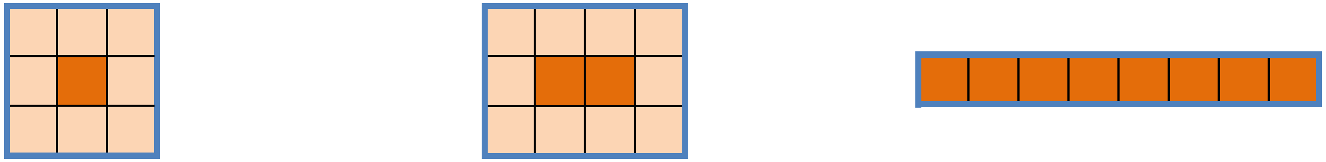


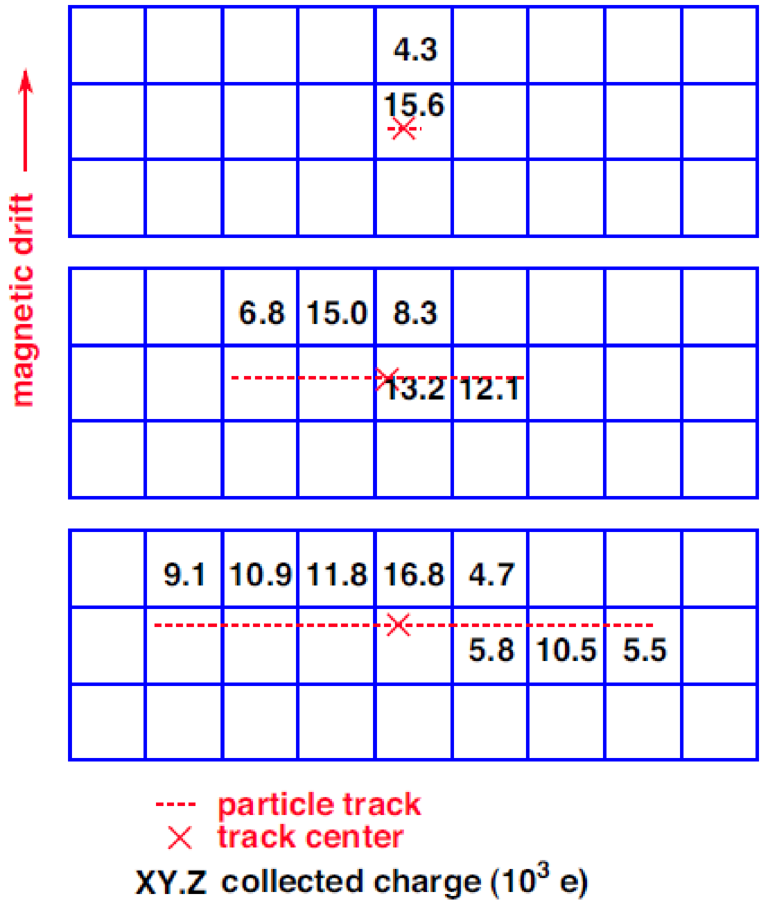
Pixel Region optimization

for CMS pixel phase2

Elia Conti

University of Perugia

Clustered hits in CMS detector



- The propagation of tracks through the barrel or forward pixel arrays produces clusters of hit pixels
- Cluster shapes and sizes depend on a quantity of factors
  - pixel size
  - Si detector
  - radiation damage
  - track angle
  - detector angle
  - magnetic deflection (Lorentz angle)

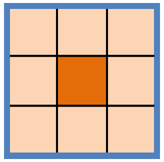
hits are distributed in clusters along a preferential direction

M. Swartz, "A Detailed Simulation of the CMS Pixel Sensor," CMS Note 2002/027

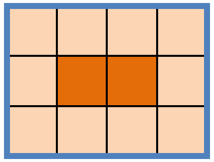
Pixel regions and clustered hits

- Clustered hits can be exploited for optimizing the pixel architecture with the grouping of pixels in pixel regions (**PR**)
  - Groups of pixels can share electronics for buffering, routing, …
- PR configurations have been studied with respect to statistical assumptions on hits
- For each PR configuration it has been estimated
  - Average number of PRs hit by a cluster
  - Required number of buffers in a PR (normalized per pixel)
  - Number of memory bits per PR (normalized per pixel)
  - Average number of active latency units (normalized per pixel)
- Three different typologies of clusters have been taken into account for this study:

3x3



4x3



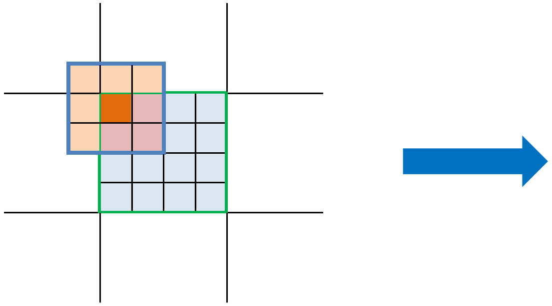
Elongated (one-dimensional)

3x3 and 4x3 clusters (1)

- Clusters with fixed size, they can contain up to
  - 9 pixel hits (3x3)
  - 12 pixel hits (4x3)
- 3x3: square cluster, does not take into account preferential dir.
- 4x3: rectangular cluster, little more contribution on one dir.
- How to calculate average number of PRs hit:
  - Center of cluster is placed on each pixel in a PR
  - The probabilities of hitting 1 – 2 – 3 – … PRs are calculated for each pixel with every possible number of hits inside the cluster (1 to 9 or 1 to 12)
  - Constraint: first hit is in the center
  - Probabilities are then combined for all the pixels in the PR

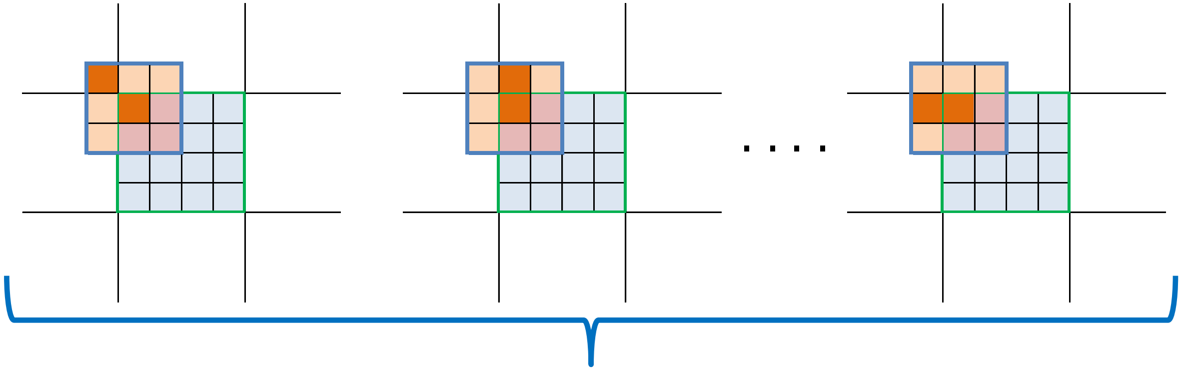
3x3 and 4x3 clusters (2)

- Example: place the center in a cell of the PR
  - 1 hit



P(1 PR hit) = 100%

  - 2 hits

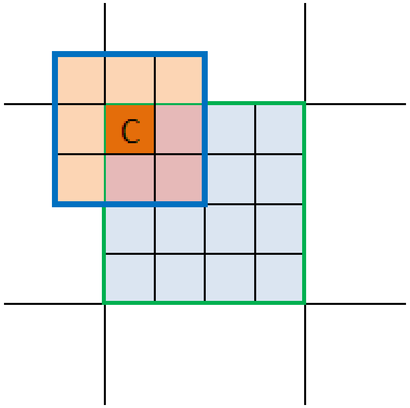


P(1 PR hit) = 3/8 = 37.5%
P(2 PRs hit) = 5/8 = 62.5%

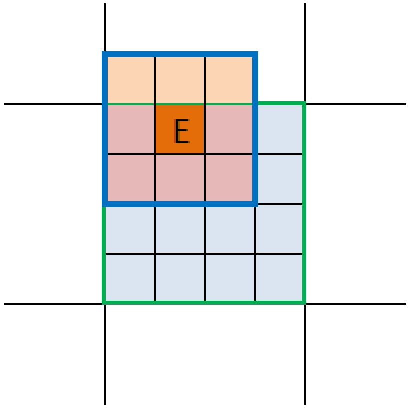
  - … up to 9 hits
- Repeat calculation for all the other cells in the PR and combine

3x3 clusters

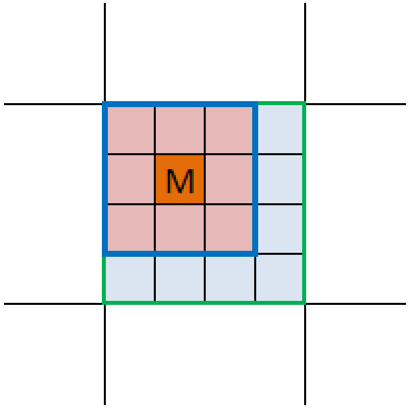
- It is possible to determine different types of PR cells that show the same probability results:



Corner cell



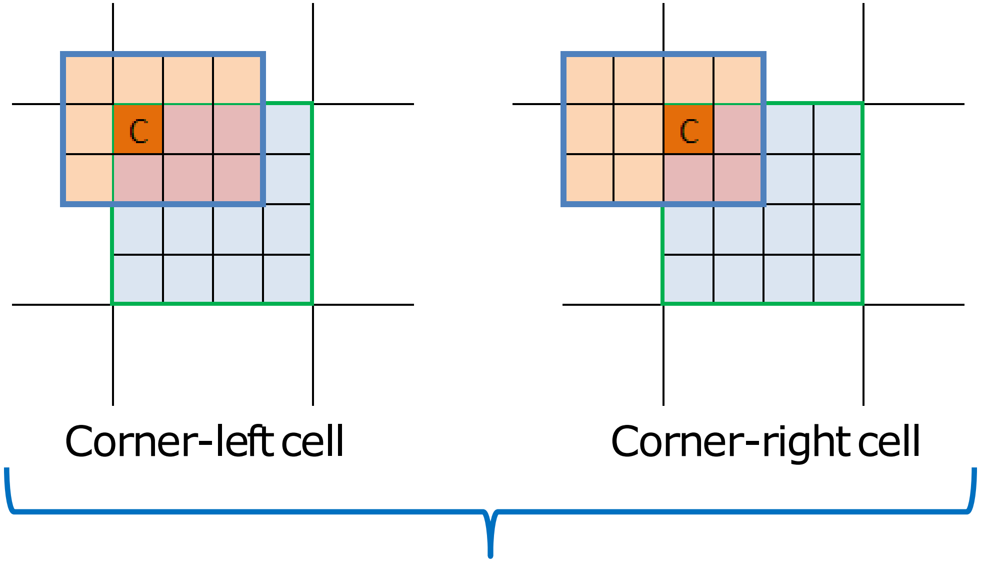
Edge cell



Middle cell

4x3 clusters (1)

- There are more than one center
- For each cell in the PR 2 distinct calculations performed, each with only one fixed center (left and right)
- 2 results averaged



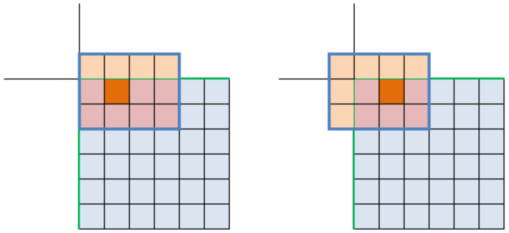
Corner-left cell

Corner-right cell

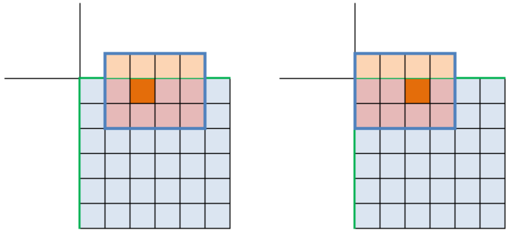
Corner cell

4x3 clusters (2)

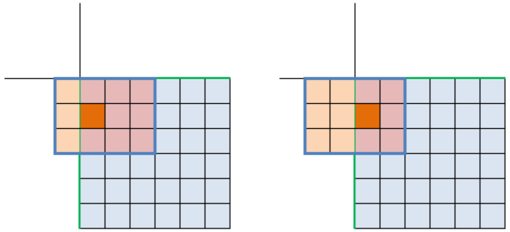
- Different types of PR cells that one can determine:



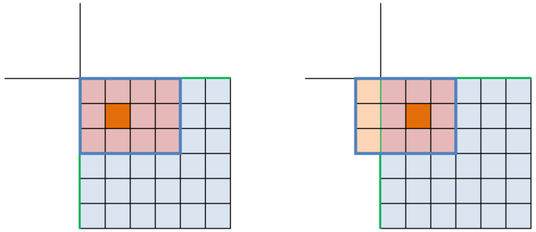
Horizontal corner-edge cell



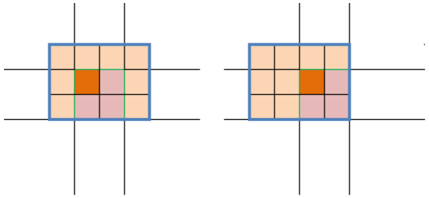
Horizontal edge cell



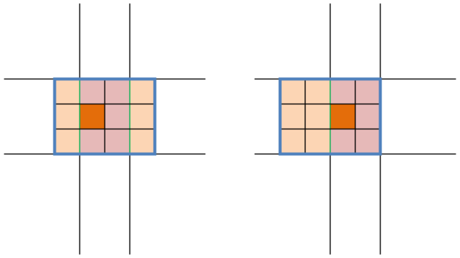
Vertical edge cell



Middle-edge cell



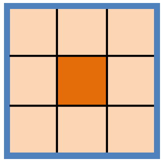
Short corner cell (for small PRs)

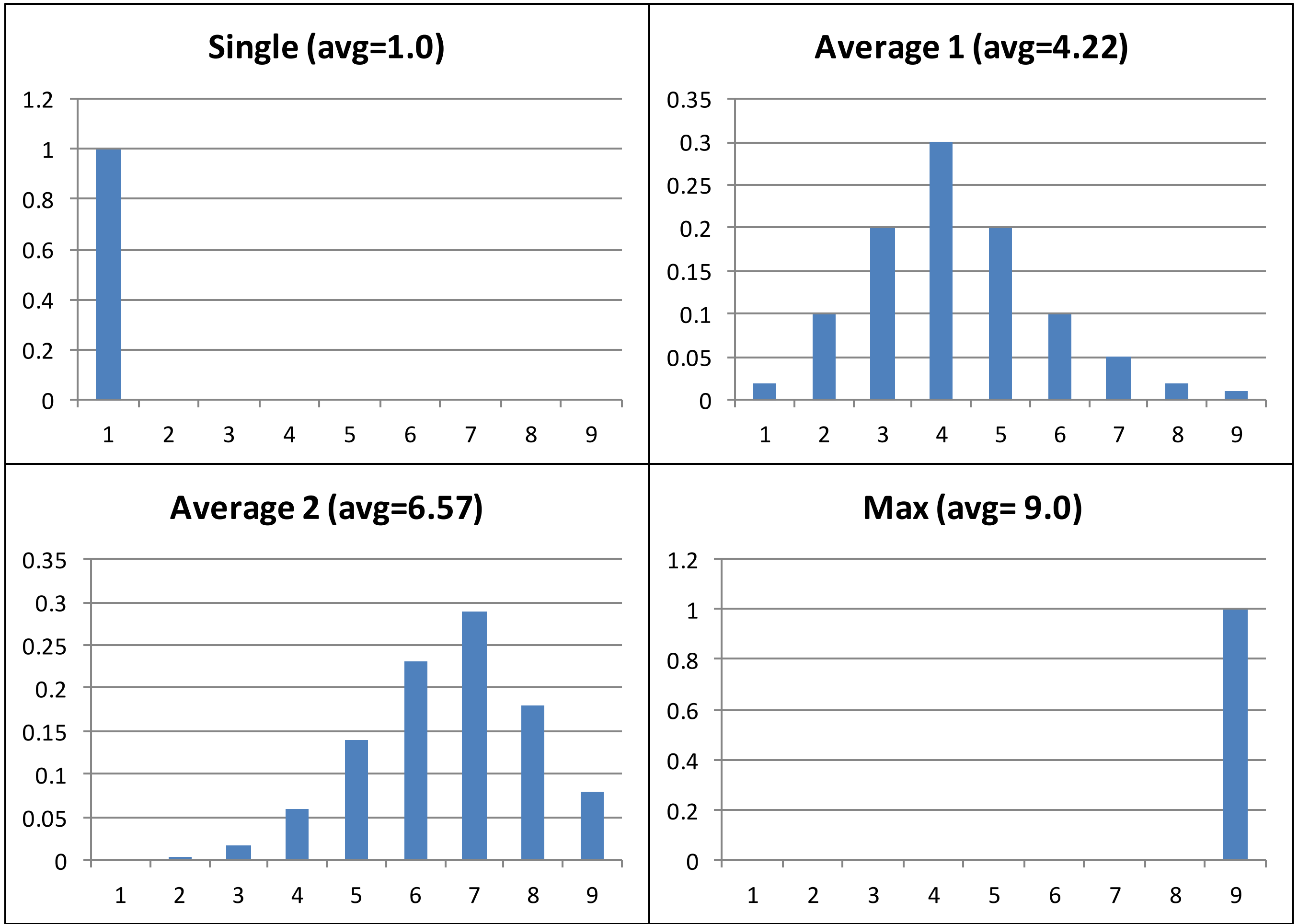


Short edge cell (for small PRs)

Hit distributions in a cluster – 3x3

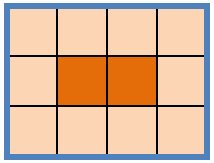
- Not all hits configurations have the same probability!
- Each estimation of the number of PRs involved is thus weighted by the statistical hit distribution in a cluster. Arbitrary distributions for 3x3 clusters:

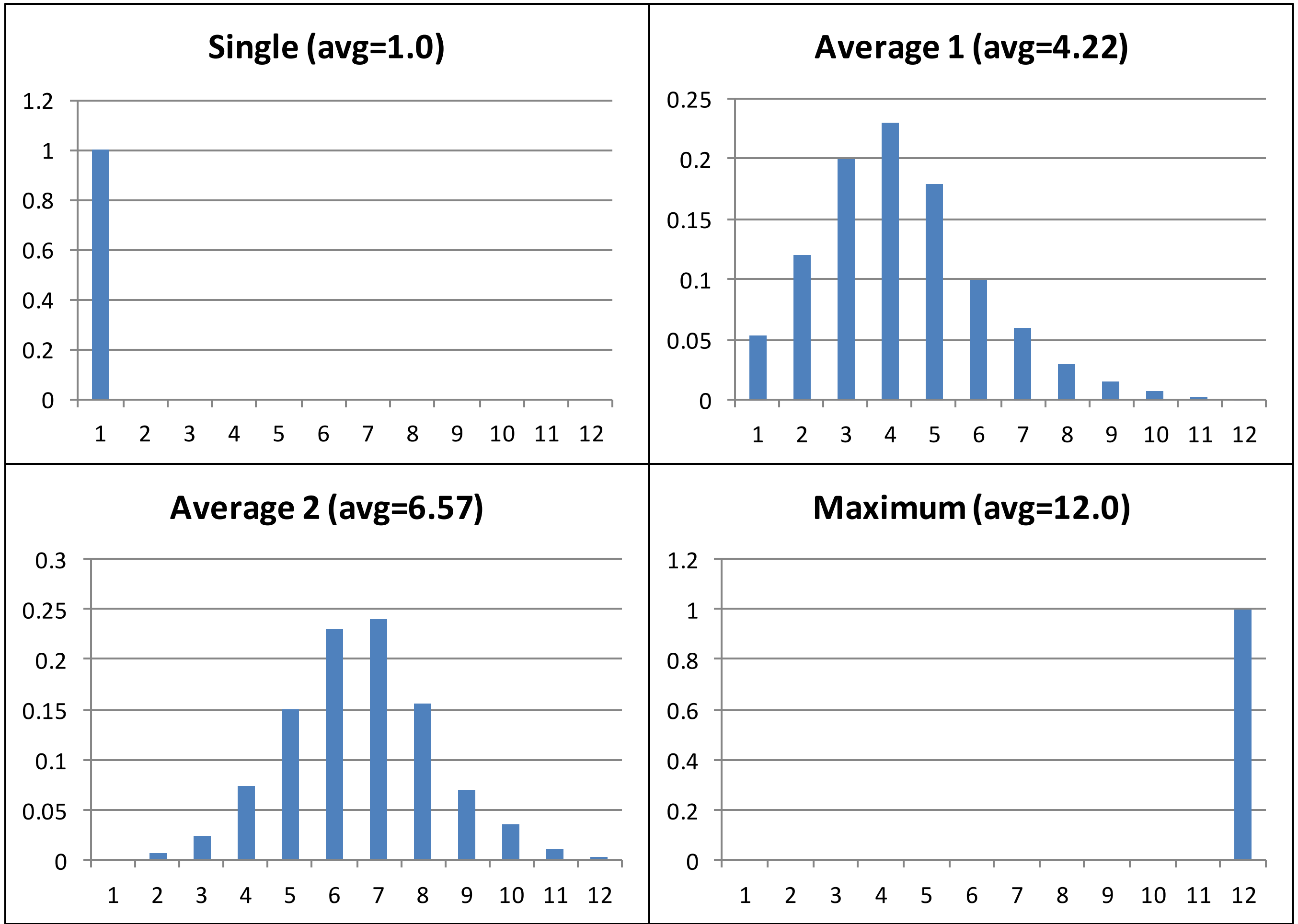




Hit distributions in a cluster – 4x3

- Similar hit distributions have been chosen for each typology of cluster
- Arbitrary hit distributions used for 3x4 clusters:





Elongated one-dimensional clusters

- Variable size depending on the number of pixel hits contained

1 hit = 1 cell

8 hit = 8 cells

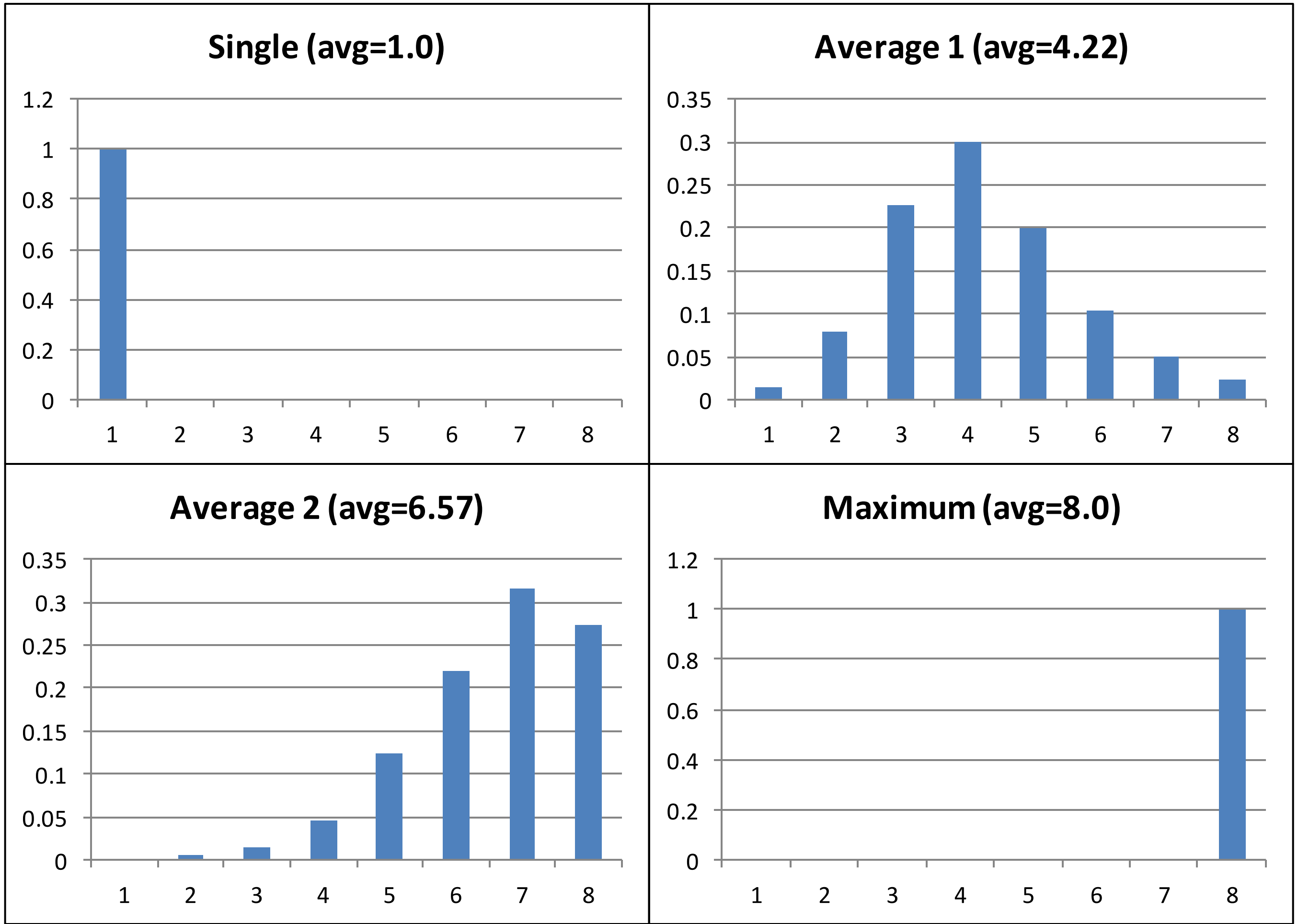
- Shape extends in only one direction
- Clusters can contain up to 8 pixel hits so that shapes are similar to the real ones
- Simplification: no component on the other direction
=> magnetic drift neglected
- Average number of PRs can be calculated with the following empirical formula:

$$PR = \frac{n+h-1}{n}$$

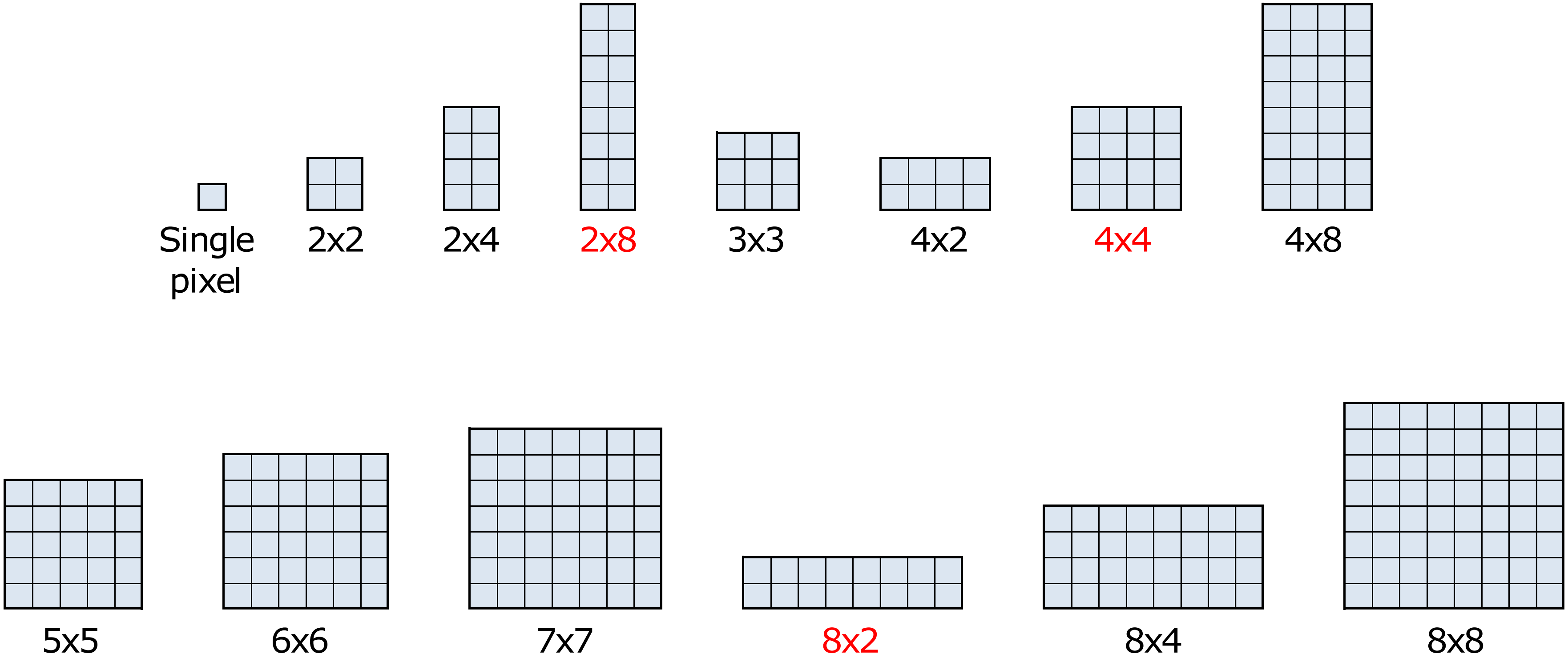
n = PR width
h = number of hits in cluster

Hit distributions in a cluster – 1-dim

- Because not all hits have the same probability, each result has been weighted by the hit distribution coefficients
- Hit distributions have been chosen similar to those of 3x3 and 4x3



Pixel regions under study



- We focus our attention on PRs containing the same number of pixels (2x8, 4x4, 8x2)

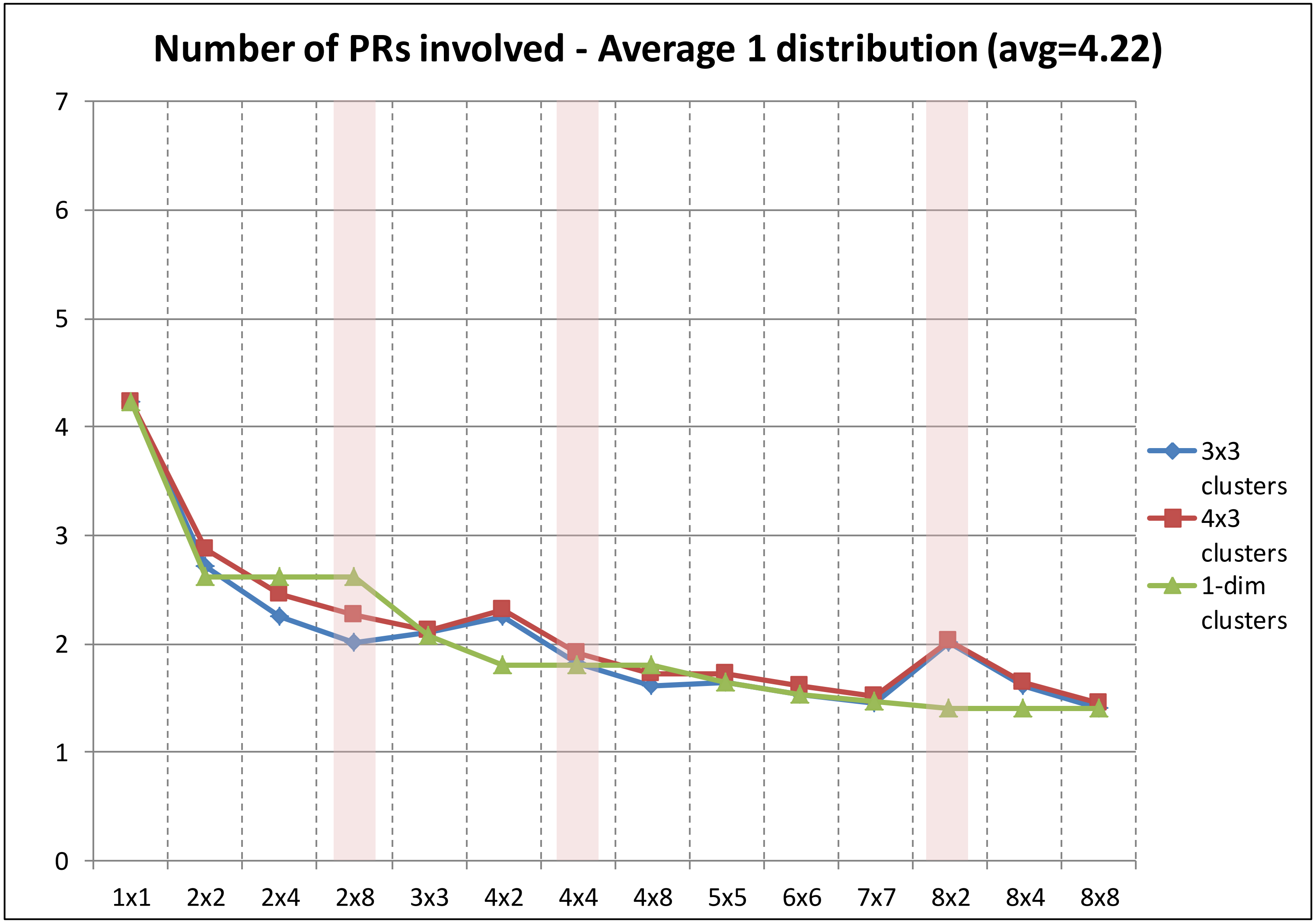
Number of PRs involved (1)

- We obtain the following results after weighting:

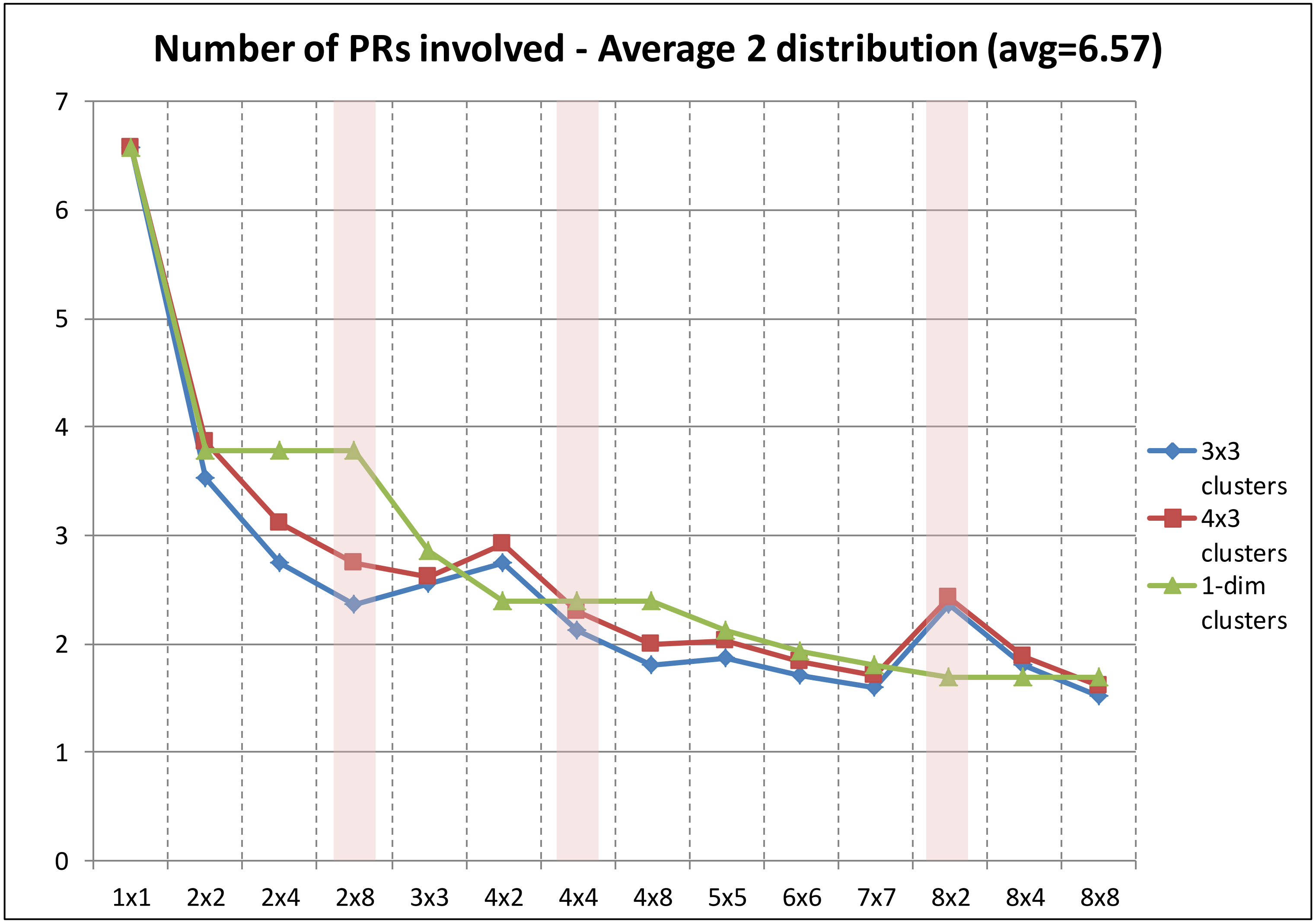
Pixel regions	3x3 clusters				4x3 clusters				1-dim clusters up to 8x1			
	Single	Average 1	Average 2	Maximum	Single	Average 1	Average 2	Maximum	Single	Average1	Average2	Maximum
1x1	1.0000	4.2200	6.5669	9.0000	1.0000	4.2240	6.5700	12.0000	1.0000	4.2220	6.5710	8.0000
2x2	1.0000	2.7135	3.5301	4.0000	1.0000	2.8716	3.8572	5.0000	1.0000	2.6110	3.7855	4.5000
2x4	1.0000	2.2450	2.7486	3.0000	1.0000	2.4619	3.1131	3.7500	1.0000	2.6110	3.7855	4.5000
2x8	1.0000	2.0107	2.3579	2.5000	1.0000	2.2570	2.7411	3.1250	1.0000	2.6110	3.7855	4.5000
3x3	1.0000	2.1066	2.5544	2.7778	1.0000	2.1249	2.6198	3.0556	1.0000	2.0740	2.8570	3.3333
4x2	1.0000	2.2450	2.7486	3.0000	1.0000	2.3102	2.9194	3.5000	1.0000	1.8055	2.3928	2.7500
4x4	1.0000	1.8166	2.1161	2.2500	1.0000	1.9160	2.3023	2.6250	1.0000	1.8055	2.3928	2.7500
4x8	1.0000	1.6024	1.7999	1.8750	1.0000	1.7189	1.9937	2.1875	1.0000	1.8055	2.3928	2.7500
5x5	1.0000	1.6468	1.8691	1.9600	1.0000	1.7279	2.0184	2.2400	1.0000	1.6444	2.1142	2.4000
6x6	1.0000	1.5355	1.7110	1.7778	1.0000	1.6038	1.8356	2.0000	1.0000	1.5370	1.9285	2.1667
7x7	1.0000	1.4568	1.6013	1.6531	1.0000	1.5159	1.7083	1.8367	1.0000	1.4603	1.7959	2.0000
8x2	1.0000	2.0107	2.3579	2.5000	1.0000	2.0185	2.4303	2.7500	1.0000	1.4028	1.6964	1.8750
8x4	1.0000	1.6024	1.7999	1.8750	1.0000	1.6397	1.8865	2.0625	1.0000	1.4028	1.6964	1.8750
8x8	1.0000	1.3983	1.5208	1.5625	1.0000	1.4503	1.6145	1.7188	1.0000	1.4028	1.6964	1.8750

- More PRs involved in 2x8 with 1-dim clusters
- Less PRs involved in 8x2 with 1-dim clusters

Number of PRs involved (2)



Number of PRs involved (3)



Number of required buffers (1)

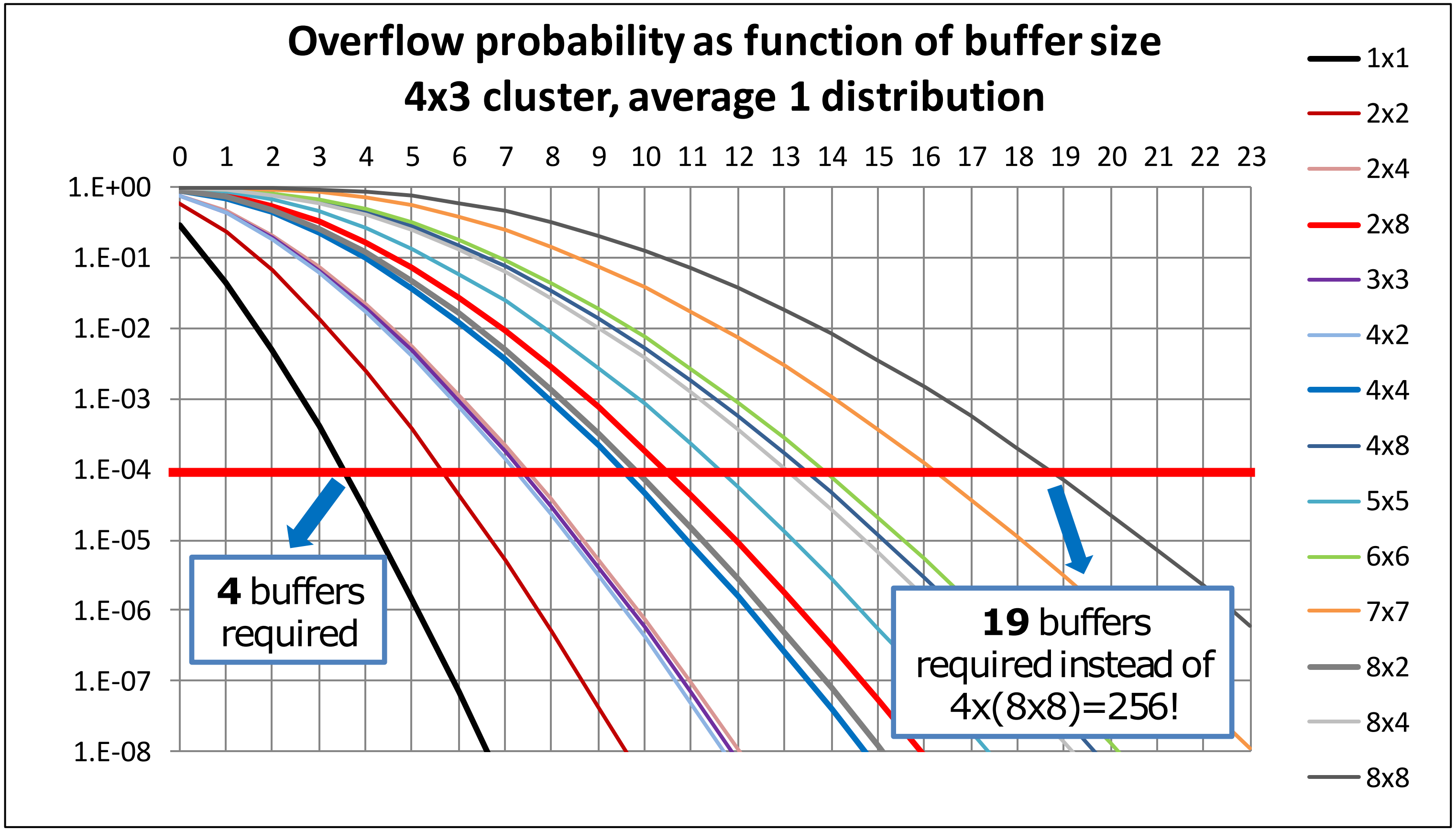
- Required number of buffers in a PR is such that the overflow probability stays below 10^{-4}
- For each hit distribution and PR size the overflow probability has been calculated from the probability of having m hits in a PR during latency:

$$P_{overflow}(m) = 1 - \sum_{i=0}^{m} \binom{i}{l/Bx} p^{i} (1-p)^{\frac{l}{Bx}-i}$$

- Assumptions:
  - Track rate: 500 MHz/cm^2
  - Trigger latency *l* = 6.4 µs
  - Bunch crossing period *Bx* = 25 ns (=40 MHz)
  - *p* = probability of having 1 hit in a PR in a single period

Number of required buffers (2)

- Required number of buffers is such that the overflow probability stays below 10^{-4}

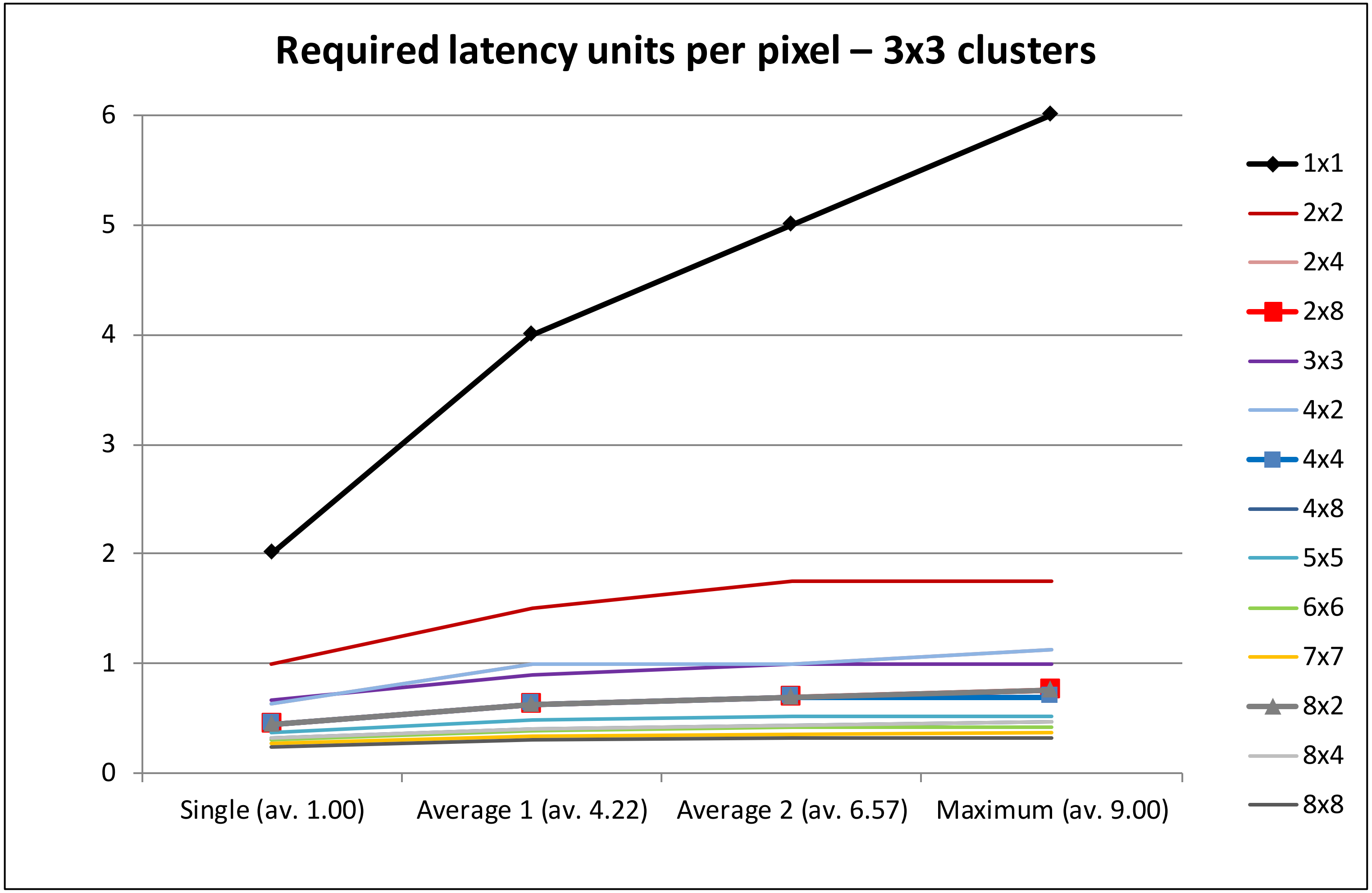


4 buffers required

19 buffers required instead of 4x(8x8)=256!

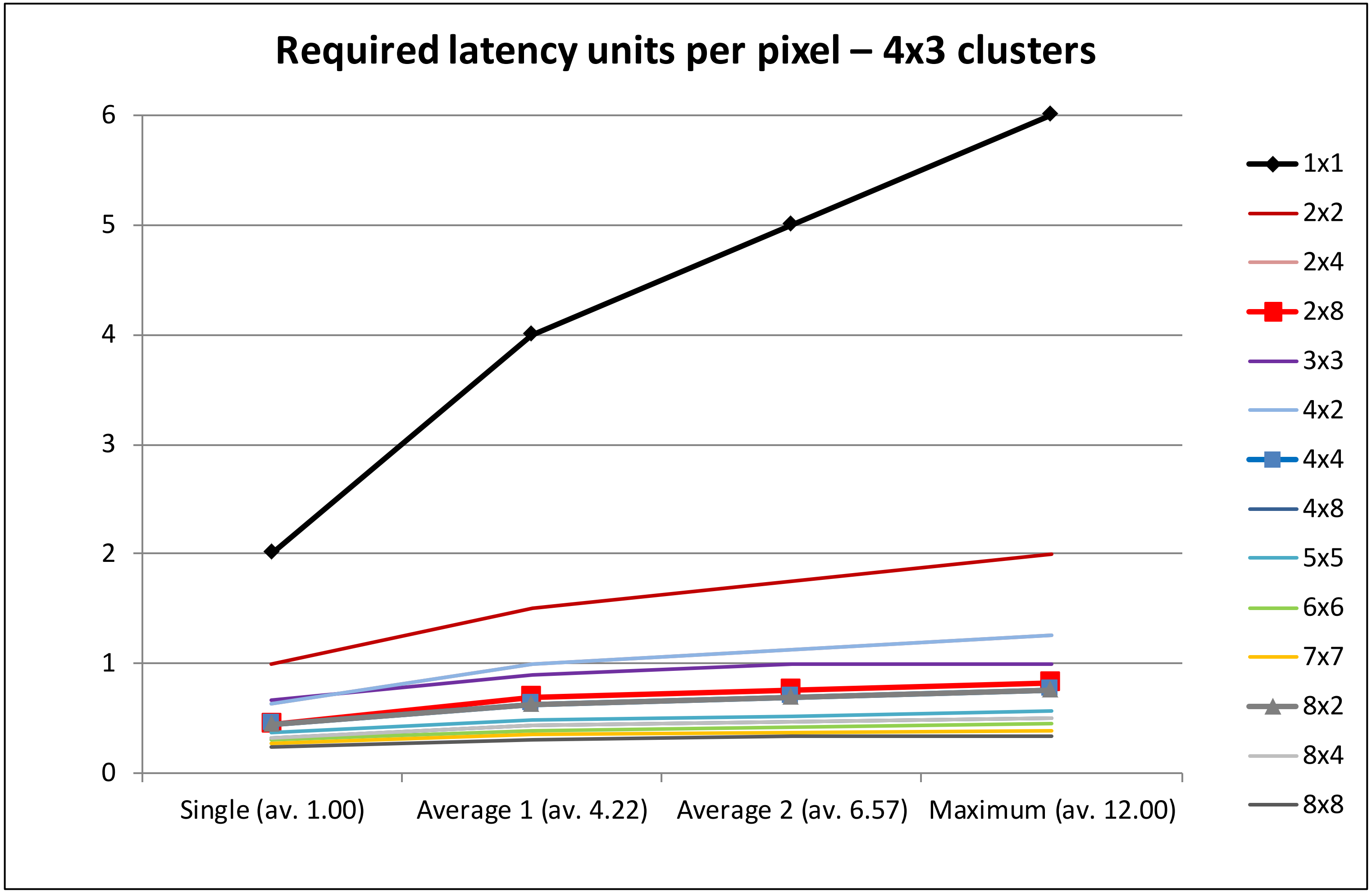
- Normalization with respect to the number of pixels in a PR

