Title: Raspberry Pi 2B+ runs FFT on GPU and CPU, energy and power comparison

Author: Qihao He, Bruce Segee, Vincent weaver

# GPU part:

Library name: GPU\_FFT

Written by: Andrew Holme

## Library description:

Reference:

ACCELERATING FOURIER TRANSFORMS USING THE GPU

<https://www.raspberrypi.org/blog/accelerating-fourier-transforms-using-the-gpu/>

General purpose code for the VideoCore IV graphics processing unit(GPU) in the BCM2835. To create an accelerated Fast Fourier Transform library. Taking the Fourier transform of a function yields its frequency spectrum (i.e. the pure harmonic functions which can be added together to reconstruct the original function).

GPU\_FFT is an FFT library for the Raspberry Pi which exploits the BCM2835 SoC V3D hardware to deliver ten times the performance that is possible on the 700 MHz ARM. Kernels are provided for all power-of-2 FFT lengths from 256 to 131,072 points inclusive.

GPU\_FFT uses single-precision floating point for data and twiddle factors, so it does not compete on accuracy with double-precision libraries; however, the relative root-mean-square (rms) error for a 2048-point transform is less than one part per million, which is not bad.

The library runs on dedicated 3D hardware in the BCM2835 SoC, and communication between ARM and GPU adds 100µs of latency which is much longer than the shortest transform takes to compute! To overcome this, batches of transforms can be executed with a single call. Typical per-transform runtimes in microseconds are:

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Points | batch=1 | batch=10 | batch=50 | FFTW | Speedup |
| 256 | 112 | 22 | 16 | 92 | 5.8x |
| 512 | 125 | 37 | 26 | 217 | 8.3x |
| 1024 | 136 | 54 | 45 | 482 | 10.7x |
| 2048 | 180 | 107 | 93 | 952 | 10.2x |
| 4096 | 298 | 256 | 240 | 3002 | 12.5x |
| 8192 | 689 | 624 | 608 | 5082 | 8.4x |
| 16384 | 1274 | 1167 | 1131 | 12005 | 10.6x |
| 32768 | 3397 | 3225 | 3196 | 31211 | 9.8x |
| 65536 | 6978 | 6703 | 6674 | 82769 | 12.4x |
| 131072 | 16734 | 16110 | 16171 | 183731 | 11.4x |

## ­Library usage:

Being able to perform lots of Fourier transforms quickly is useful for all sorts of audio and radio applications including, unsurprisingly, GPS. Ham radio enthusiasts will also find Andrew’s work very useful.

Last October, Eben attended the Radio Society of Great Britain (RSGB) Convention, where radio amateurs told him they wanted a speedy fast Fourier transform (FFT) library to do Software Defined Radio (SDR) projects on the Pi.

## Library operate:

To get GPU\_FFT enter the following at the command prompt:

sudo rpi-update && sudo reboot

To build and run the example program:

directory:

cd /opt/vc/src/hello\_pi/hello\_fft

make

sudo mknod char\_dev c 100 0

sudo ./hello\_fft.bin

API documentation can be found in the hello\_fft folder.

File: hello\_fft usage:

$ sudo ./hello\_fft.bin

Usage: hello\_fft.bin log2\_N [jobs [loops]]

log2\_N = log2(FFT\_length), log2\_N = 8...22

jobs = transforms per batch, jobs>0, default 1

loops = number of test repeats, loops>0, default 1

e.g.

