C++ free style assignment: Bee tracker

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Introduction

Beekeepers and searchers try to better understand the behavior of bees to prevent the mortality of colonies.

What can be collected for now ?

- Beehive weight
- Inside and outside temperature
- Humidity
- Sound
- ...

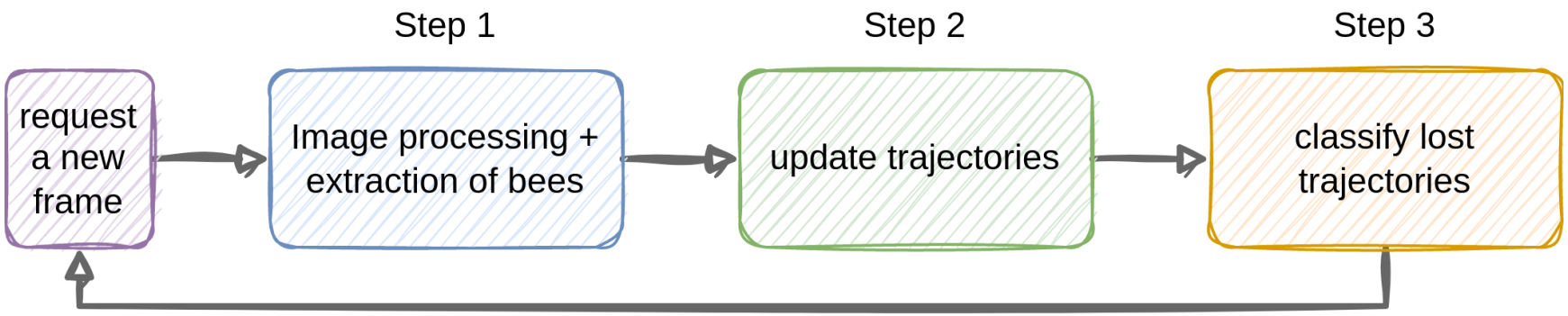
$\Rightarrow$ Lack of data from the activity at the beehive entrance

Introduction

- Put a camera on top of the beehive
- Real time video processing and paths tracking
- Low power budget (solar powered system)

Typical Hardware: Raspberry pi zero 2w (4x Cortex-A53) + camera $\Rightarrow$ Presented benchmarks have been done on a Raspberry pi 3B (roughly the same SoC)

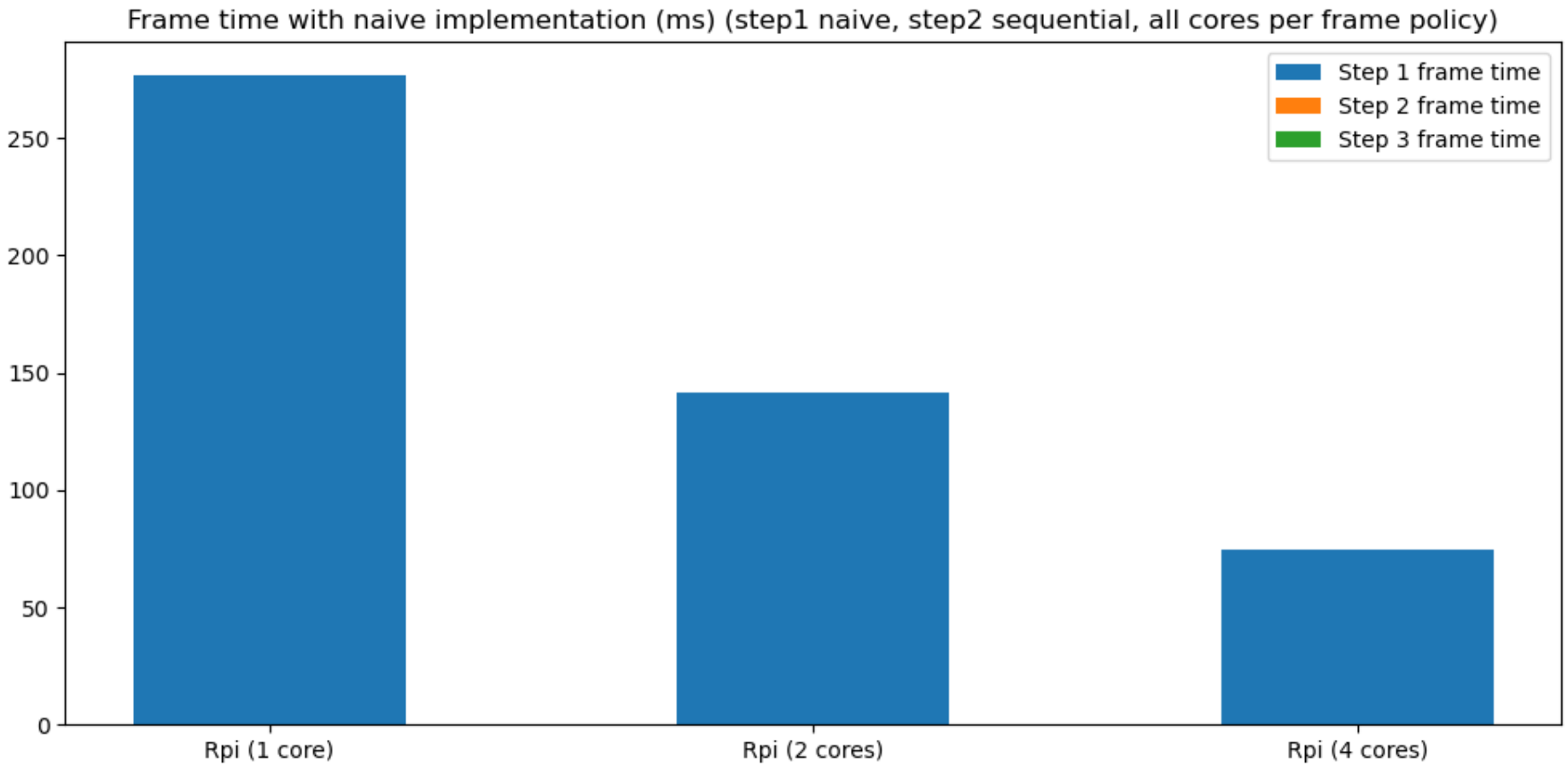
Software architecture overview



Approach based on two recent papers

- **Bee hive traffic monitoring by tracking bee flight paths**, *Baptiste Magnier, Gaëtan Ekszterowicz, Joseph Laurent, Matthias Rival, François Pfister* (2018)
- **Multiple honey bees tracking and trajectory modeling**, *Baptiste Magnier, Eliyahou Gabbay, Faysal Bougamale, Behrang Moradi, François Pfister, Pierre Slangen* (2019)