Number of required buffers – 3x3 clust



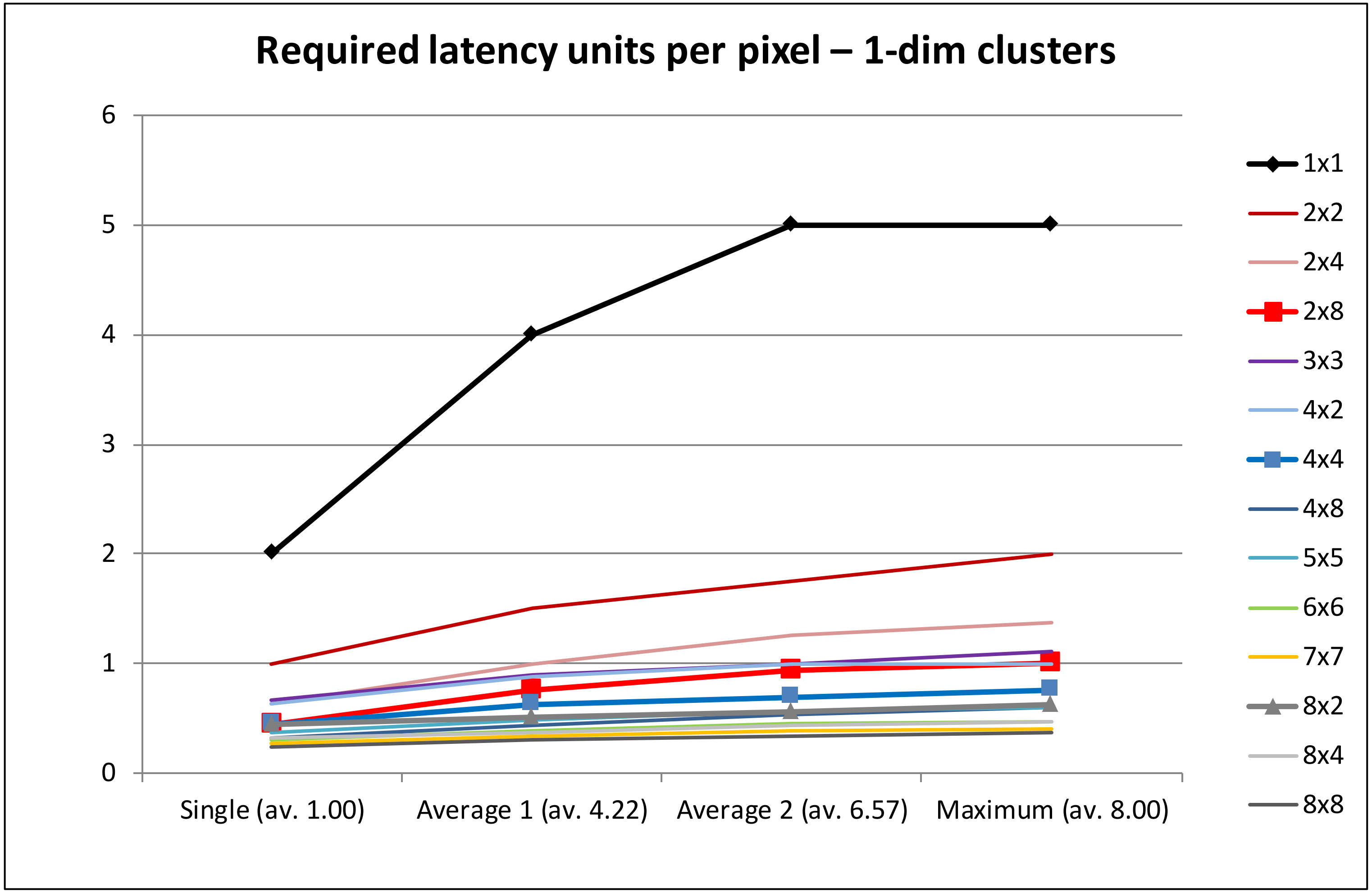
- The bigger the region, the less number of buffers per pixel is required

Number of required buffers – 4x3 clust



- The bigger the region, the less number of buffers per pixel is required

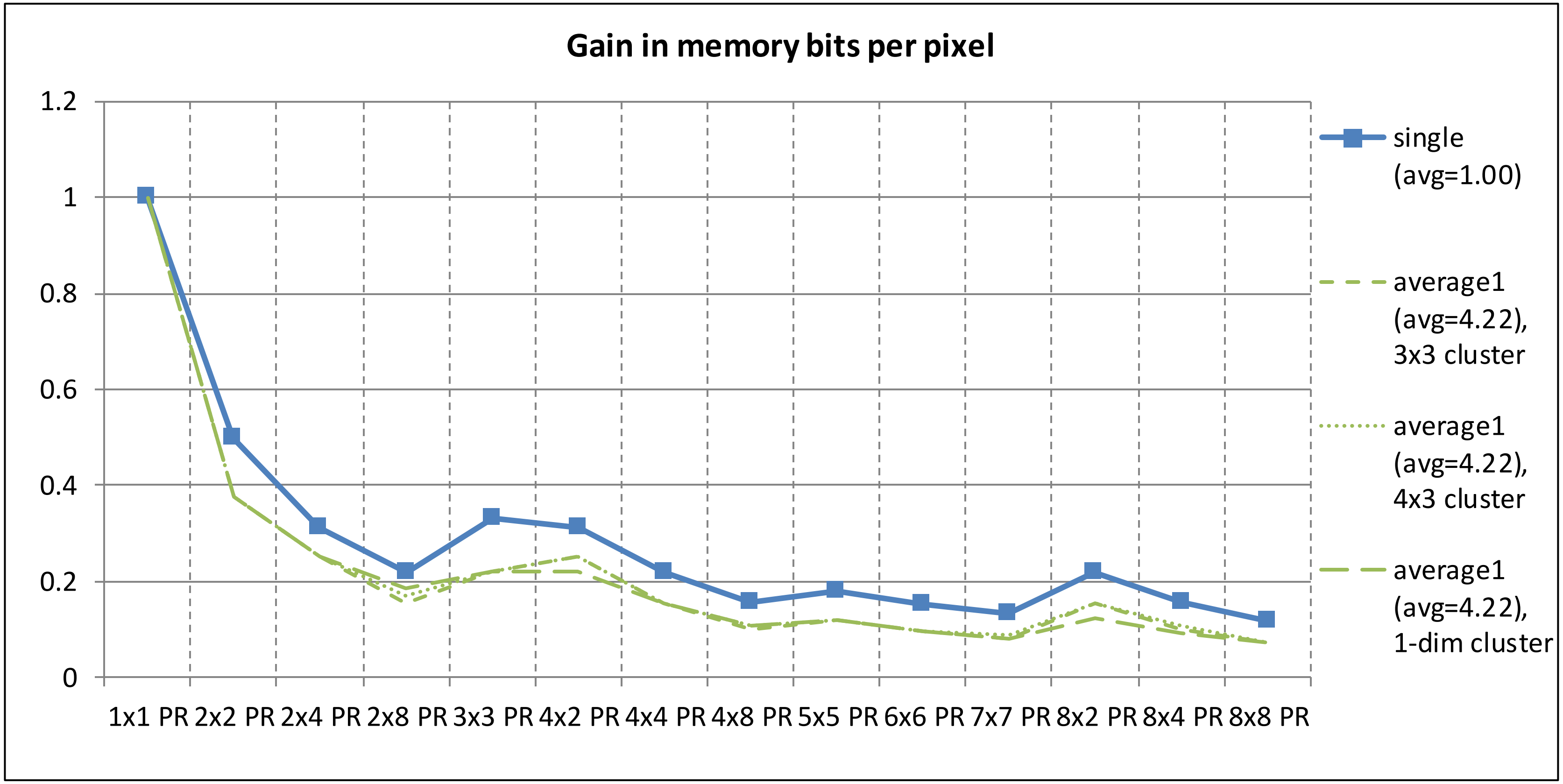
Number of required buffers – 1-dim clust



- The bigger the region, the less number of buffers per pixel is required
- 4x4 PR maintains same behavior

Number of required buffers – gain

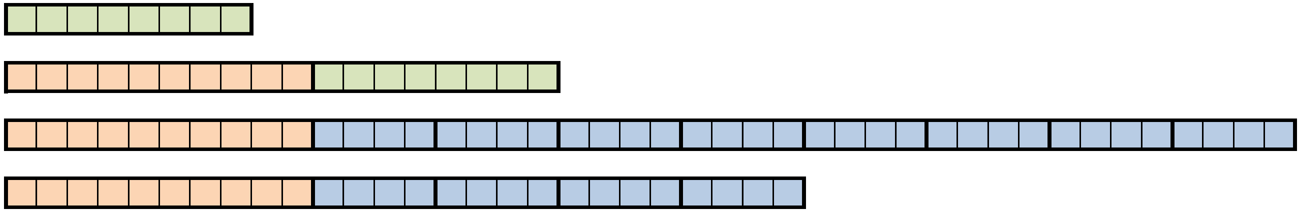
- What we gain from shared buffers in PRs with respect to single pixels



- We need less buffers **in any case** by grouping pixels in PRs
- Gain tends to saturate as PR size increases

Number of memory bits in PR buffers

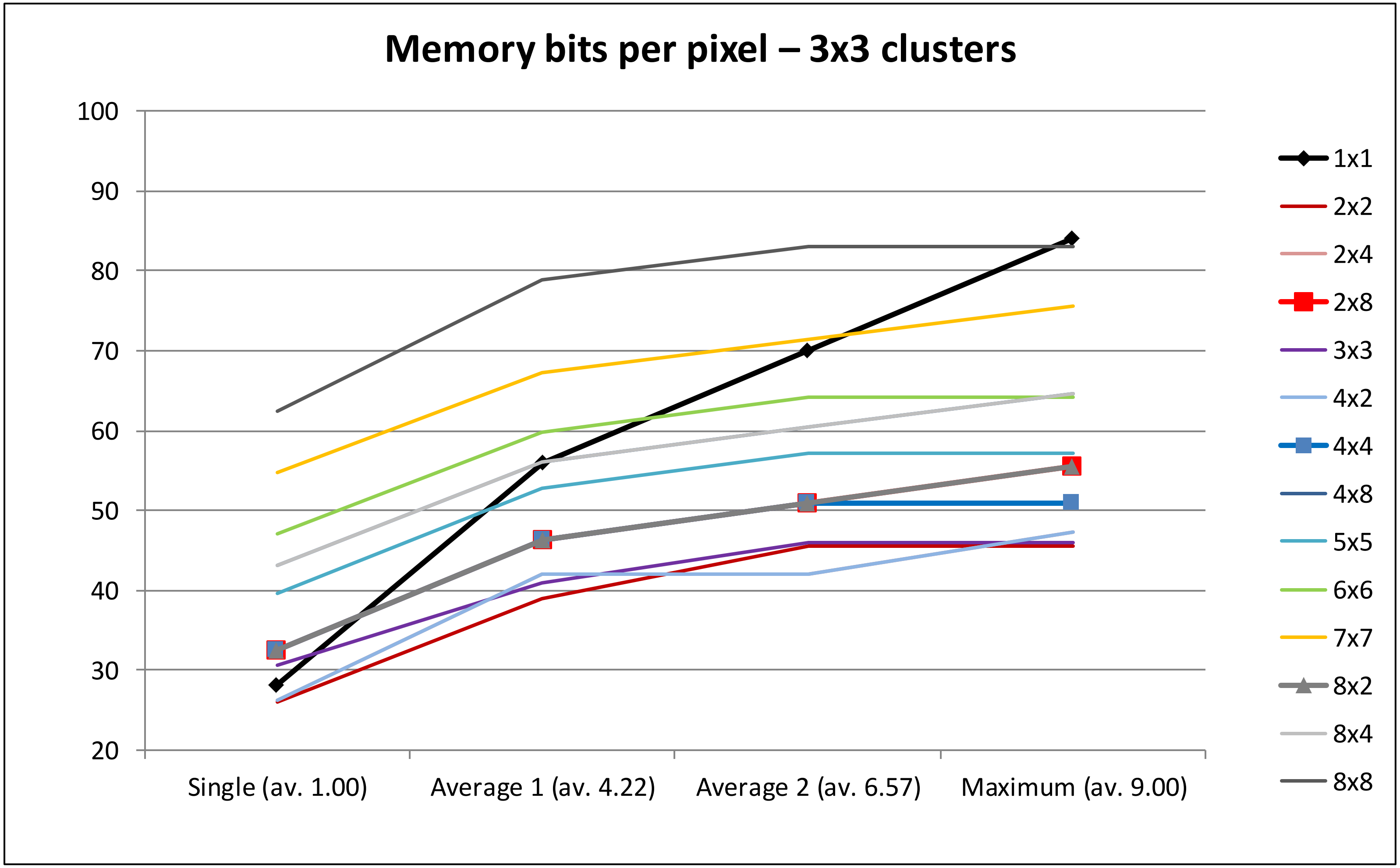
- Assumptions: 10 bit B-ID, 4 bit ToT, 512 pixels/column
- 5 memory organizations:
  - Binary: $(\mathit{1b\ hit} * \mathit{pix\_in\_PR})$
  - Binary + B-ID: $\mathit{B\text{-}ID} + (\mathit{1b\ hit} * \mathit{pix\_in\_PR})$
  - Full ToT: $\mathit{B\text{-}ID} + (\mathit{ToT} * \mathit{pix\_in\_PR})$
  - Max 4 ToT: $\mathit{B\text{-}ID} + \{\mathit{ToT} * [(\mathit{pix\_in\_PR}<4)\ ?\ \mathit{pix\_in\_PR}\ :\ 4]\}$
  - Max 8 ToT: $\mathit{B\text{-}ID} + \{\mathit{ToT} * [(\mathit{pix\_in\_PR}<8)\ ?\ \mathit{pix\_in\_PR}\ :\ 8]\}$
- Example: 2x4 PR



  - Binary
  - Binary + B-ID
  - Full ToT
  - Max 4 ToT
- Worst case: full ToT
- Number of memory bits/pixel:

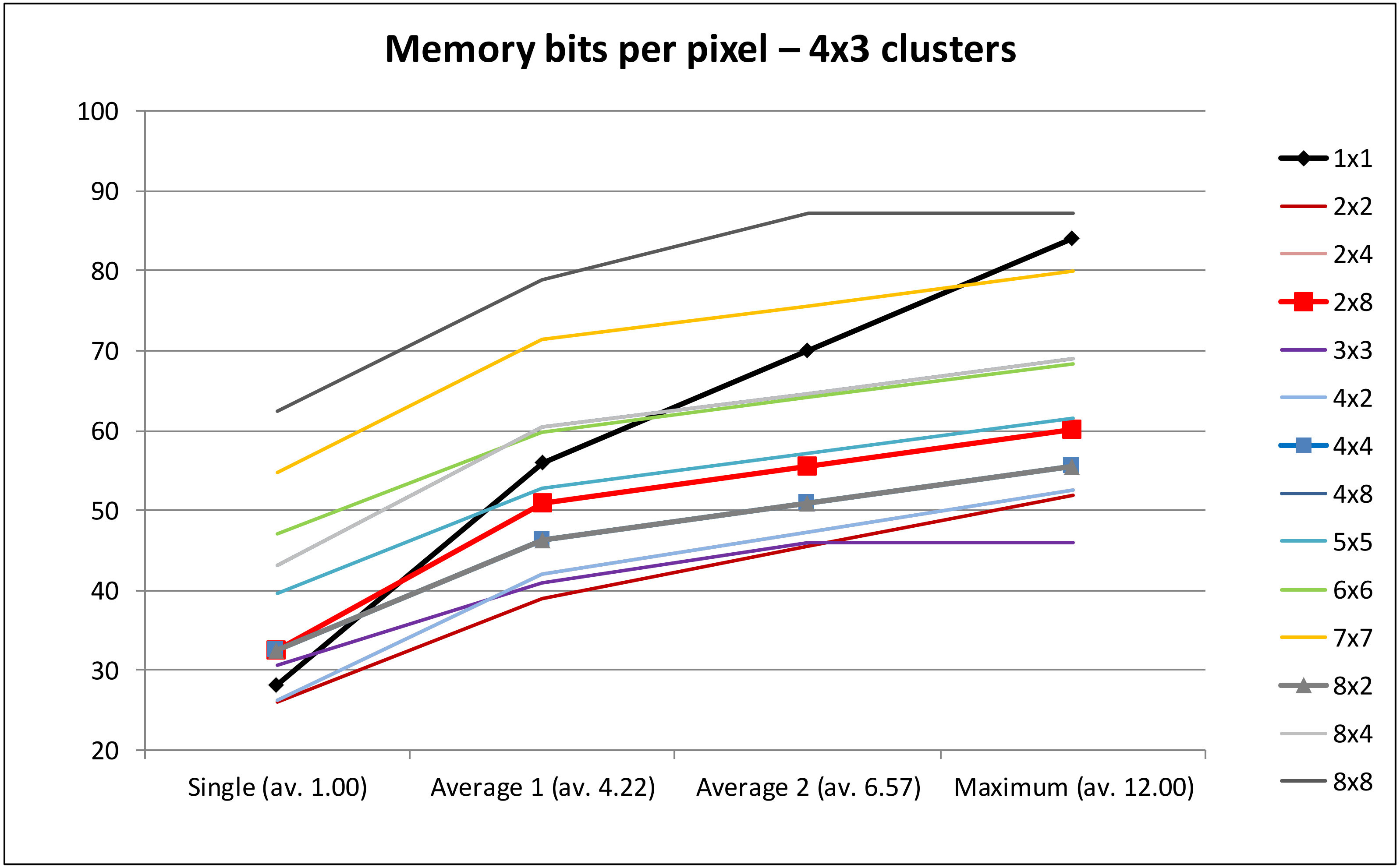
$$\mathit{buf\_per\_pix} * [\mathit{B\text{-}ID} + (\mathit{ToT} * \mathit{pix\_in\_PR})]$$