$ sudo ./hello\_fft.bin 8

rel\_rms\_err = 3.3e-07, usecs = 45, k = 0

$ sudo ./hello\_fft.bin 22

rel\_rms\_err = 1.5e-06, usecs = 782379, k = 0

$ sudo ./hello\_fft.bin 8 2 2

rel\_rms\_err = 3.1e-07, usecs = 33, k = 0

rel\_rms\_err = 3.1e-07, usecs = 23, k = 1

## Library results:

pi@raspberrypi:/opt/vc/src/hello\_pi/hello\_fft $ sudo ./hello\_fft.bin 8 1 1

rel\_rms\_err = 3.3e-07, usecs = 44, k = 0

pi@raspberrypi:/opt/vc/src/hello\_pi/hello\_fft $ sudo ./hello\_fft.bin 8 2 1

rel\_rms\_err = 3.1e-07, usecs = 30, k = 0

pi@raspberrypi:/opt/vc/src/hello\_pi/hello\_fft $ sudo ./hello\_fft.bin 8 4 1

rel\_rms\_err = 2.8e-07, usecs = 22, k = 0

pi@raspberrypi:/opt/vc/src/hello\_pi/hello\_fft $ sudo ./hello\_fft.bin 8 8 1

rel\_rms\_err = 2.7e-07, usecs = 19, k = 0

pi@raspberrypi:/opt/vc/src/hello\_pi/hello\_fft $ sudo ./hello\_fft.bin 8 16 1

rel\_rms\_err = 2.6e-07, usecs = 28, k = 0

pi@raspberrypi:/opt/vc/src/hello\_pi/hello\_fft $ sudo ./hello\_fft.bin 8 32 1

rel\_rms\_err = 2.6e-07, usecs = 17, k = 0

pi@raspberrypi:/opt/vc/src/hello\_pi/hello\_fft $ sudo ./hello\_fft.bin 8 64 1

rel\_rms\_err = 2.5e-07, usecs = 16, k = 0

pi@raspberrypi:/opt/vc/src/hello\_pi/hello\_fft $ sudo ./hello\_fft.bin 8 16 1

rel\_rms\_err = 2.6e-07, usecs = 17, k = 0

pi@raspberrypi:/opt/vc/src/hello\_pi/hello\_fft $ sudo ./hello\_fft.bin 8 128 1

rel\_rms\_err = 0.062, usecs = 17, k = 0

pi@raspberrypi:/opt/vc/src/hello\_pi/hello\_fft $ sudo ./hello\_fft.bin 8 256 1

rel\_rms\_err = 0.062, usecs = 16, k = 0

pi@raspberrypi:/opt/vc/src/hello\_pi/hello\_fft $ sudo ./hello\_fft.bin 8 512 1

rel\_rms\_err = 0.71, usecs = 15, k = 0

pi@raspberrypi:/opt/vc/src/hello\_pi/hello\_fft $ sudo ./hello\_fft.bin 8 1024 1

rel\_rms\_err = 0.94, usecs = 15, k = 0

pi@raspberrypi:/opt/vc/src/hello\_pi/hello\_fft $ sudo ./hello\_fft.bin 8 2048 1

rel\_rms\_err = 1, usecs = 15, k = 0

pi@raspberrypi:/opt/vc/src/hello\_pi/hello\_fft $ sudo ./hello\_fft.bin 8 4096 1

rel\_rms\_err = 1.1, usecs = 15, k = 0

pi@raspberrypi:/opt/vc/src/hello\_pi/hello\_fft $ sudo ./hello\_fft.bin 8 8192 1

rel\_rms\_err = 1.1, usecs = 15, k = 0

pi@raspberrypi:/opt/vc/src/hello\_pi/hello\_fft $ sudo ./hello\_fft.bin 8 1 4

rel\_rms\_err = 3.3e-07, usecs = 44, k = 0

rel\_rms\_err = 3.3e-07, usecs = 31, k = 1

rel\_rms\_err = 3.3e-07, usecs = 31, k = 2

rel\_rms\_err = 3.3e-07, usecs = 31, k = 3

pi@raspberrypi:/opt/vc/src/hello\_pi/hello\_fft $ sudo ./hello\_fft.bin 8 1 8

rel\_rms\_err = 3.3e-07, usecs = 51, k = 0

rel\_rms\_err = 3.3e-07, usecs = 31, k = 1