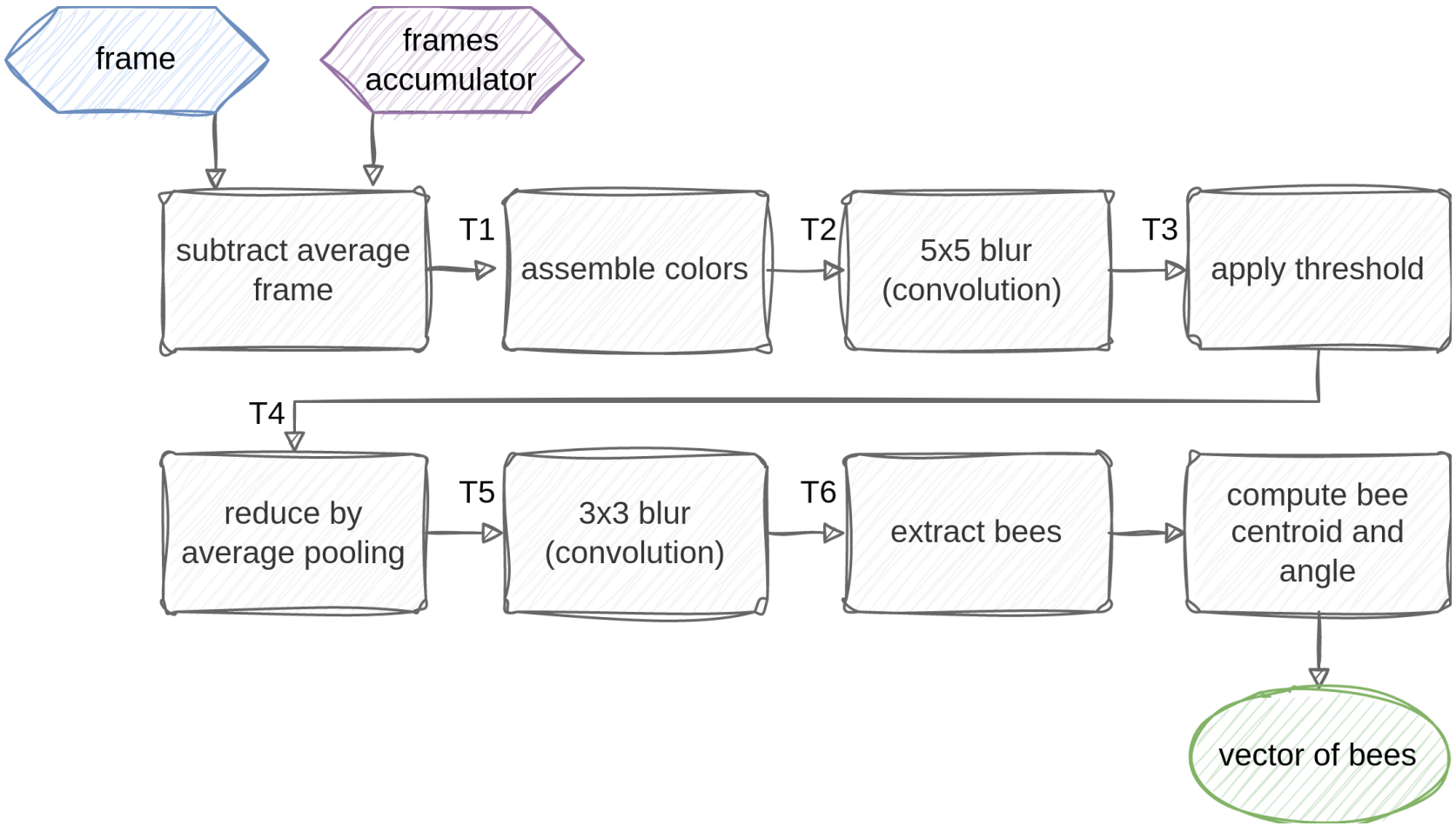
Early benchmark: < 15 *fps*



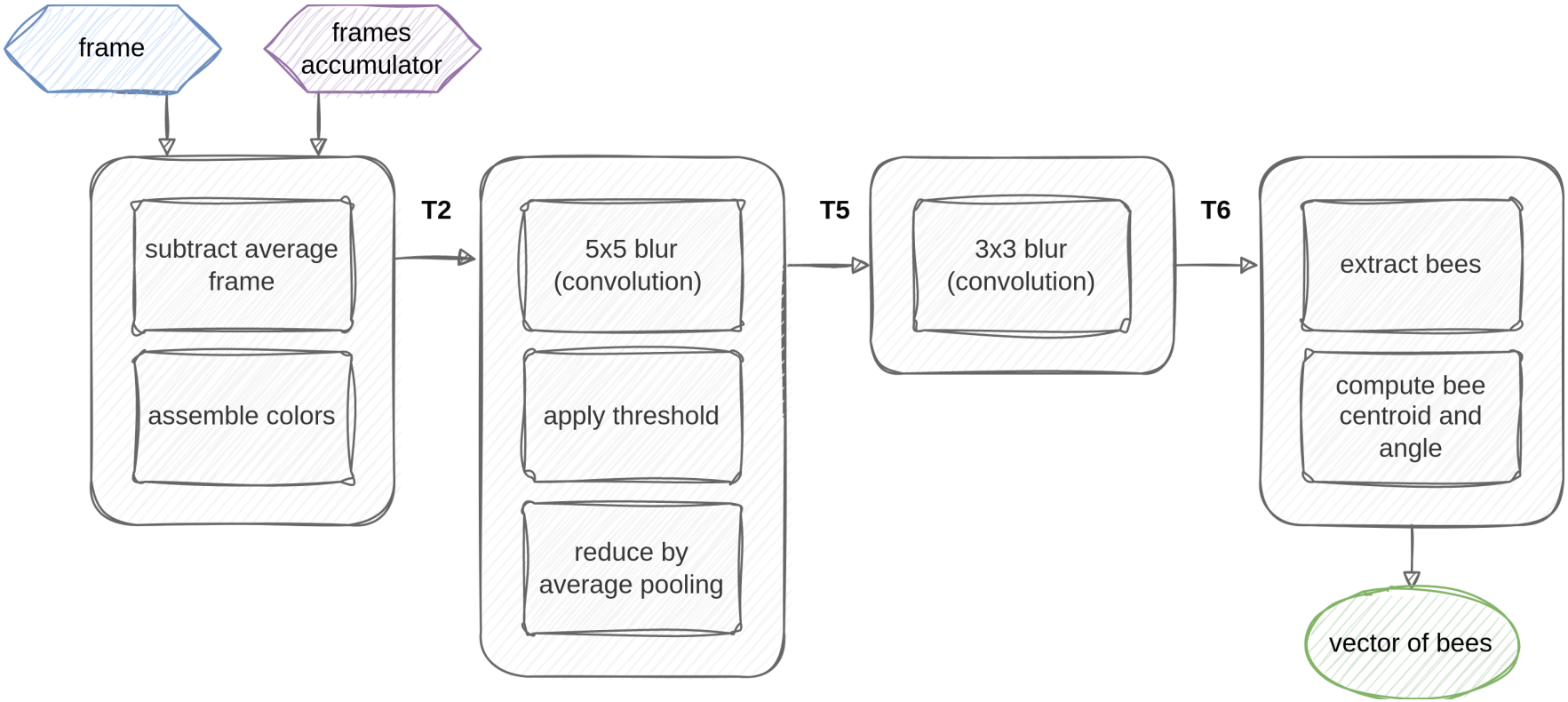
Step 1 is the bottleneck

Optimization will mostly focus on step 1

Step 1 naive architecture



Fuse operations when possible



Optimization of convolution

Switch from Gaussian blur to simple blur:

$$\begin{pmatrix} 1 & 4 & 7 & 1 & 1 \\ 4 & 16 & 26 & 16 & 4 \\ 7 & 16 & 41 & 26 & 7 \\ 4 & 16 & 26 & 16 & 4 \\ 1 & 4 & 7 & 4 & 1 \end{pmatrix} \Rightarrow \begin{pmatrix} 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 \end{pmatrix} = \begin{pmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{pmatrix} x \begin{pmatrix} 1 & 1 & 1 & 1 & 1 \end{pmatrix}$$