Buffer memory bits – 3x3 clust

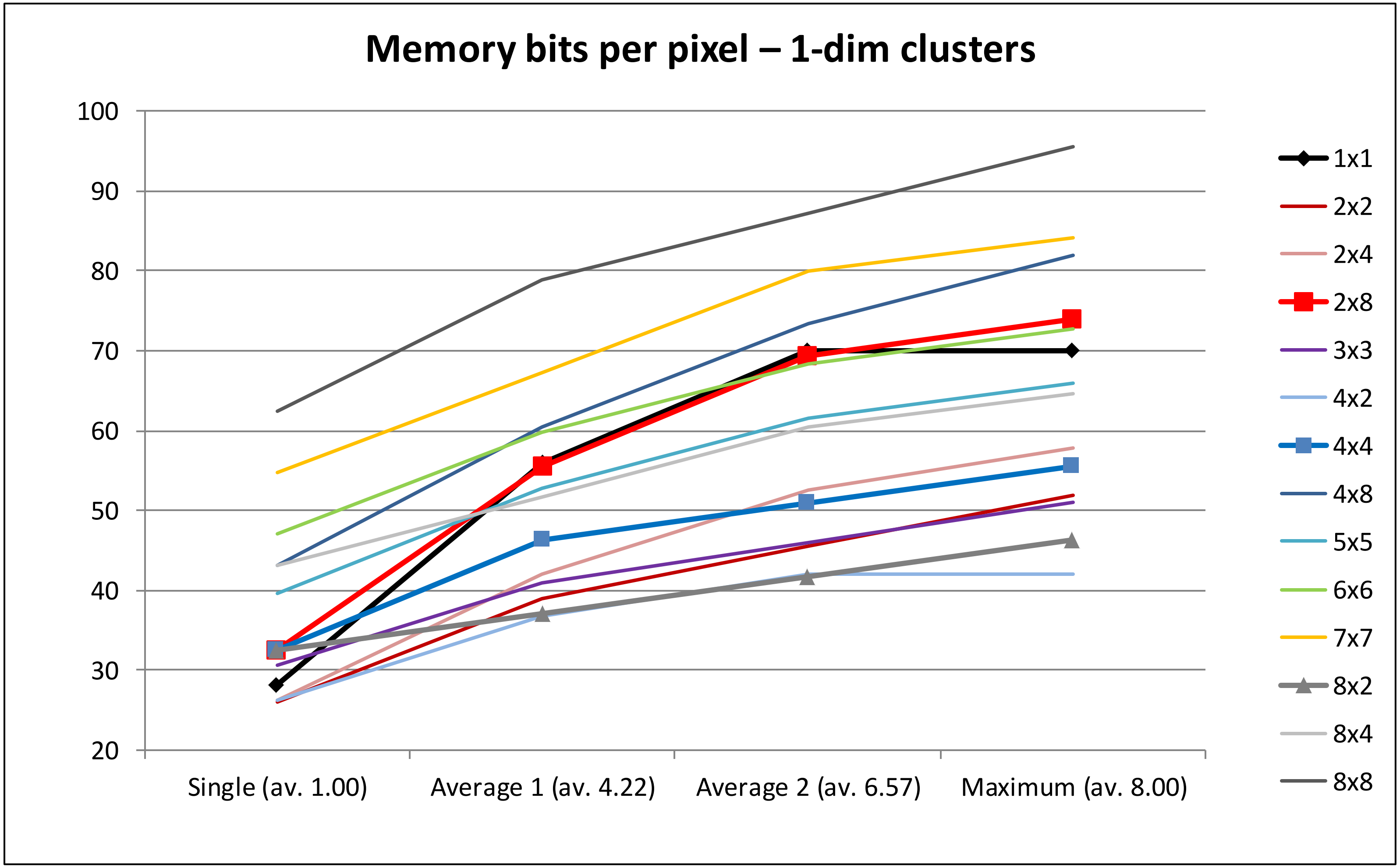


- What we gain from sharing buffers is partially lost in buffer width, especially for large PRs

Buffer memory bits – 4x3 clust

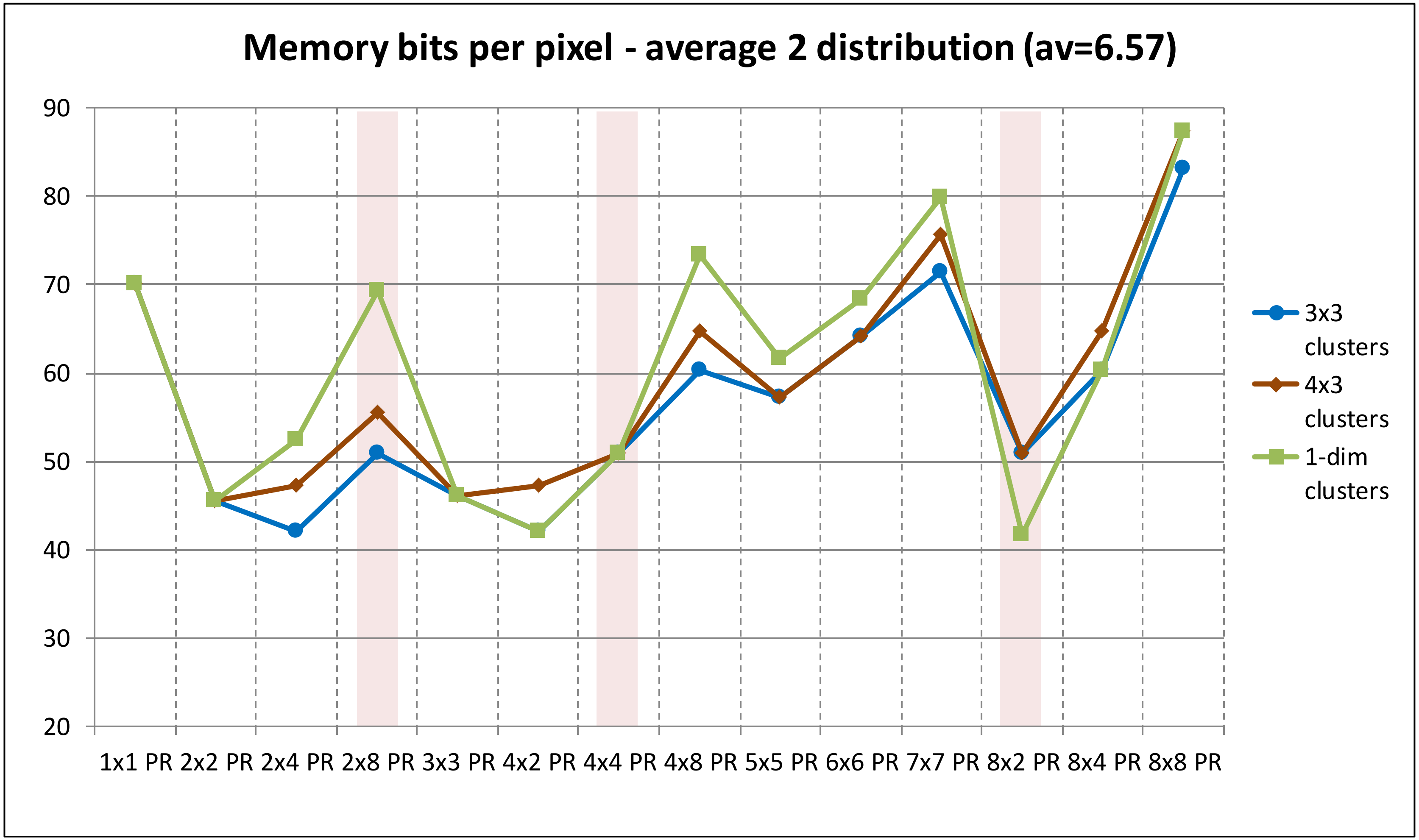


Buffer memory bits – 1-dim clust



- When the preferential direction dominates we need less bits in regions with shapes consistent with that – 4x4 PR maintains same behavior

Buffer memory bits (continued)



- When the preferential direction dominates we need less bits in regions with shapes consistent with that – 4x4 PR maintains same behavior

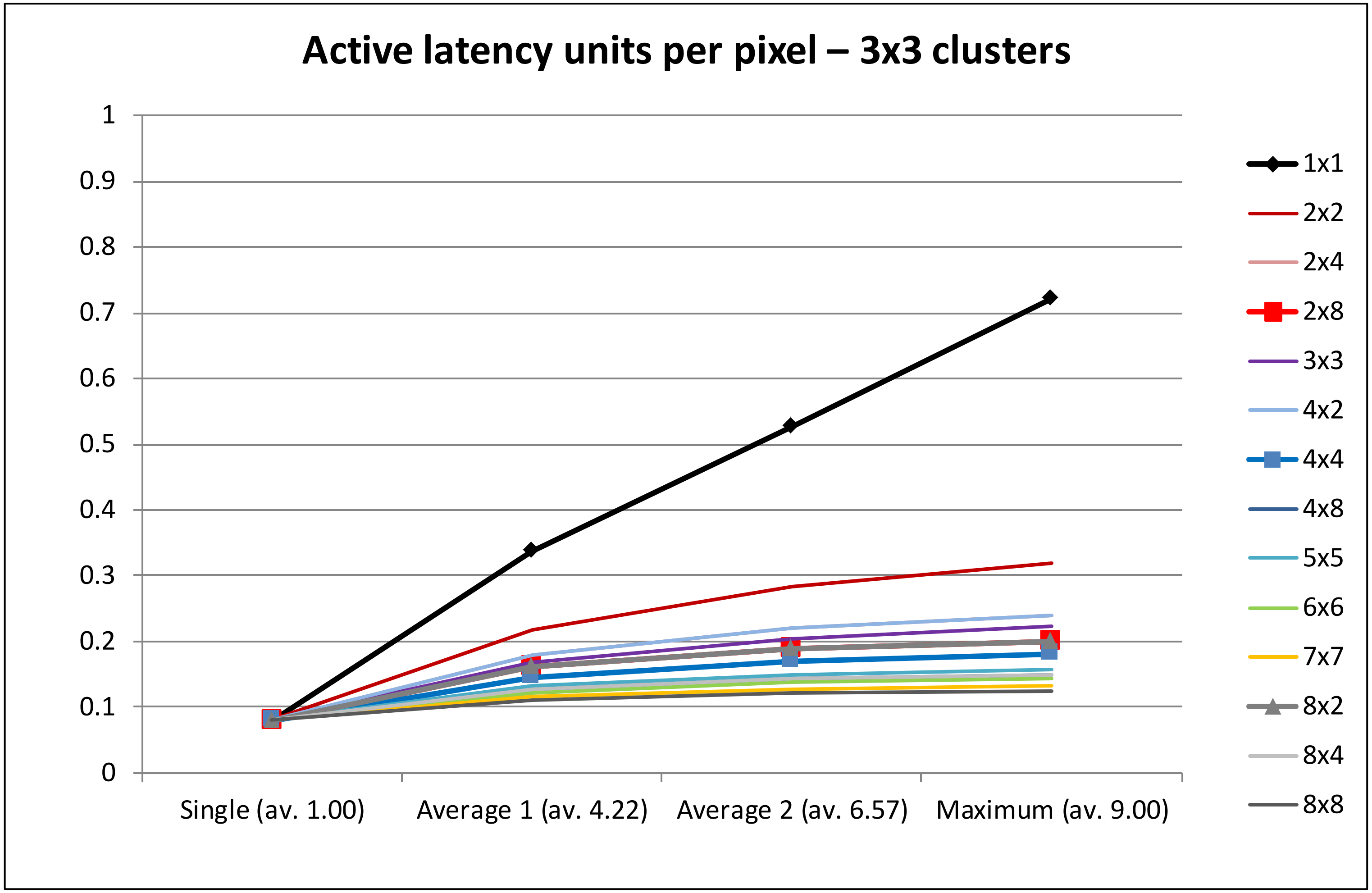
Active buffer units and power

- Less buffers means less power (static)
- Less active “latency/buffer units” means less power (dynamic)
- Number of active latency units/pixel:

$$\frac{p\cdot\frac{l}{Bx}}{pix\_in\_PR}$$

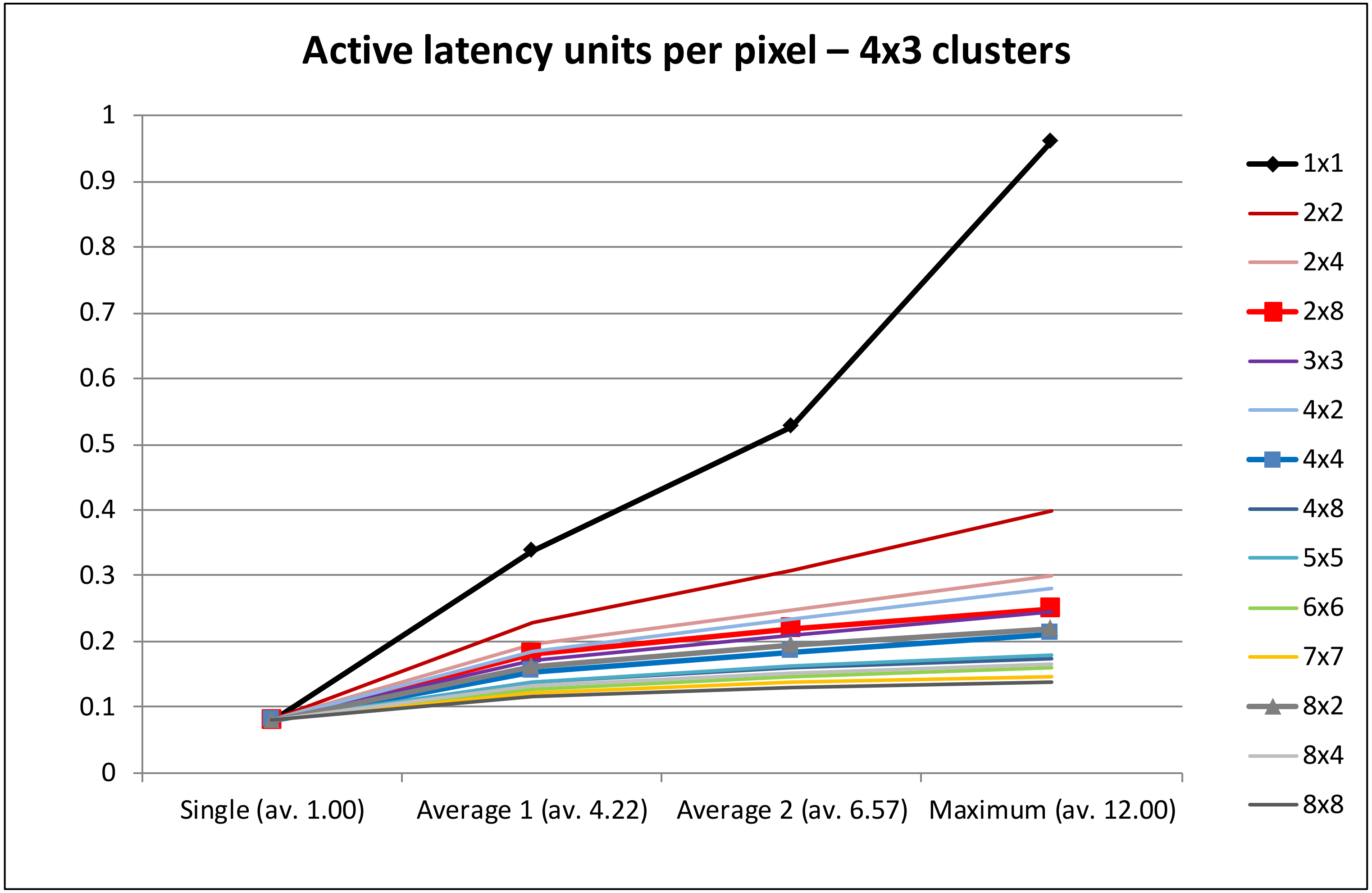
→ numerator: average hits in PR in l/Bx periods

Active buffer units and power – 3x3



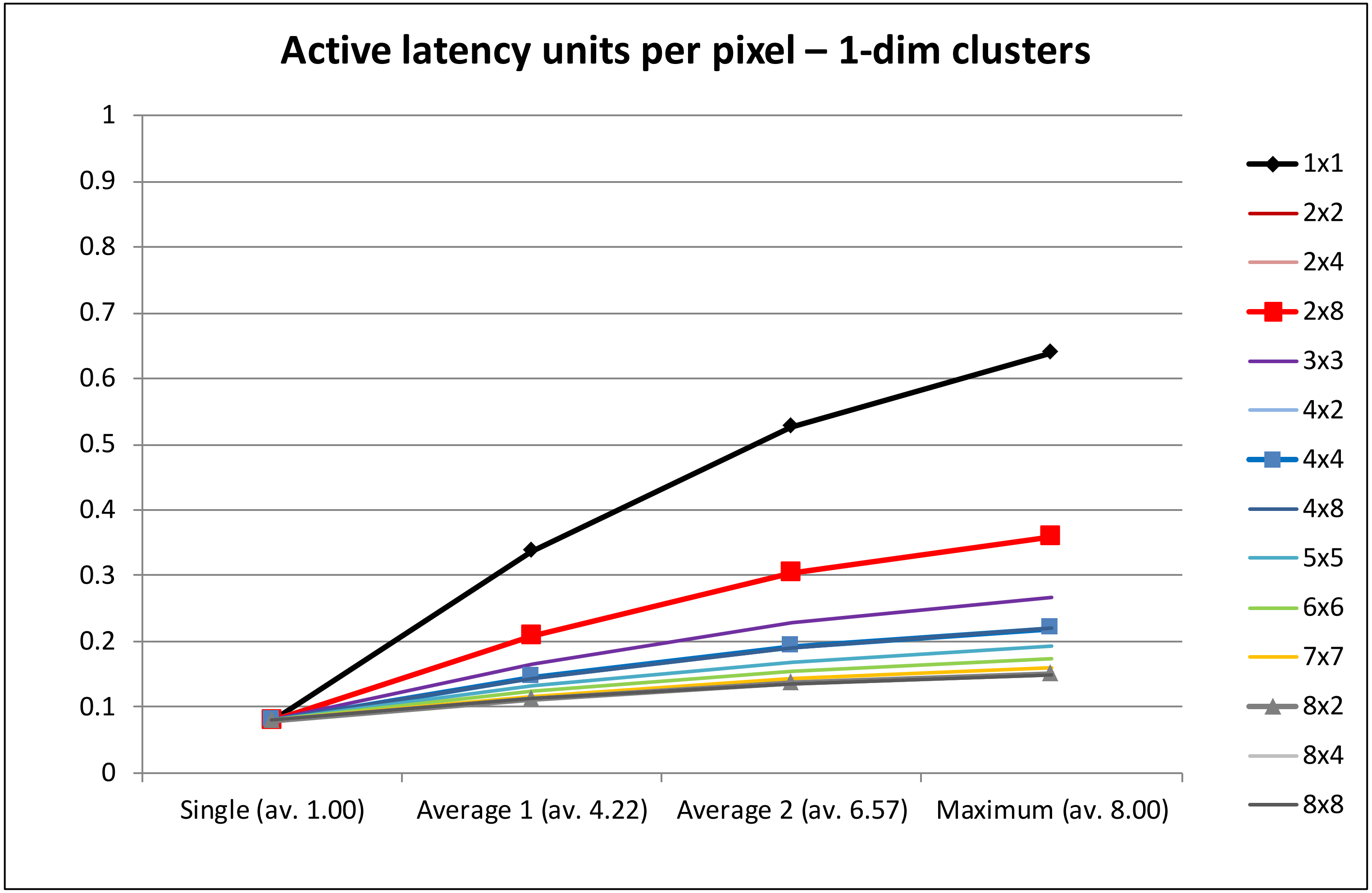
- Less buffers per pixel, less digital power consumption per pixel