rel\_rms\_err = 3.3e-07, usecs = 32, k = 2

rel\_rms\_err = 3.3e-07, usecs = 32, k = 3

rel\_rms\_err = 3.3e-07, usecs = 32, k = 4

rel\_rms\_err = 3.3e-07, usecs = 33, k = 5

rel\_rms\_err = 3.3e-07, usecs = 31, k = 6

rel\_rms\_err = 3.3e-07, usecs = 31, k = 7

pi@raspberrypi:/opt/vc/src/hello\_pi/hello\_fft $ sudo ./hello\_fft.bin 8 1 16

rel\_rms\_err = 3.3e-07, usecs = 43, k = 0

rel\_rms\_err = 3.3e-07, usecs = 31, k = 1

rel\_rms\_err = 3.3e-07, usecs = 32, k = 2

rel\_rms\_err = 3.3e-07, usecs = 31, k = 3

rel\_rms\_err = 3.3e-07, usecs = 32, k = 4

rel\_rms\_err = 3.3e-07, usecs = 33, k = 5

rel\_rms\_err = 3.3e-07, usecs = 32, k = 6

rel\_rms\_err = 3.3e-07, usecs = 31, k = 7

rel\_rms\_err = 3.3e-07, usecs = 30, k = 8

rel\_rms\_err = 3.3e-07, usecs = 30, k = 9

rel\_rms\_err = 3.3e-07, usecs = 30, k = 10

rel\_rms\_err = 3.3e-07, usecs = 30, k = 11

rel\_rms\_err = 3.3e-07, usecs = 29, k = 12

rel\_rms\_err = 3.3e-07, usecs = 31, k = 13

rel\_rms\_err = 3.3e-07, usecs = 30, k = 14

rel\_rms\_err = 3.3e-07, usecs = 31, k = 15

pi@raspberrypi:/opt/vc/src/hello\_pi/hello\_fft $ sudo ./hello\_fft.bin 8 1 32

rel\_rms\_err = 3.3e-07, usecs = 46, k = 0

rel\_rms\_err = 3.3e-07, usecs = 31, k = 1

rel\_rms\_err = 3.3e-07, usecs = 32, k = 2

rel\_rms\_err = 3.3e-07, usecs = 31, k = 3

rel\_rms\_err = 3.3e-07, usecs = 32, k = 4

rel\_rms\_err = 3.3e-07, usecs = 31, k = 5

rel\_rms\_err = 3.3e-07, usecs = 32, k = 6

rel\_rms\_err = 3.3e-07, usecs = 30, k = 7

rel\_rms\_err = 3.3e-07, usecs = 31, k = 8

rel\_rms\_err = 3.3e-07, usecs = 29, k = 9

rel\_rms\_err = 3.3e-07, usecs = 29, k = 10

rel\_rms\_err = 3.3e-07, usecs = 29, k = 11

rel\_rms\_err = 3.3e-07, usecs = 29, k = 12

rel\_rms\_err = 3.3e-07, usecs = 30, k = 13

rel\_rms\_err = 3.3e-07, usecs = 32, k = 14

rel\_rms\_err = 3.3e-07, usecs = 31, k = 15

rel\_rms\_err = 3.3e-07, usecs = 30, k = 16

rel\_rms\_err = 3.3e-07, usecs = 30, k = 17

rel\_rms\_err = 3.3e-07, usecs = 30, k = 18

rel\_rms\_err = 3.3e-07, usecs = 29, k = 19

rel\_rms\_err = 3.3e-07, usecs = 30, k = 20

rel\_rms\_err = 3.3e-07, usecs = 30, k = 21

rel\_rms\_err = 3.3e-07, usecs = 29, k = 22

rel\_rms\_err = 3.3e-07, usecs = 29, k = 23

rel\_rms\_err = 3.3e-07, usecs = 29, k = 24

rel\_rms\_err = 3.3e-07, usecs = 29, k = 25

rel\_rms\_err = 3.3e-07, usecs = 30, k = 26

rel\_rms\_err = 3.3e-07, usecs = 29, k = 27

rel\_rms\_err = 3.3e-07, usecs = 29, k = 28

rel\_rms\_err = 3.3e-07, usecs = 29, k = 29

rel\_rms\_err = 3.3e-07, usecs = 29, k = 30

rel\_rms\_err = 3.3e-07, usecs = 31, k = 31