Optimization of convolution

Switch from Gaussian blur to simple blur:

$$\begin{pmatrix} 1 & 4 & 7 & 1 & 1 \\ 4 & 16 & 26 & 16 & 4 \\ 7 & 16 & 41 & 26 & 7 \\ 4 & 16 & 26 & 16 & 4 \\ 1 & 4 & 7 & 4 & 1 \end{pmatrix} \Rightarrow \begin{pmatrix} 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 \end{pmatrix} = \begin{pmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{pmatrix} x \begin{pmatrix} 1 & 1 & 1 & 1 & 1 \end{pmatrix}$$

Reduction of the number of operations:

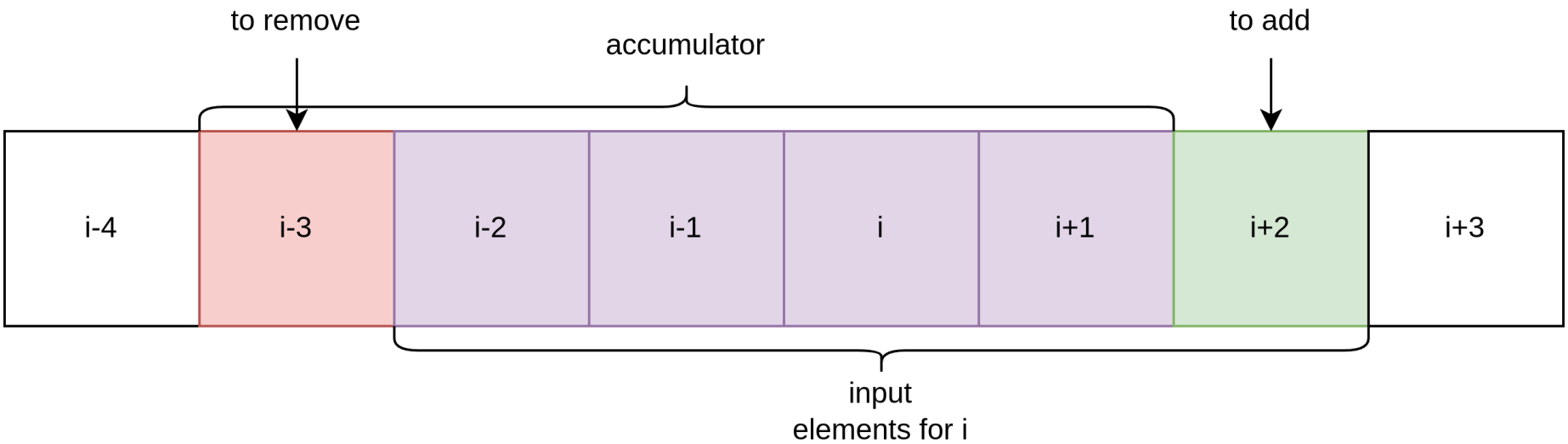
- 5x5 kernel: from 25 to 10: -60%
- 3x3 kernel: from 9 to 6: -33%

Optimization of convolution

The two kernels are only composed of ones:

Common operations between elements

An accumulator and a sliding windows can be used instead of classical convolution



Manual Vectorization

Arm Neon / x86 SSE

- 128-bit vectors
- 8 x `(u)int16_t`

Use of intrinsics instead of assembly:

```
// get input
int16x8_t input = vreinterpretq_s16_u16(inputBloc[inputBlocIndex++]);
// add to accumulator
accumulator = vaddq_s16(accumulator, input);
// put result
outputBloc[outputBlocIndex++] = vreinterpretq_u16_s16(vshrq_n_s16(accumulator, 2));
// update accumulator
accumulator = vsubq_s16(accumulator, previous[0]);
```

```
// get input
__m128i input = inputBloc[inputBlocIndex++];
// add to accumulator
accumulator = _mm_add_epi16(accumulator, input);
// put result / 4 in output bloc
outputBloc[outputBlocIndex++] = _mm_srai_epi16(accumulator, 2);
// update accumulator
accumulator = _mm_sub_epi16(accumulator, previous[0]);
```

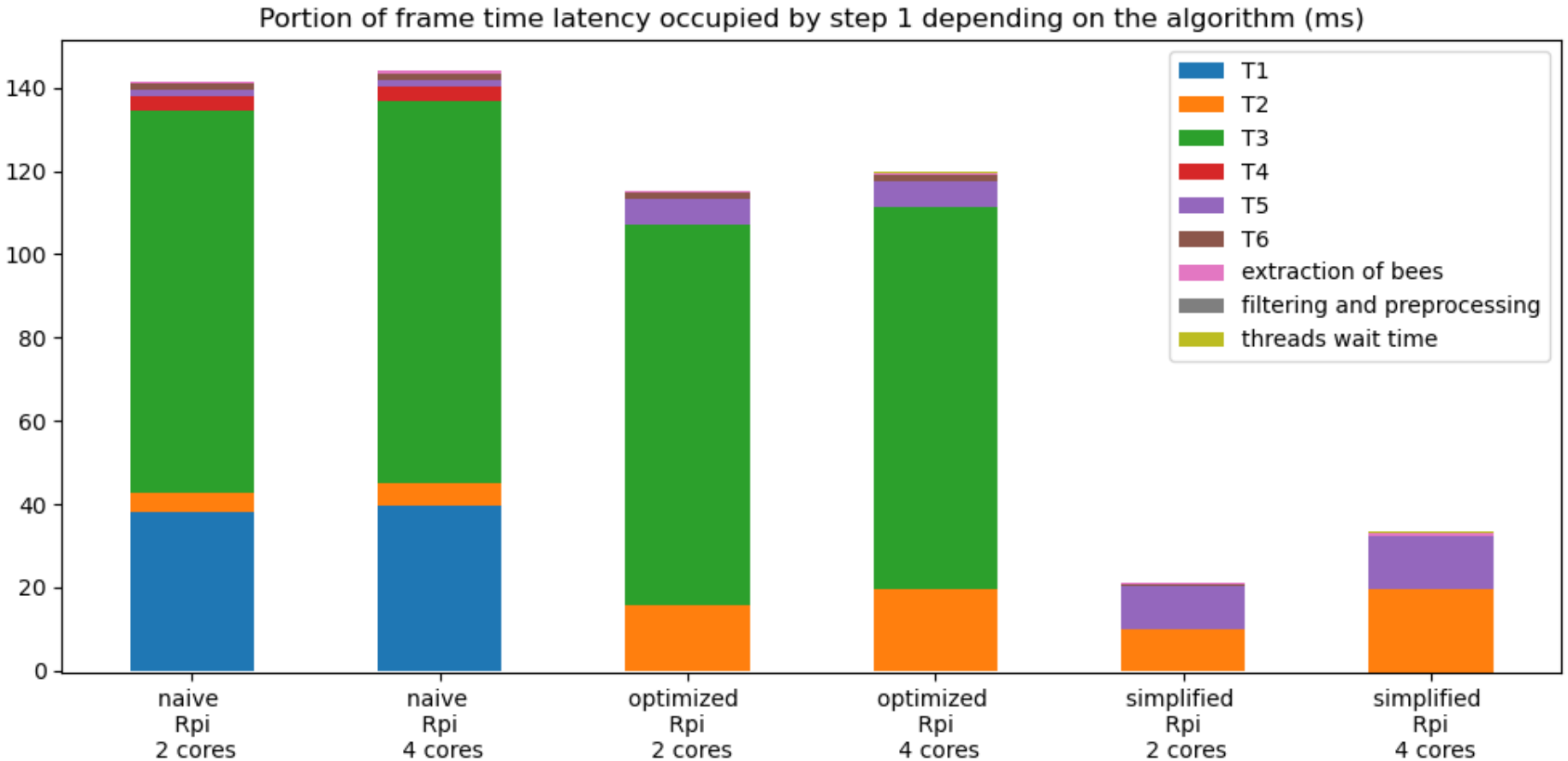
Manual Vectorization challenge

Biggest challenges:

- Intrinsics are not easy to learn
- 8 elements at a time: need to handle corner cases
- Need to load contiguous 128-BIT data for better performance

- De-interleave RGB images
  - Load with de-interleave on Neon, shuffle on SSE
  - Do the arithmetic for each channel
  - Store frames accumulator directly de-interleaved
- Convolution with horizontal kernel:
  - Load a 8x8 bloc (8x 128-BIT loads)
  - Transpose the input bloc
  - Do the arithmetic
  - Transpose the output bloc
  - Store a 8x8 bloc (8x 128-bit stores)

Results


Portion of frame time latency occupied by step 1 depending on the algorithm (ms)
0
20
40
60
80
100
120
140
T1
T2
T3
T4
T5
T6
extraction of bees
filtering and preprocessing
threads wait time
naive Rpi 2 cores
naive Rpi 4 cores
optimized Rpi 2 cores
optimized Rpi 4 cores
simplified Rpi 2 cores
simplified Rpi 4 cores

Step 2: Parallel implementation

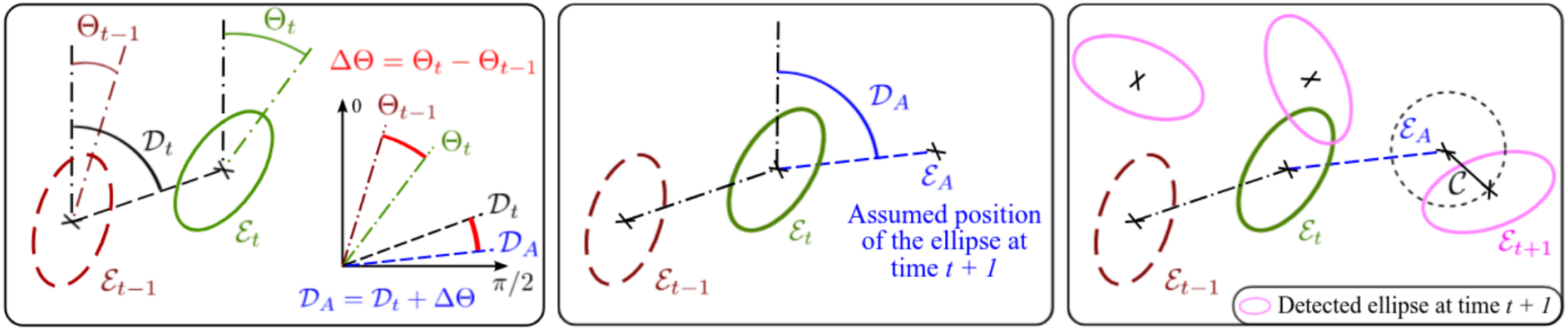


Figure 4: Concordance computation between the assumed ellipse and a detected one.