Active buffer units and power – 4x3



- Less buffers per pixel, less digital power consumption per pixel

Active buffer units and power – 1-dim



- Less buffers per pixel, less digital power consumption per pixel

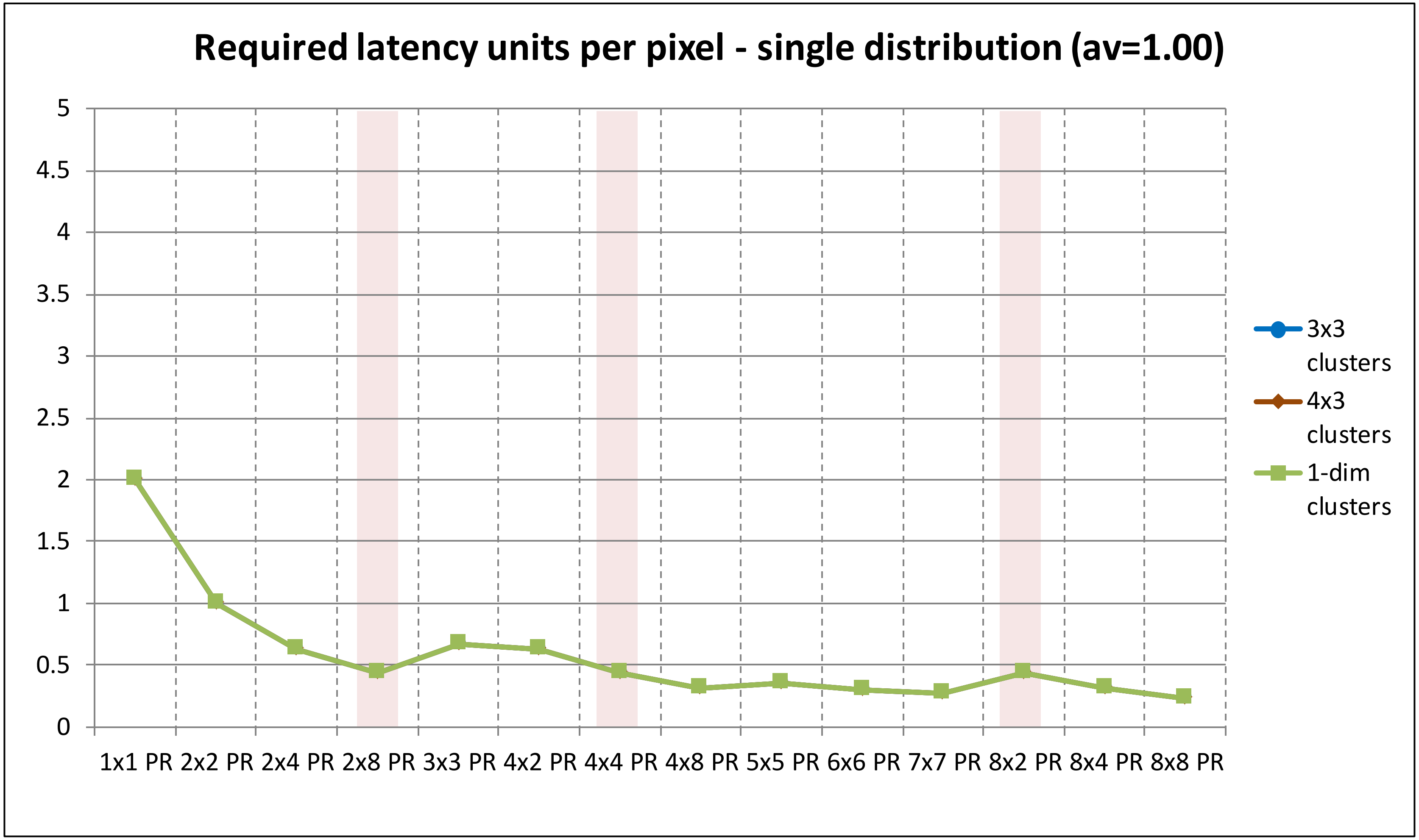
Conclusion

- Statistical study of grouping detector pixels in regions with 3 different assumptions on particle hits
- Grouping pixels allows to use less buffers/pixel but on the other hand these buffers may need to be wider
- Using 4x4 PR can be a reasonable trade-off between number and width of buffers
- Following step: simulation of real hit patterns
  (using Timepix3 SystemVerilog verification framework by T. Poikela)