pi@raspberrypi:/opt/vc/src/hello\_pi/hello\_fft $ sudo ./hello\_fft.bin 22 1 1

rel\_rms\_err = 1.5e-06, usecs = 781473, k = 0

pi@raspberrypi:/opt/vc/src/hello\_pi/hello\_fft $ sudo ./hello\_fft.bin 22 2 1

rel\_rms\_err = 1.5e-06, usecs = 783190, k = 0

pi@raspberrypi:/opt/vc/src/hello\_pi/hello\_fft $ sudo ./hello\_fft.bin 22 4 1

Out of memory. Try a smaller batch or increase GPU memory.

pi@raspberrypi:/opt/vc/src/hello\_pi/hello\_fft $ sudo ./hello\_fft.bin 22 8 1

Out of memory. Try a smaller batch or increase GPU memory.

pi@raspberrypi:/opt/vc/src/hello\_pi/hello\_fft $ sudo ./hello\_fft.bin 22 2 2

rel\_rms\_err = 1.5e-06, usecs = 785348, k = 0

rel\_rms\_err = 1.5e-06, usecs = 781543, k = 1

pi@raspberrypi:/opt/vc/src/hello\_pi/hello\_fft $ sudo ./hello\_fft.bin 22 2 4

rel\_rms\_err = 1.5e-06, usecs = 781577, k = 0

rel\_rms\_err = 1.5e-06, usecs = 778754, k = 1

rel\_rms\_err = 1.5e-06, usecs = 778890, k = 2

rel\_rms\_err = 1.5e-06, usecs = 778164, k = 3

$ cd /opt/vc/src/hello\_pi/hello\_fft

$ sudo perf\_3.16 stat -d ./hello\_fft.bin 21 4

rel\_rms\_err = 1.5e-06, usecs = 384048, k = 0

Performance counter stats for './hello\_fft.bin 21 4':

16611.682000 task-clock (msec) # 0.884 CPUs utilized

331 context-switches # 0.020 K/sec

0 cpu-migrations # 0.000 K/sec

16,477 page-faults # 0.992 K/sec

11,577,399,763 cycles # 0.697 GHz [37.56%]

1,285,911,727 stalled-cycles-frontend # 11.11% frontend cycles idle [37.54%]

11,624,766 stalled-cycles-backend # 0.10% backend cycles idle [37.36%]

3,590,951,918 instructions # 0.31 insns per cycle

# 0.36 stalled cycles per insn [24.99%]

491,596,173 branches # 29.593 M/sec [25.14%]

12,319,210 branch-misses # 2.51% of all branches [25.08%]

27,138,104 L1-dcache-loads # 1.634 M/sec [25.06%]

697,059 L1-dcache-load-misses # 2.57% of all L1-dcache hits [25.08%]

<not supported> LLC-loads

<not supported> LLC-load-misses

18.790153624 seconds time elapsed

$ cd ~/QH\_directory/userland/host\_applications/linux/apps/hello\_pi/hello\_fft

$ sudo perf\_3.16 stat -d ./hello\_fft.bin 20 10

rel\_rms\_err = 1.4e-06, usecs = 192471, k = 0

Performance counter stats for './hello\_fft.bin 20 10':

20842.337000 task-clock (msec) # 0.812 CPUs utilized

599 context-switches # 0.029 K/sec

0 cpu-migrations # 0.000 K/sec

20,571 page-faults # 0.987 K/sec

14,530,940,586 cycles # 0.697 GHz [37.67%]

1,611,996,079 stalled-cycles-frontend # 11.09% frontend cycles idle [37.42%]

14,560,086 stalled-cycles-backend # 0.10% backend cycles idle [37.28%]