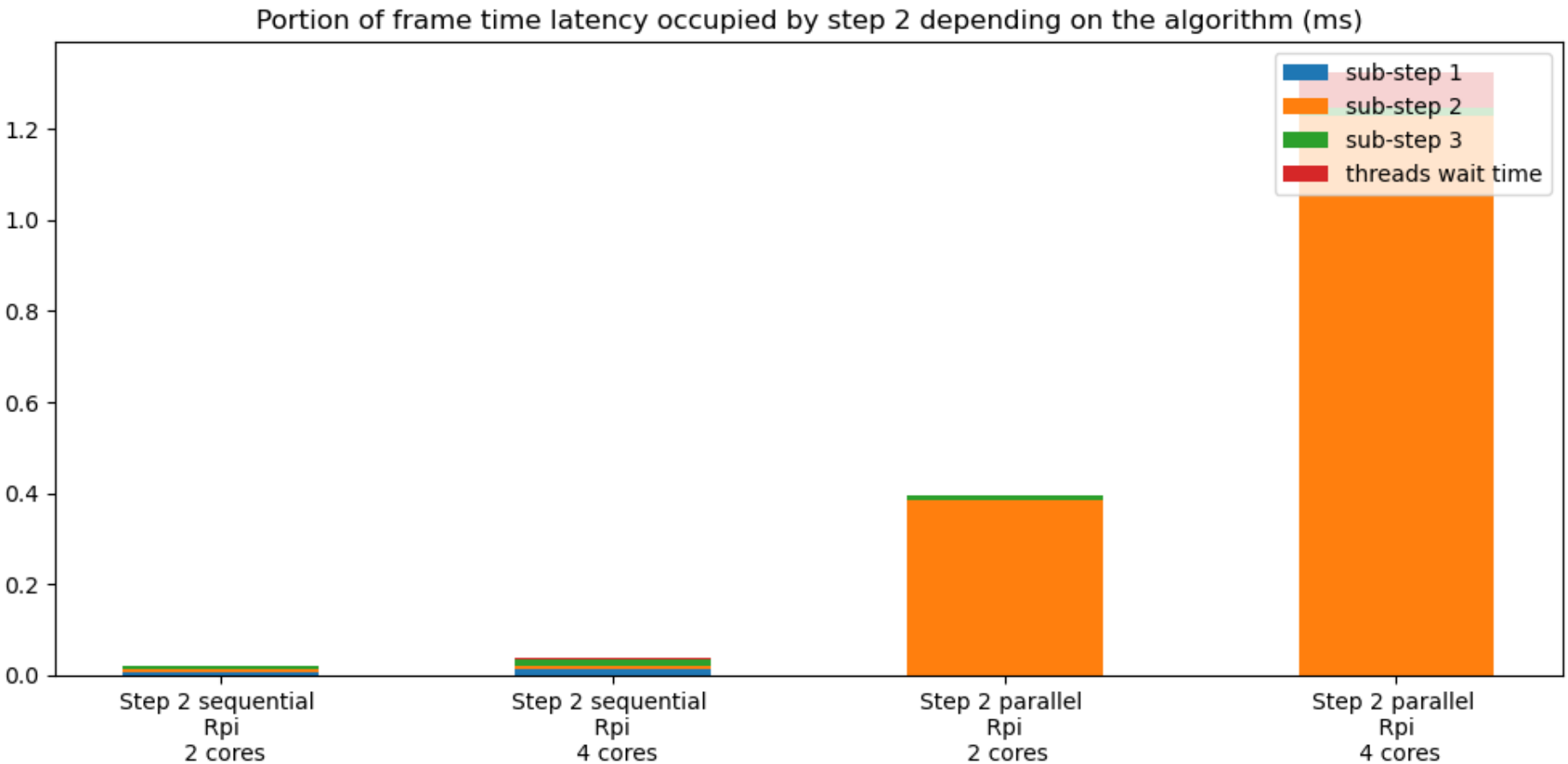
Work distribution

Each thread has a set of trajectories to process

Concurrency management

Use of a vector of Atomics to know if a bee has been picked or not

...but sequential implementation remains better



Work scheduling

Most of Step 1 is (massively) parallel

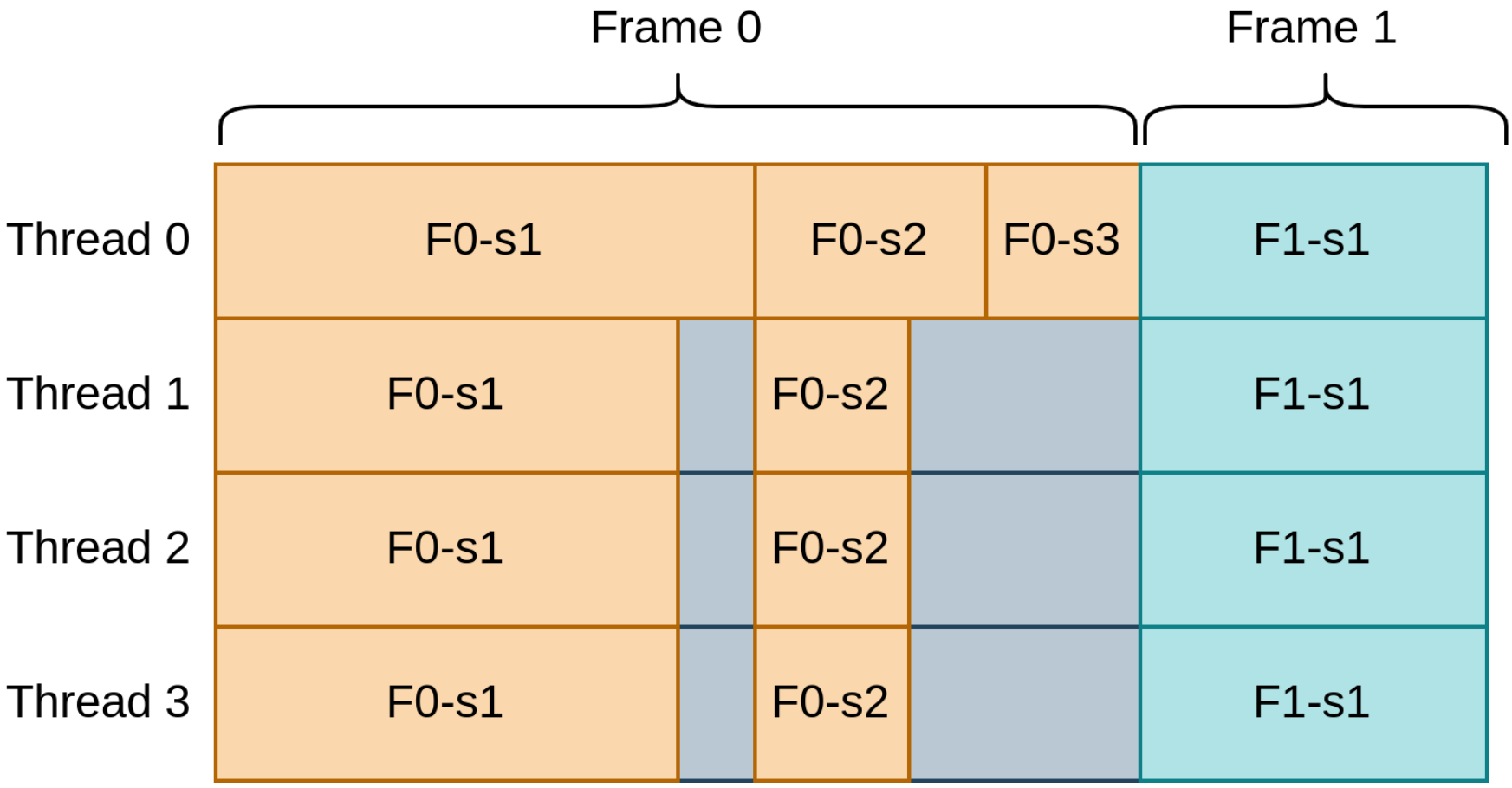
OpenMP is used to provide parallelism with some issues:

- All cores work on memory intensive sections at the same time
- Some sections of the whole algorithm remains sequential

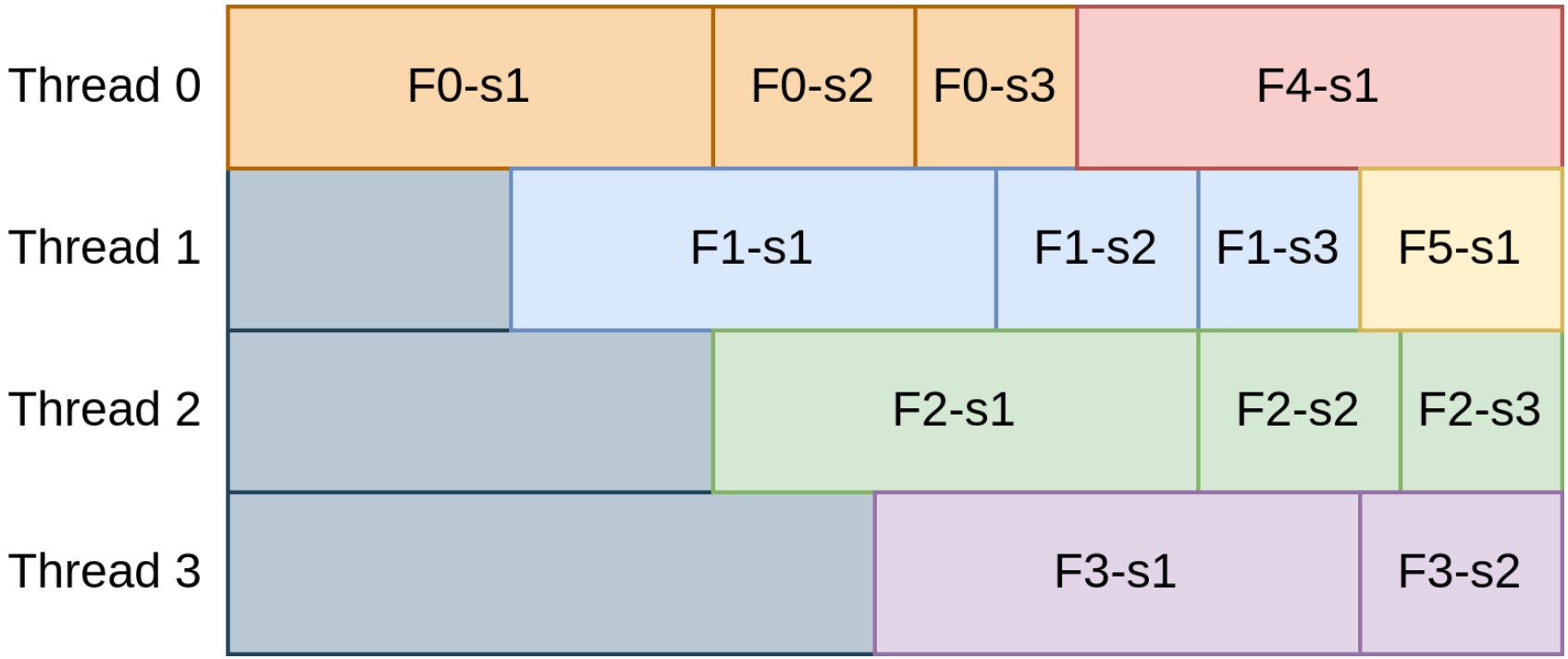
What about frames ?