BACKUP SLIDES

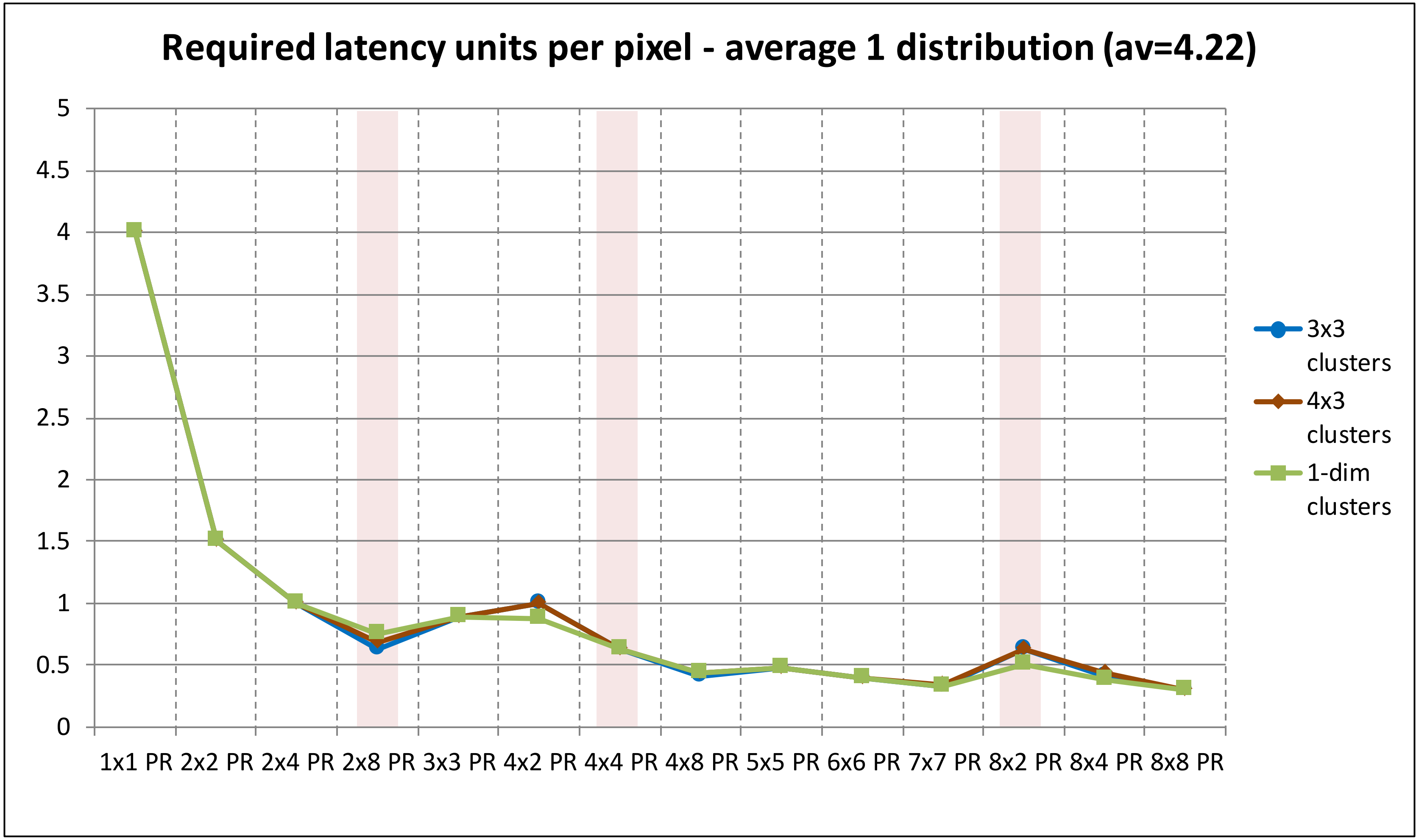
Comparative plots

- Number of required buffers per pixel for each distribution



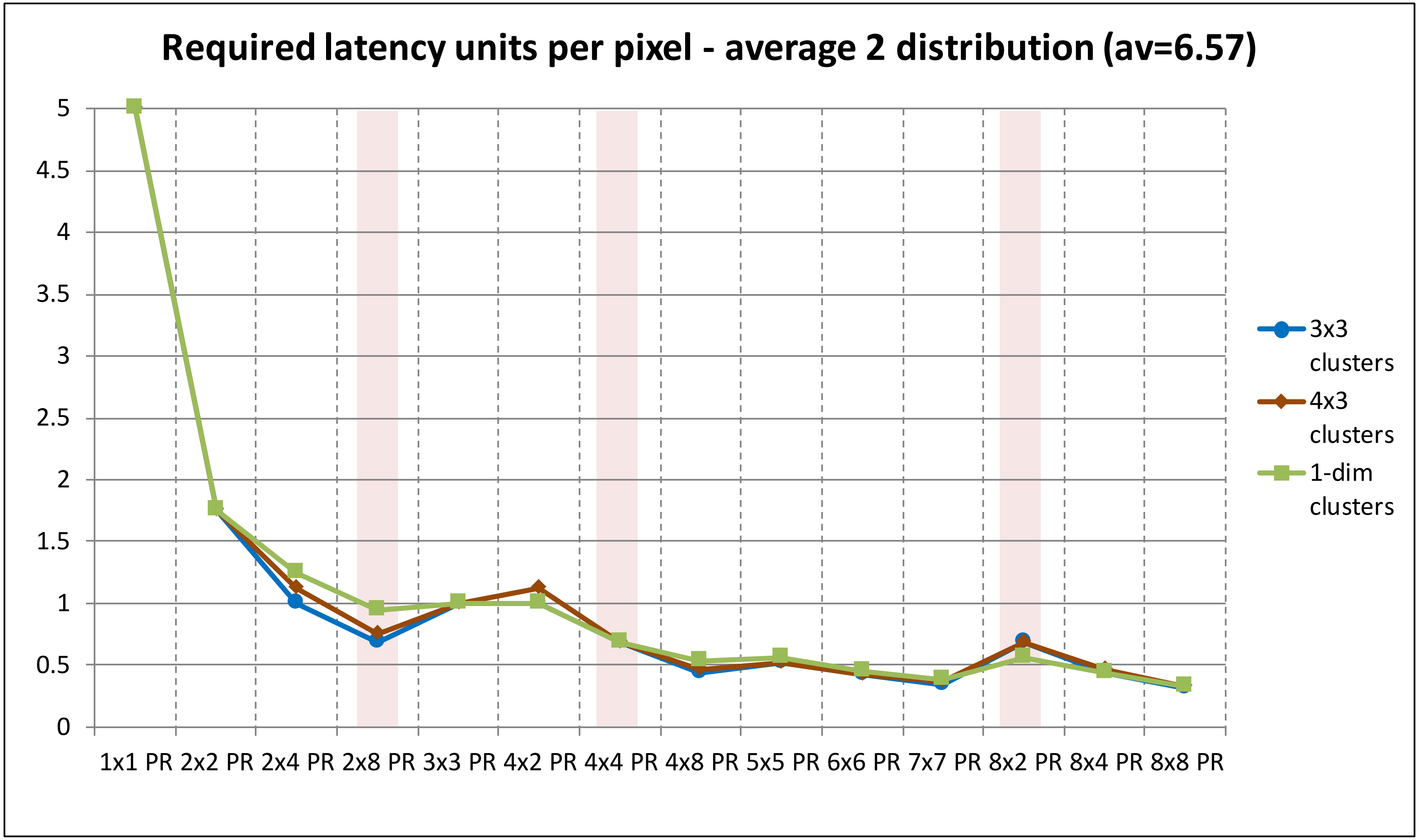
Comparative plots

- Number of required buffers per pixel for each distribution



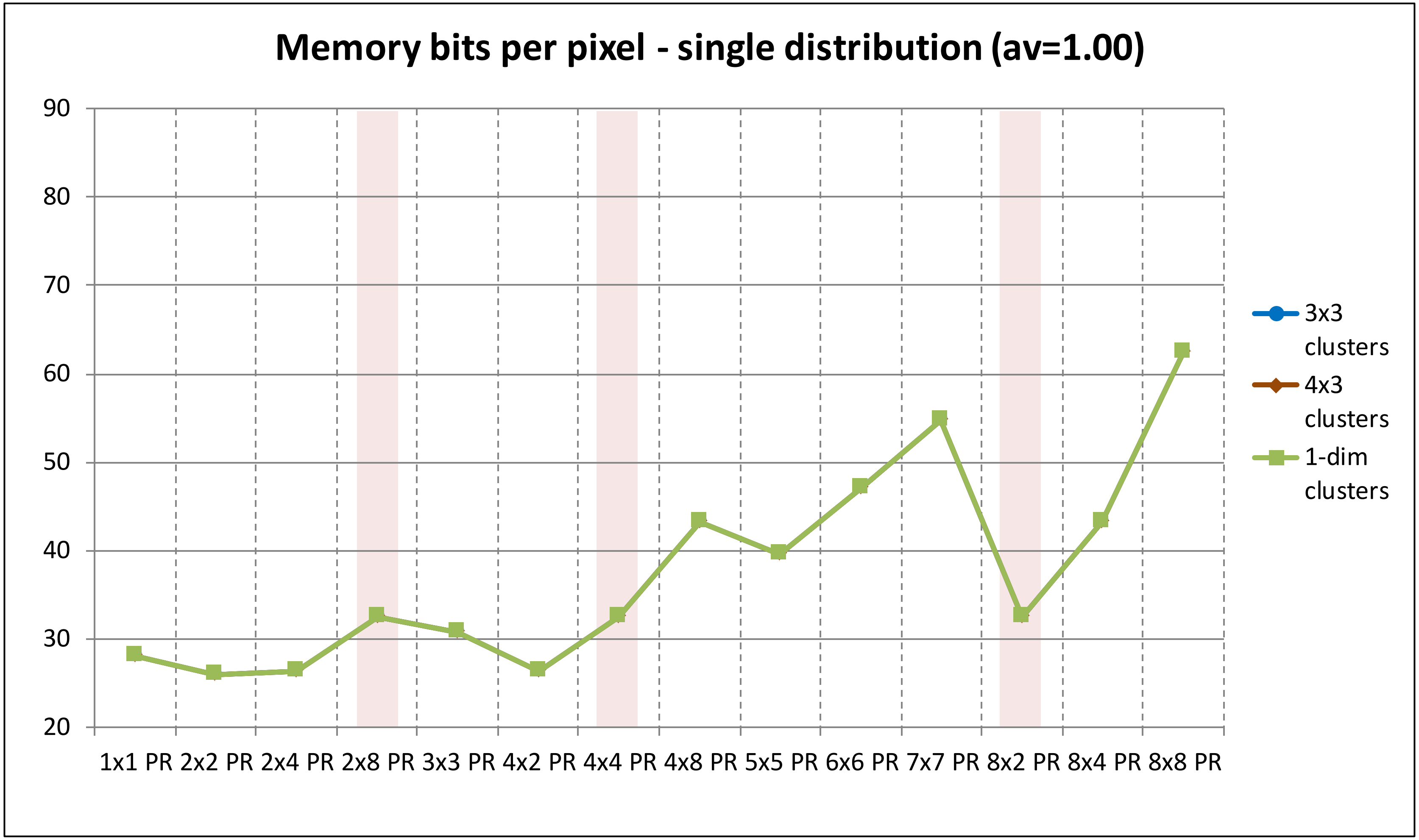
Comparative plots

- Number of required buffers per pixel for each distribution



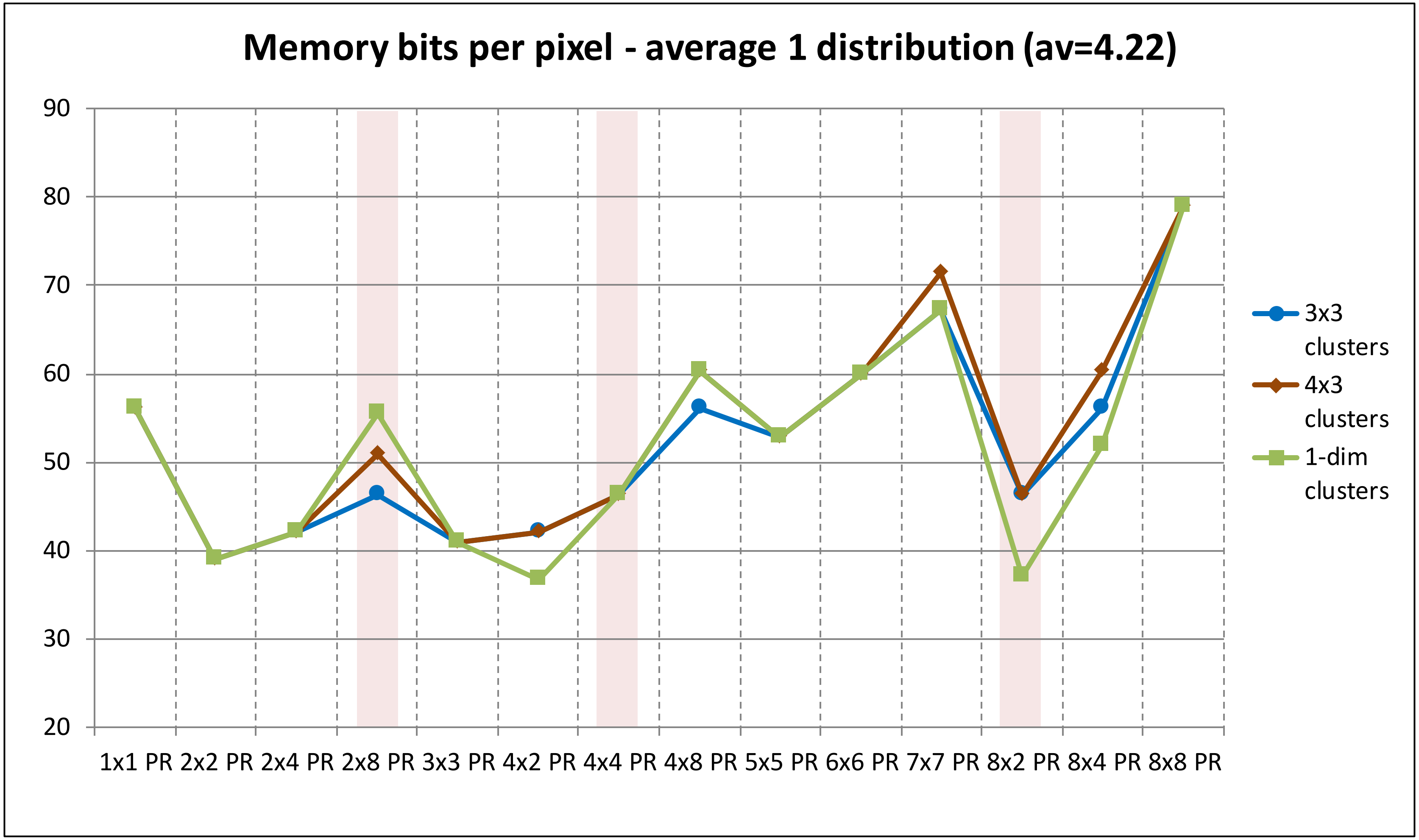
Comparative plots

- Number of memory bits per pixel for each distribution



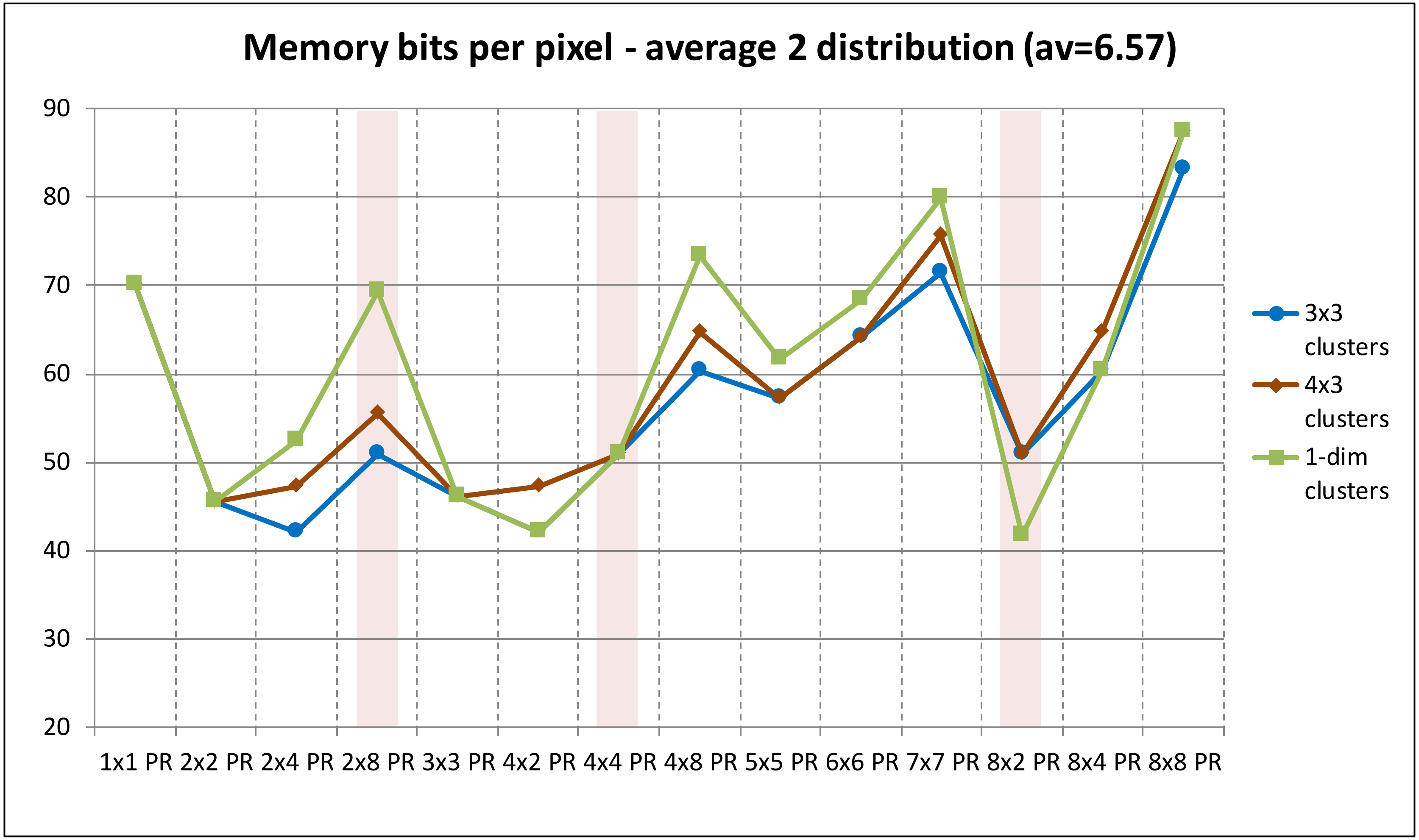
Comparative plots

- Number of memory bits per pixel for each distribution



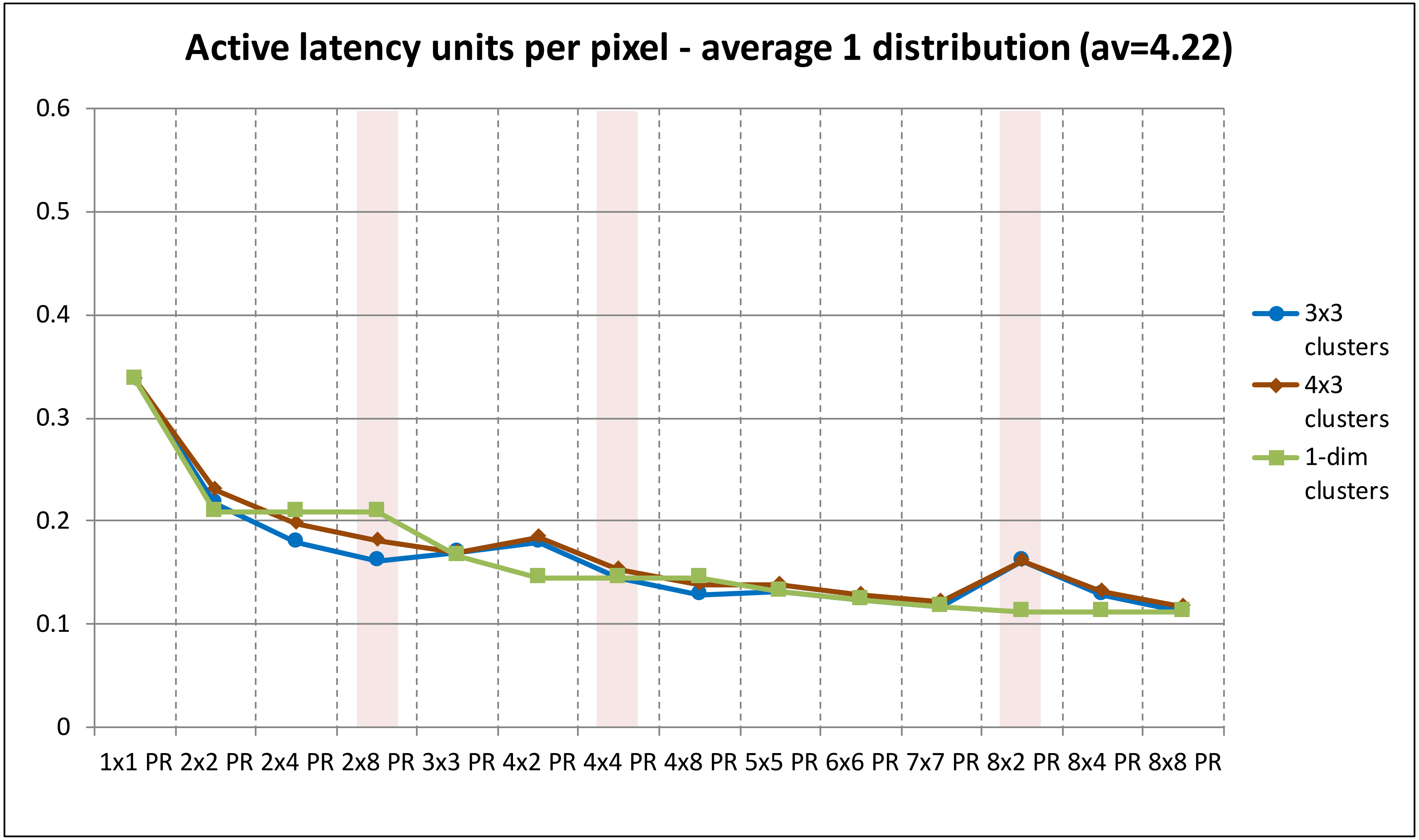
Comparative plots

- Number of memory bits per pixel for each distribution



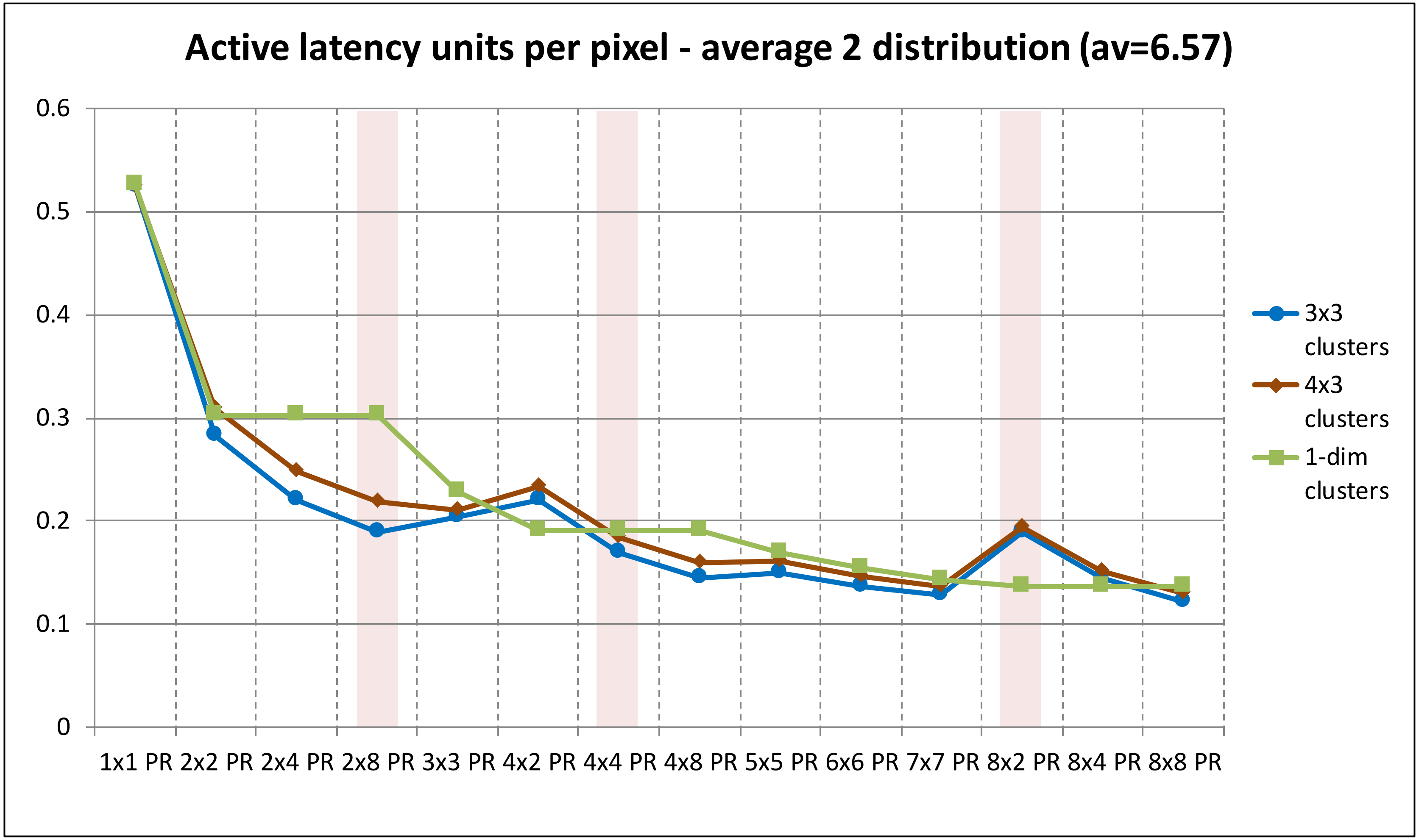
Comparative plots

- Number of active buffers per pixel for each distribution



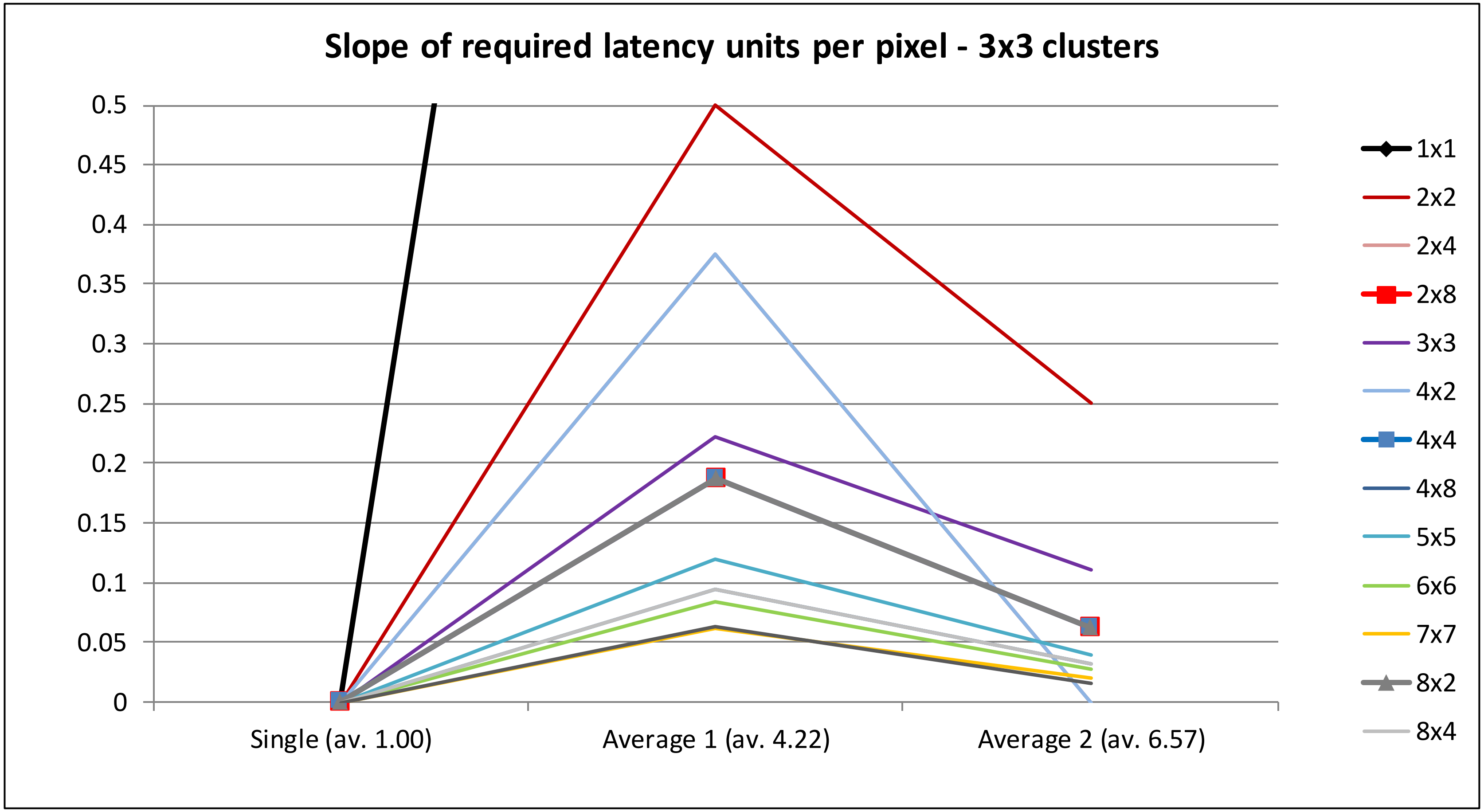
Comparative plots

- Number of active buffers per pixel for each distribution



Number of buffers required for PR – slope

- The bigger the PR, the less the number of buffers depends on clustered hit distributions