4,522,659,463 instructions # 0.31 insns per cycle

# 0.36 stalled cycles per insn [24.94%]

615,849,834 branches # 29.548 M/sec [25.04%]

14,833,907 branch-misses # 2.41% of all branches [25.11%]

32,706,289 L1-dcache-loads # 1.569 M/sec [25.19%]

1,152,936 L1-dcache-load-misses # 3.53% of all L1-dcache hits [25.16%]

<not supported> LLC-loads

<not supported> LLC-load-misses

25.663854775 seconds time elapsed

$ sudo perf\_3.16 stat -d ./hello\_fft.bin 20 1

rel\_rms\_err = 1.5e-06, usecs = 191712, k = 0

Performance counter stats for './hello\_fft.bin 20 1':

2073.859000 task-clock (msec) # 0.895 CPUs utilized

45 context-switches # 0.022 K/sec

0 cpu-migrations # 0.000 K/sec

2,138 page-faults # 0.001 M/sec

1,445,726,218 cycles # 0.697 GHz [37.45%]

168,054,051 stalled-cycles-frontend # 11.62% frontend cycles idle [37.85%]

2,340,102 stalled-cycles-backend # 0.16% backend cycles idle [38.15%]

439,204,097 instructions # 0.30 insns per cycle

# 0.38 stalled cycles per insn [25.45%]

60,354,270 branches # 29.102 M/sec [25.31%]

1,630,240 branch-misses # 2.70% of all branches [25.16%]

4,900,540 L1-dcache-loads # 2.363 M/sec [25.60%]

155,059 L1-dcache-load-misses # 3.16% of all L1-dcache hits [25.15%]

<not supported> LLC-loads

<not supported> LLC-load-misses

2.316615205 seconds time elapsed

$ sudo perf\_3.16 stat -d ./hello\_fft.bin 20 10 1

rel\_rms\_err = 1.4e-06, usecs = 192392, k = 0

Performance counter stats for './hello\_fft.bin 20 10 1':

20795.216000 task-clock (msec) # 0.820 CPUs utilized

622 context-switches # 0.030 K/sec

0 cpu-migrations # 0.000 K/sec

20,571 page-faults # 0.989 K/sec

14,462,479,493 cycles # 0.695 GHz [37.65%]

1,591,452,238 stalled-cycles-frontend # 11.00% frontend cycles idle [37.42%]

14,030,599 stalled-cycles-backend # 0.10% backend cycles idle [37.63%]

4,527,389,098 instructions # 0.31 insns per cycle

# 0.35 stalled cycles per insn [25.28%]

618,832,550 branches # 29.758 M/sec [25.06%]

14,727,795 branch-misses # 2.38% of all branches [24.83%]

36,632,522 L1-dcache-loads # 1.762 M/sec [24.99%]

997,478 L1-dcache-load-misses # 2.72% of all L1-dcache hits [25.00%]

<not supported> LLC-loads

<not supported> LLC-load-misses

25.369885801 seconds time elapsed

$ sudo perf\_3.16 stat -d ./hello\_fft.bin 20 10 2

rel\_rms\_err = 1.4e-06, usecs = 193745, k = 0

rel\_rms\_err = 1.4e-06, usecs = 194533, k = 1

Performance counter stats for './hello\_fft.bin 20 10 2':

41489.336000 task-clock (msec) # 0.813 CPUs utilized

1,241 context-switches # 0.030 K/sec

0 cpu-migrations # 0.000 K/sec

20,567 page-faults # 0.496 K/sec

28,924,373,678 cycles # 0.697 GHz [37.64%]

3,146,747,530 stalled-cycles-frontend # 10.88% frontend cycles idle [37.61%]

27,314,821 stalled-cycles-backend # 0.09% backend cycles idle [37.43%]

9,032,409,981 instructions # 0.31 insns per cycle

# 0.35 stalled cycles per insn [24.85%]

1,234,499,221 branches # 29.755 M/sec [24.84%]

29,373,667 branch-misses # 2.38% of all branches [25.05%]