Most of the operations can be done on multiple frames in parallel

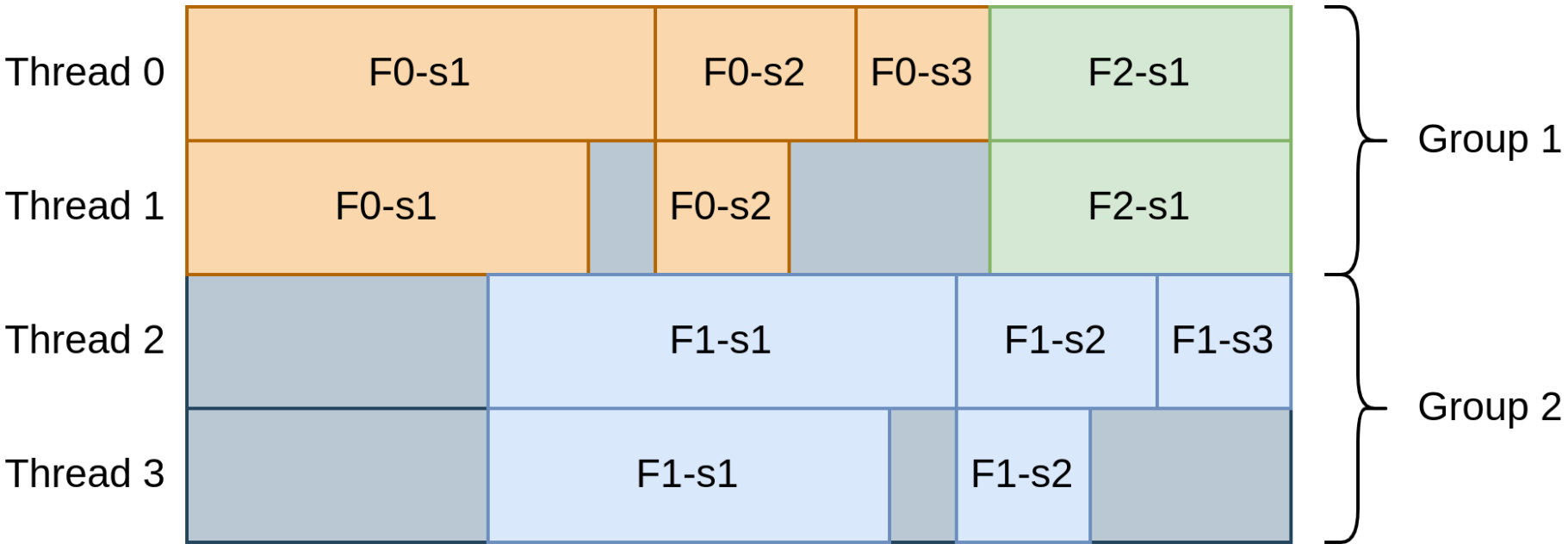
Possible policies: All thread on each frame



Possible policies: One thread per frame



Possible policies: Hybrid approach



Global concurrency challenge

Shared structures

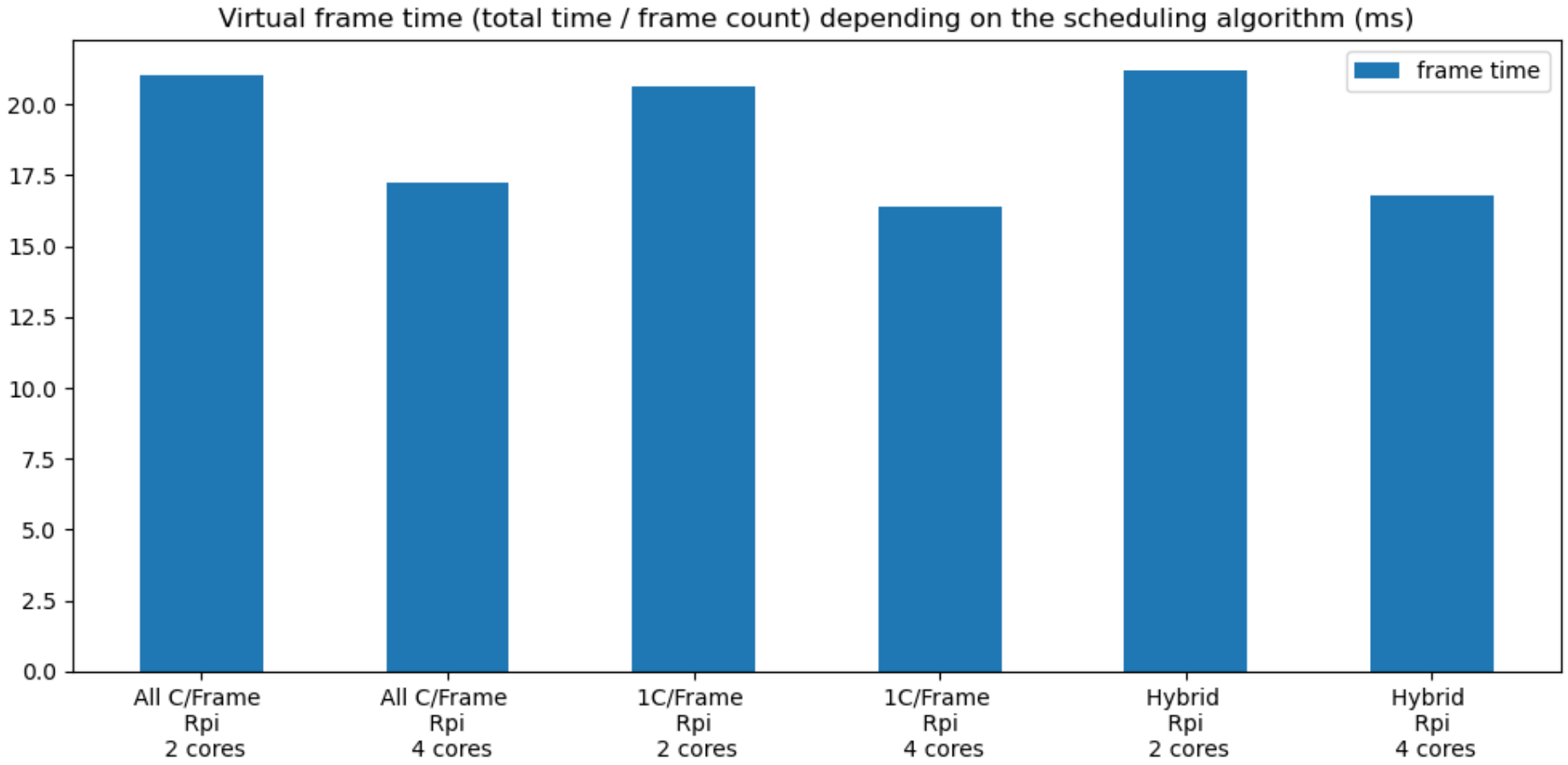
- Frames accumulator: Cut it into N blocs (N is determined by a benchmark) which can be locked by a thread if it's free and already updated with previous frame.
- Tracked bees: Access are done in a critical section

