 220 | 106400 | 53200 | 0    |
| Utilization (%) | 92       | 58  | 9      | 32    | 0    |

## 2.3 Evaluation

The measured system speedup over the fixed-point CPU implementation is 34.94x. The measured classification accuracy on the 8k MNIST test sample is 19.96% both on FPGA and on CPU.

## 2.4 Reflection

The width of TDATA signal in AXI Stream interface is 64bit. Each input data has 256 bytes, i.e., 32 words, and a tile of 128 inputs has 4096 words. Our design, as reported in [Table 11](#), took exactly 4096 cycles to load the 4096 words, but the following computation took only another 1287 cycles. Thus I believe the design is memory-bandwidth limited. That is, if we can load more data at a single cycle, we can achieve a higher overall throughput.

## 3 Open-ended Design Optimization

### 3.1 Hardware Compatible

#### 3.1.1 Reducing the Input Dimension

The size of input is determined by the dimension of inputs (originally  $16 \times 16$ ) and the depth of each pixel (8-bit in the previous design). A search is done by trying different pair of input dimension and depth and calculating the prediction accuracy using linear regression model, which is actually a lower bound we can achieve. The result is as [Figure 10](#).

It is shown that

When the input size is shrunk to  $8 \times 8$ , the misclassifications rate is 15.96%, which is slightly worse than our target (over 85% in accuracy). However, this is a desirable configuration, which means we can fit an input in precisely 8 bytes. Thus I believe it is worth sacrificing some accuracy here and getting it back using a more aggressive model.

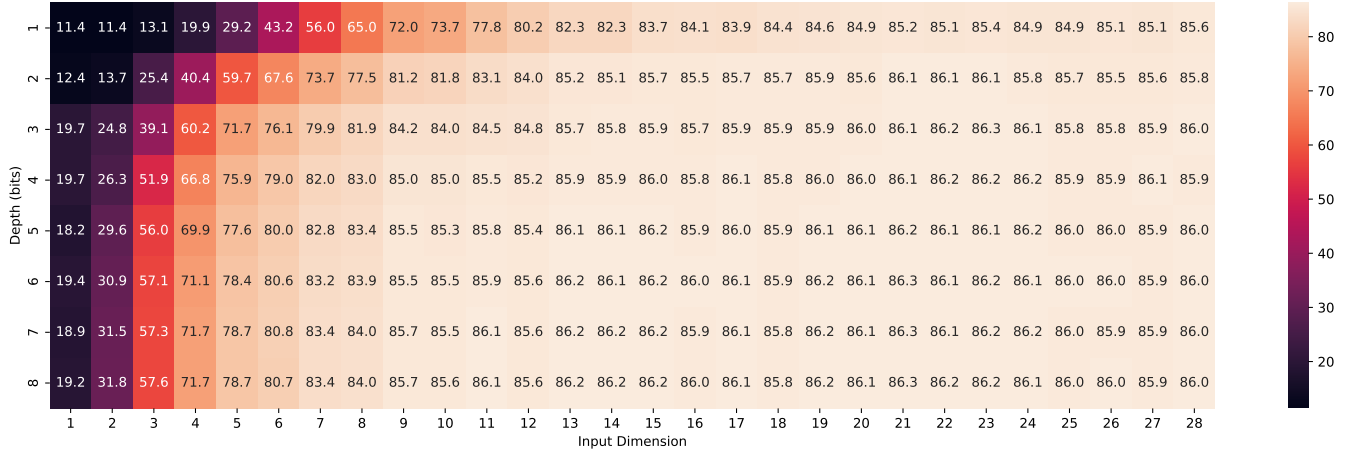


Figure 10: Accuracy of prediction using floating point numbers under different input size

#### 3.1.2 Improve Prediction Accuracy

The accuracy is improve by using a more complex model, which includes a ReLU activated input layer ( $64 \times 16$ ), which is unbiased, and a biased output layer ( $16 \times 10$ ). Using ReLU with an unbiased input layer, we can refrain from floating point calculation while keep the linear property.

$$\mathbf{O} = \text{ReLU}(\mathbf{I} \cdot \mathbf{W}_1) \cdot \mathbf{W}_2 + \mathbf{b}$$

To get a better training result, we add a Softmax layer after the model and use train towards minimized cross entropy loss. This layer can be removed when predicting on FPGA, which will not affect the final result.

#### 3.1.3 Evaluation

The design latency is 200699 cycles.

It took 4.54 ms to generate the prediction while the CPU used 169.64 ms, which means the FPGA solution achieves a 37.36x speedup against the CPU solution. The prediction accuracy is 88.18% on both FPGA and CPU.

## 3.2 Enhancing a Single AXI Transfer

In order to accomodate more data in a single AXI transfer<sup>2</sup>, we need to increase the TDATA width.

The width in the default design is 64 bits, which took 32 cycles to transfer a single input of 256 bytes. By widening the TDATA width to 256 bits, it takes only 8 cycles to transfer the 256 bytes ([Table 13](#)).

The overall latency of our design is 159646 cycles. Its utilization is as [Table 14](#).

<sup>2</sup>Stream terms

Table 13: LOAD\_INPUT latency under different TDATA width

| TDATA width (bits) | Latency (cycles) | Iteration Latency | Initiation Interval (achieved) | Trip Count | Pipelined |
|--------------------|------------------|-------------------|--------------------------------|------------|-----------|
| 64                 | 4096             | 32                | 32                             | 128        | yes       |
| 128                | 2048             | 16                | 16                             | 128        | yes       |
| 256                | 1024             | 8                 | 8                              | 128        | yes       |

Table 14: Utilization Report with 256-bit AXI Stream

| Name            | BRAM_18K | DSP | FF     | LUT   | URAM |
|-----------------|----------|-----|--------|-------|------|
| DSP             | -        | 192 | -      | -     | -    |
| Expression      | -        | -   | 0      | 4703  | -    |
| FIFO            | -        | -   | -      | -     | -    |
| Instance        | 0        | 0   | 36     | 1352  | -    |
| Memory          | 202      | -   | 32     | 3     | -    |
| Multiplexer     | -        | -   | -      | 3577  | -    |
| Register        | -        | -   | 6552   | 128   | -    |
| Total           | 202      | 192 | 6620   | 9763  | 0    |
| Available       | 280      | 220 | 106400 | 53200 | 0    |
| Utilization (%) | 72       | 87  | 6      | 18    | 0    |

Since we modified the AXI data width, the data width of DMA IP needs to be fixed manually as [Figure 11](#).

The evaluation shows that FPGA took 3.85 ms to produce the result, while CPU took 169.33 ms as well. That is a 44x speedup which is better but not that better as we expected. It is because the maximum AXI data width of Zynq 7000 processor is 64 bit, which limited the bandwidth.

The accuracy is still 88.18%.

Figure 11: Adjust AXI data width by re-customizing AXI-DMA IP