Number of buffers required for PR - slope

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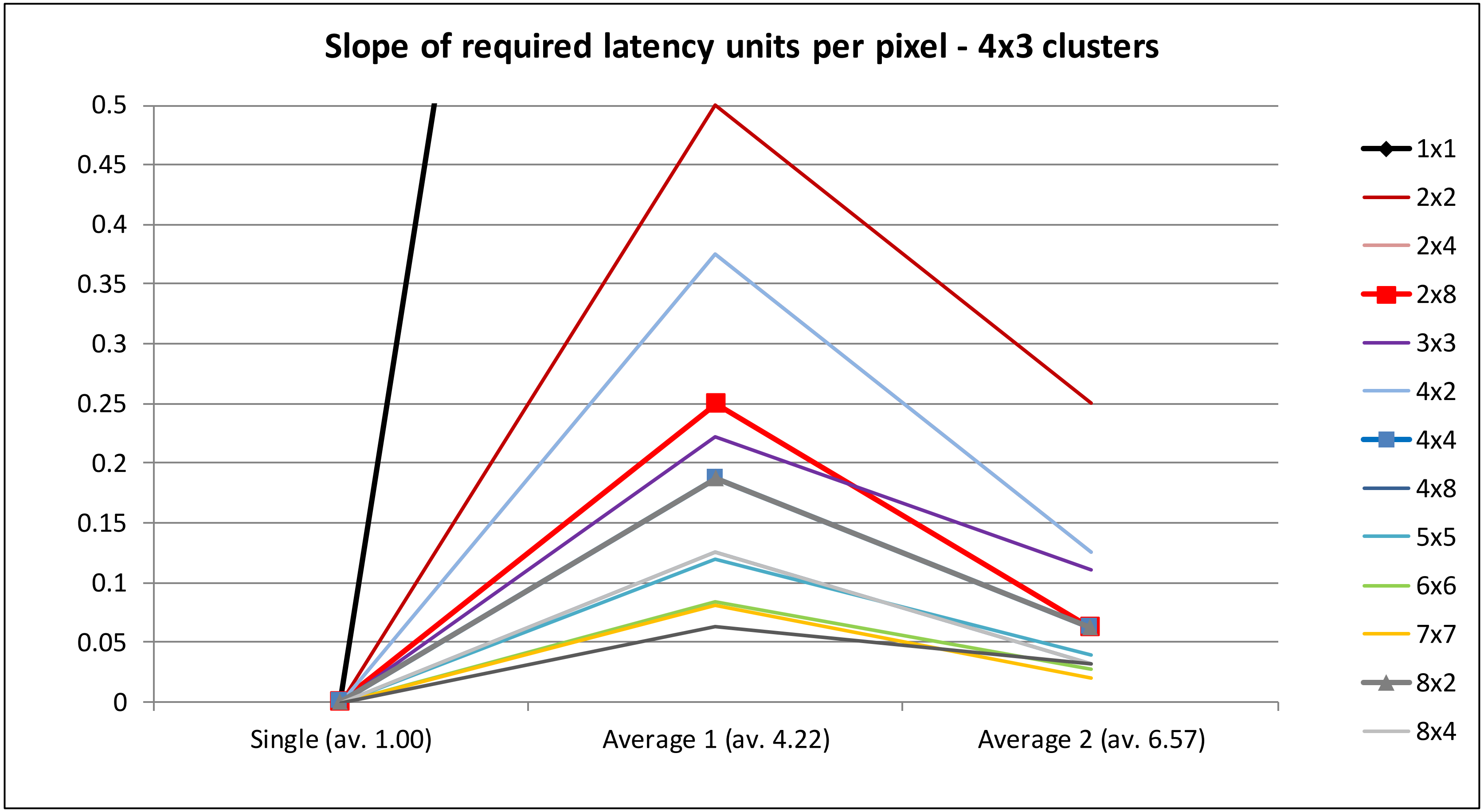

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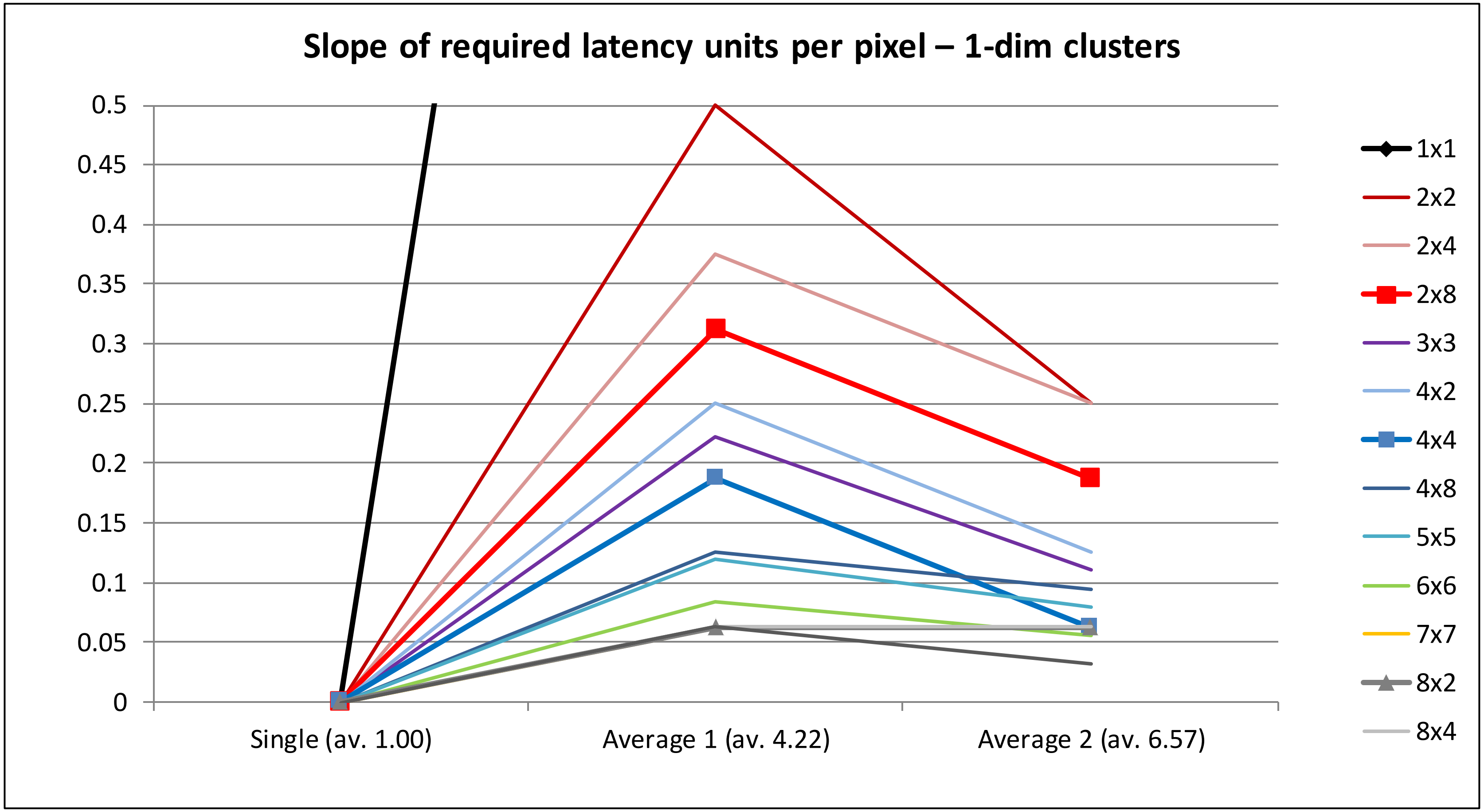
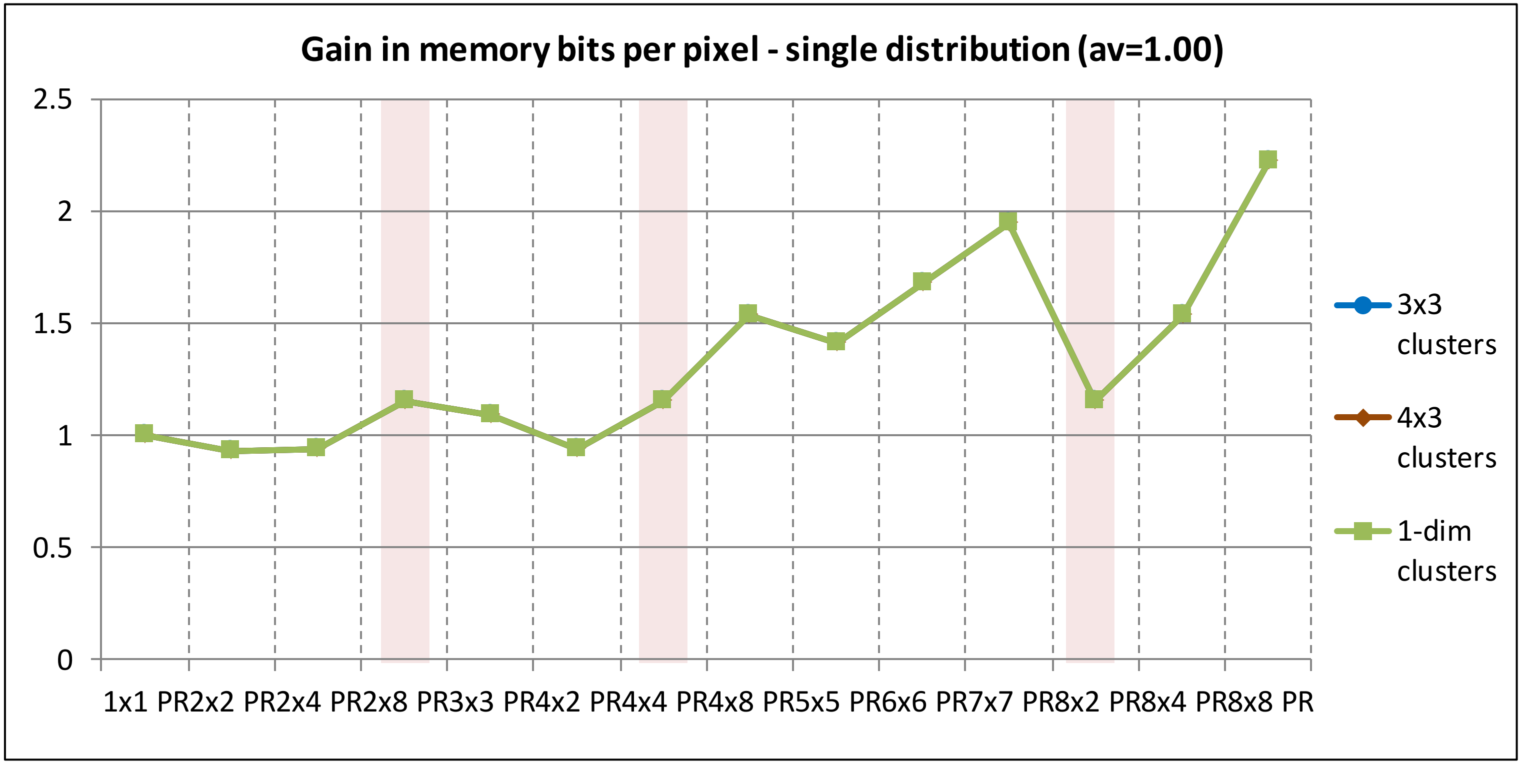


Buffer memory bits per PRs – gain (1)

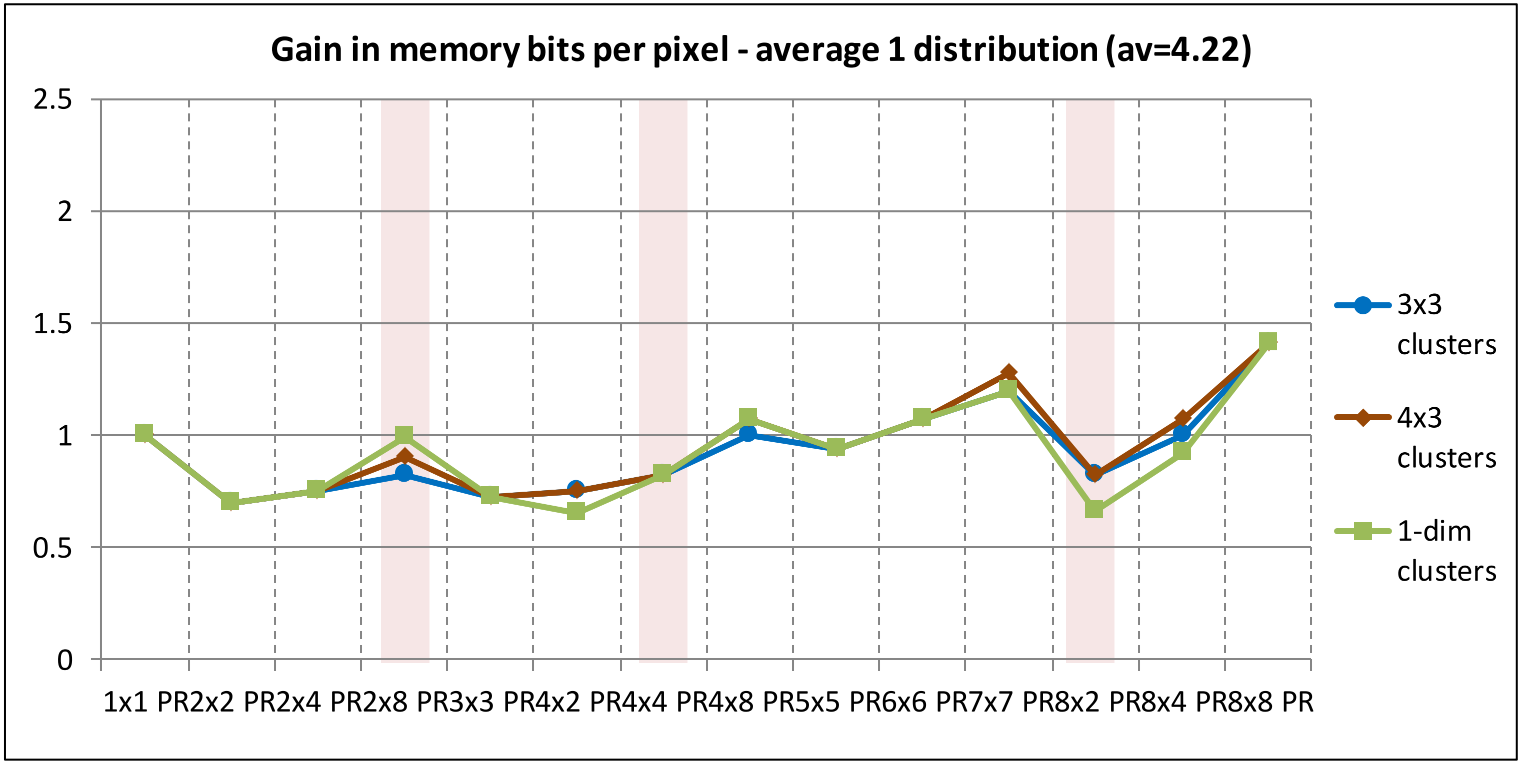
- What we gain from shared buffers in PRs with respect to single pixels



- For ‘single’ distribution we need more memory bits per pixel with PRs bigger than 4x4

Buffer memory bits per PRs – gain (2)

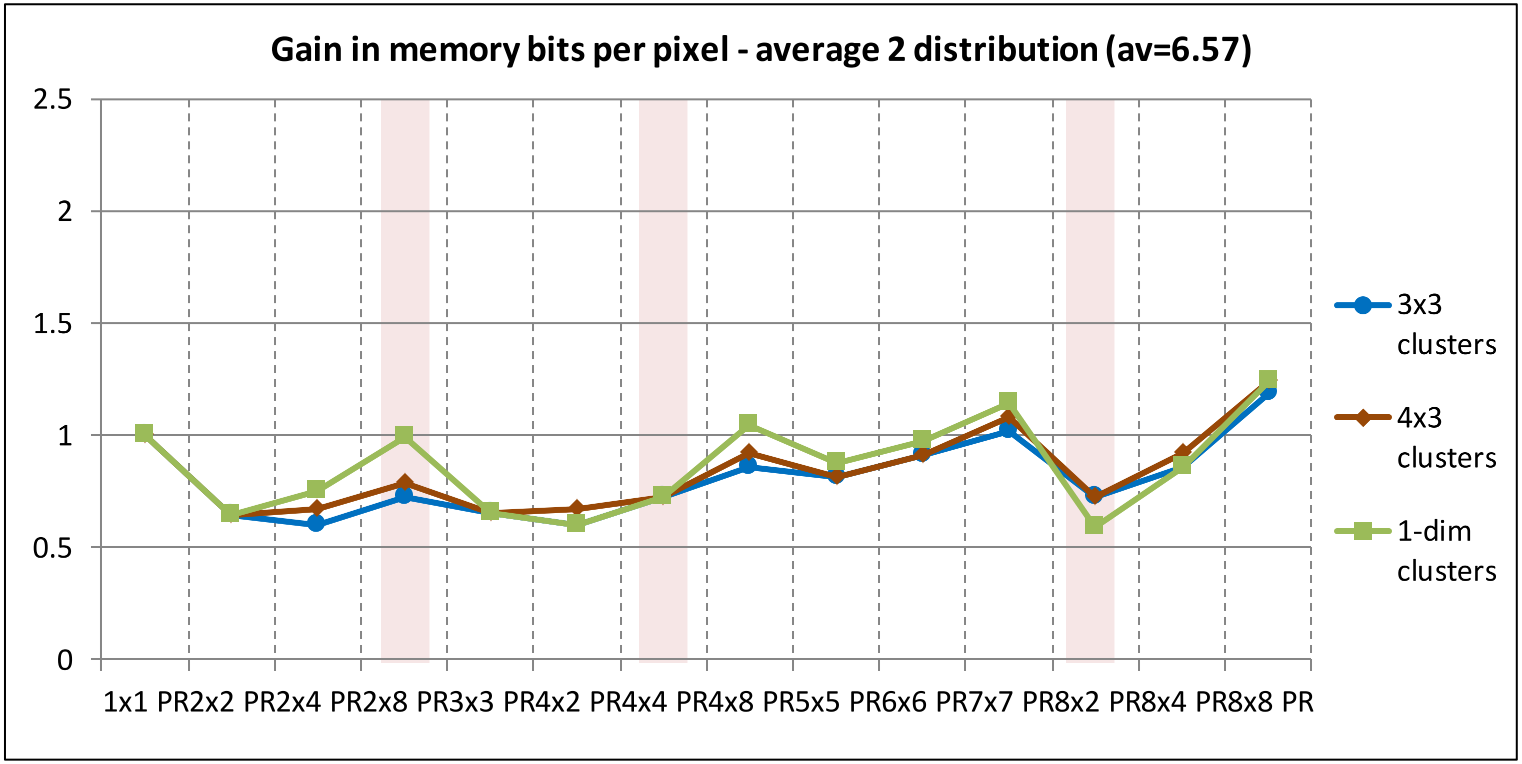
- What we gain from shared buffers in PRs with respect to single pixels



- For 'average1' distribution we need slightly less memory bits per pixel with PR sizes up to 4x4

Buffer memory bits per PRs – gain (3)

- What we gain from shared buffers in PRs with respect to single pixels



- For 'average2' distribution we need slightly less memory bits per pixel for most PRs