Critical sections

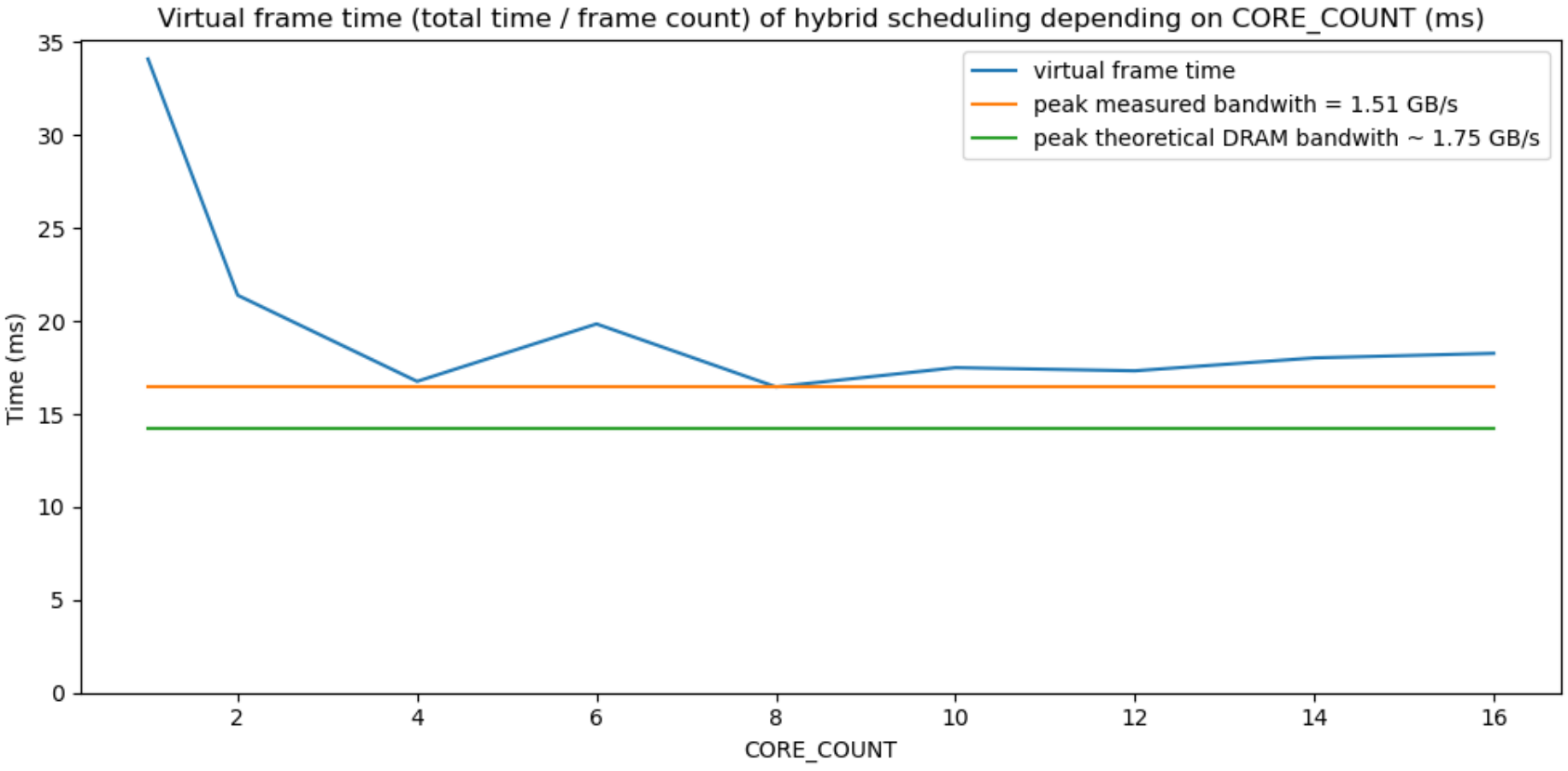
Not simple Mutex, a thread can lock it only if the previous frame has already been processed.

$\Rightarrow$ All global concurrency is managed by the `GlobalConcurrency` class.

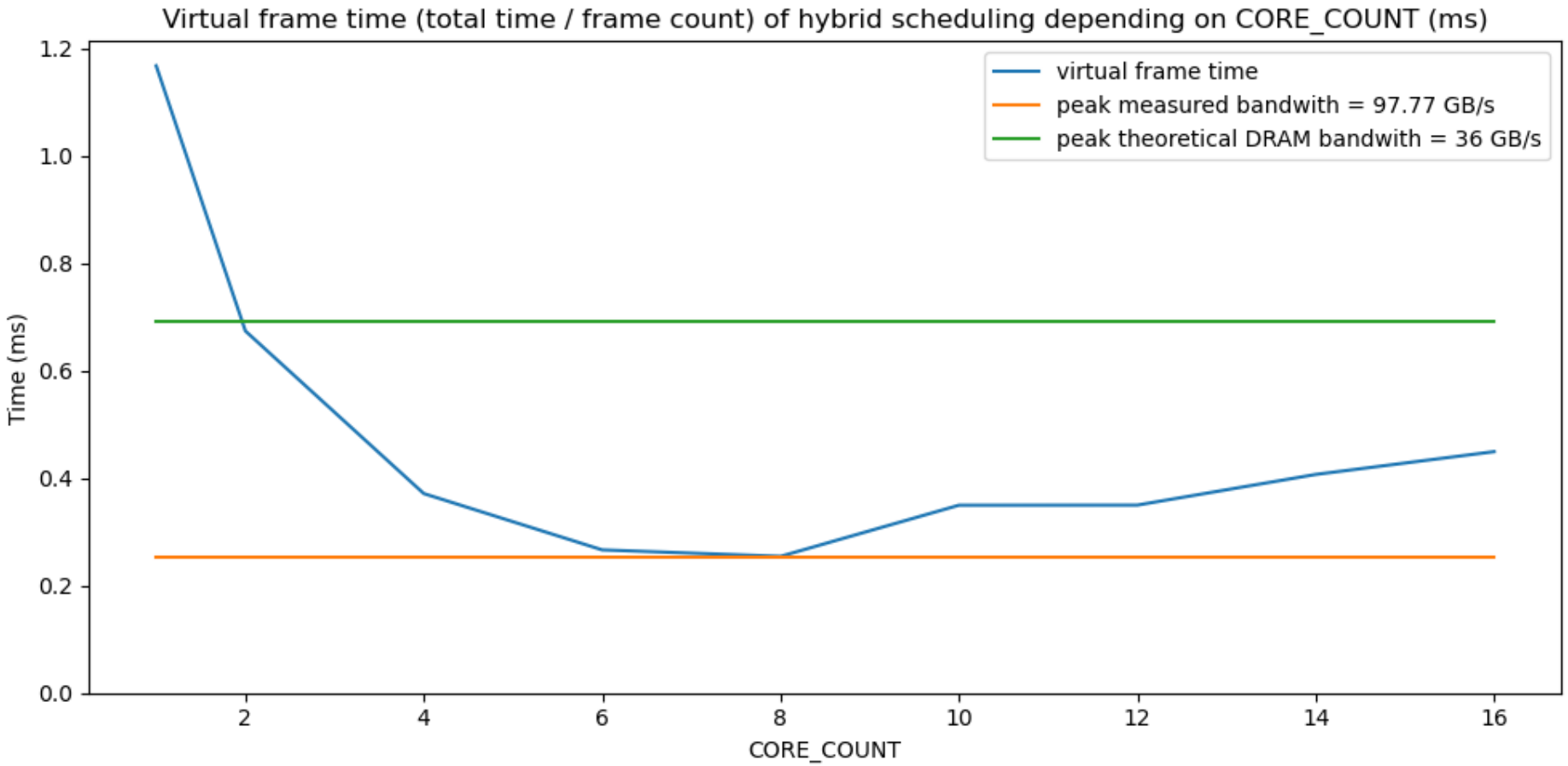
Results


Virtual frame time (total time / frame count) depending on the scheduling algorithm (ms)
frame time
20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
0.0
All C/Frame Rpi 2 cores
All C/Frame Rpi 4 cores
1C/Frame Rpi 2 cores
1C/Frame Rpi 4 cores
Hybrid Rpi 2 cores
Hybrid Rpi 4 cores