59,944,125 L1-dcache-loads # 1.445 M/sec [25.11%]

2,015,937 L1-dcache-load-misses # 3.36% of all L1-dcache hits [25.19%]

<not supported> LLC-loads

<not supported> LLC-load-misses

51.033239728 seconds time elapsed

$ sudo perf\_3.16 stat -d ./hello\_fft.bin 8 10 2

rel\_rms\_err = 2.7e-07, usecs = 20, k = 0

rel\_rms\_err = 2.7e-07, usecs = 18, k = 1

Performance counter stats for './hello\_fft.bin 8 10 2':

35.376000 task-clock (msec) # 0.814 CPUs utilized

11 context-switches # 0.311 K/sec

0 cpu-migrations # 0.000 K/sec

97 page-faults # 0.003 M/sec

1,315,035 cycles # 0.037 GHz

4,507,197 stalled-cycles-frontend # 342.74% frontend cycles idle

441,497 stalled-cycles-backend # 33.57% backend cycles idle

4,967,122 instructions # 3.78 insns per cycle

# 0.91 stalled cycles per insn [59.55%]

942,058 branches # 26.630 M/sec [39.51%]

40,161 branch-misses # 4.26% of all branches [16.84%]

<not counted> L1-dcache-loads

<not counted> L1-dcache-load-misses

<not supported> LLC-loads

<not supported> LLC-load-misses

0.043437430 seconds time elapsed

$ sudo perf\_3.16 stat -d ./hello\_fft.bin 8 1 2

rel\_rms\_err = 3.3e-07, usecs = 53, k = 0

rel\_rms\_err = 3.3e-07, usecs = 34, k = 1

Performance counter stats for './hello\_fft.bin 8 1 2':

25.234000 task-clock (msec) # 0.741 CPUs utilized

17 context-switches # 0.674 K/sec

0 cpu-migrations # 0.000 K/sec

91 page-faults # 0.004 M/sec

3,416,788 cycles # 0.135 GHz

5,496,335 stalled-cycles-frontend # 160.86% frontend cycles idle

459,694 stalled-cycles-backend # 13.45% backend cycles idle

4,608,842 instructions # 1.35 insns per cycle

# 1.19 stalled cycles per insn [42.36%]

787,847 branches # 31.222 M/sec [18.20%]

<not counted> branch-misses

<not counted> L1-dcache-loads

<not counted> L1-dcache-load-misses

<not supported> LLC-loads

<not supported> LLC-load-misses

0.034069553 seconds time elapsed

$ sudo perf\_3.16 stat -d ./hello\_fft.bin 8 50 2

rel\_rms\_err = 2.5e-07, usecs = 18, k = 0

rel\_rms\_err = 2.5e-07, usecs = 18, k = 1

Performance counter stats for './hello\_fft.bin 8 50 2':

85.593000 task-clock (msec) # 0.905 CPUs utilized

13 context-switches # 0.152 K/sec

0 cpu-migrations # 0.000 K/sec

141 page-faults # 0.002 M/sec

59,446,895 cycles # 0.695 GHz [33.73%]

18,211,275 stalled-cycles-frontend # 30.63% frontend cycles idle [44.18%]

447,559 stalled-cycles-backend # 0.75% backend cycles idle

9,224,249 instructions # 0.16 insns per cycle

# 1.97 stalled cycles per insn [43.85%]

1,173,759 branches # 13.713 M/sec [33.63%]

72,115 branch-misses # 6.14% of all branches [28.20%]

82,373 L1-dcache-loads # 0.962 M/sec [27.02%]

58,372 L1-dcache-load-misses # 70.86% of all L1-dcache hits [26.00%]

<not supported> LLC-loads

<not supported> LLC-load-misses

0.094569758 seconds time elapsed

## Conclusion:

Rel\_rms\_err, time,

Bigger job size, bigger rel\_rms\_err.

More batches, less rel\_rms\_err.

More batches, less compute time for each task.

# CPU part:

Numpy