The memory bandwidth issue

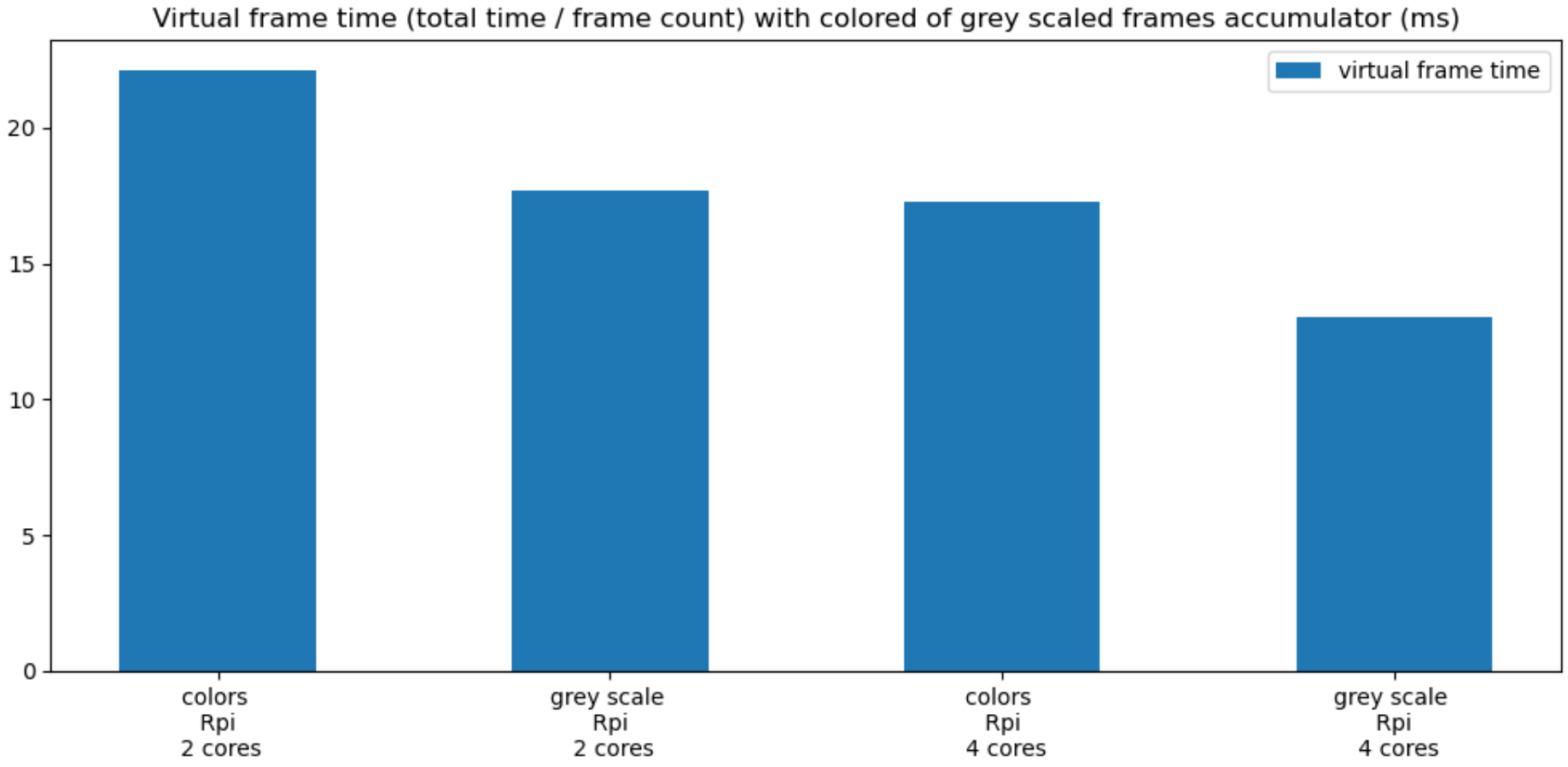


The memory bandwidth issue

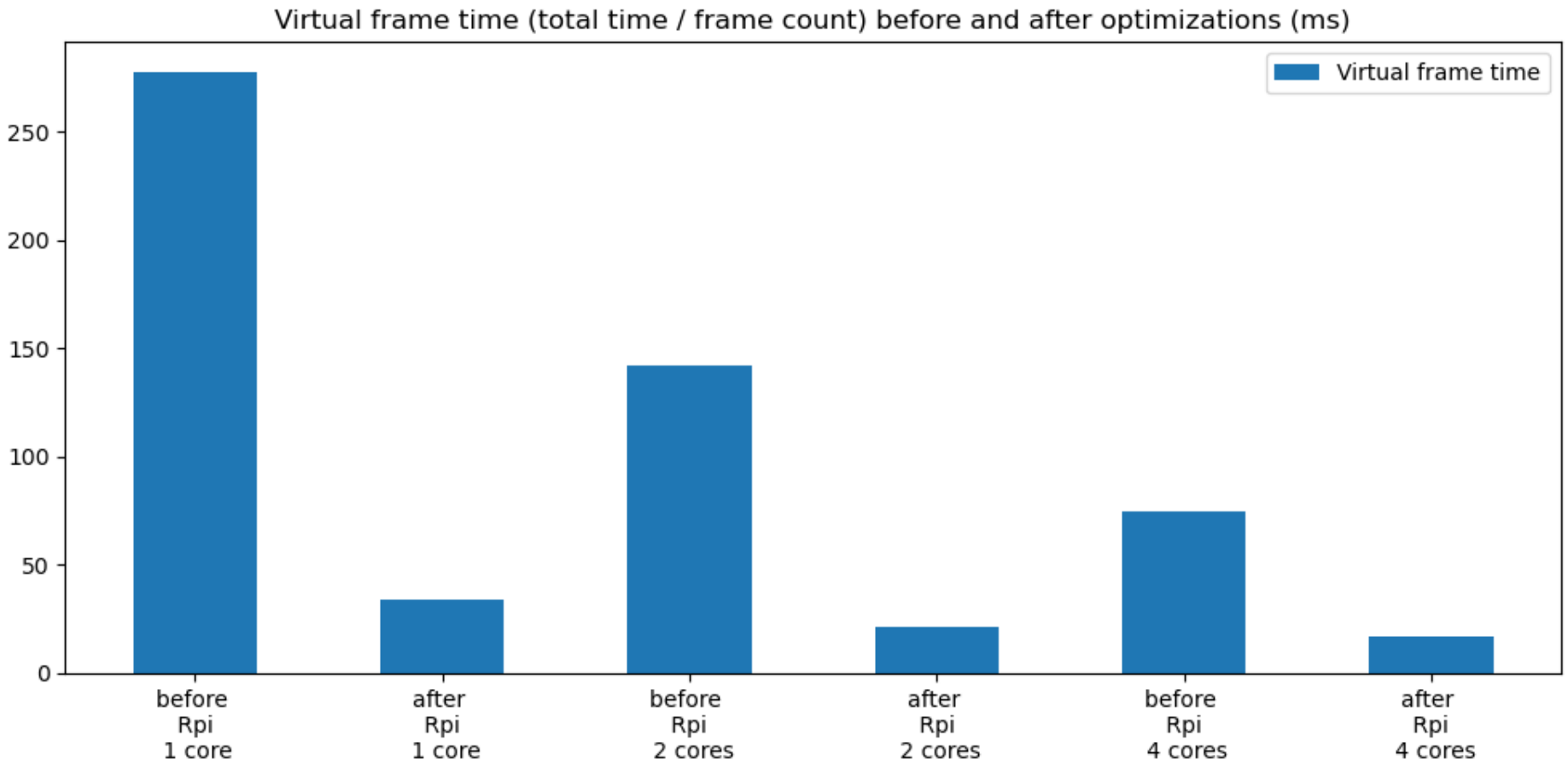


$\Rightarrow$ Cache is big enough to store the frames accumulator

Grey scale processing



Final benchmarks: 60 fps



60 fps on real time with camera seems possible !

Around 75 fps in HD grey scale benchmarks, impact of camera on bandwidth, margin

Future work

- Tweak parameters to have the best accuracy
- Get frame from the camera
- Make it real time compatible
- Evaluate if a CNN model is a good option to provide better accuracy
- Make a working prototype :)

Vielen Dank !