TPP : Transparent Page Placement for CXL-Enabled Tiered-Memory

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Memory Today Tightly Coupled to CPU

Memory is homogeneous

• same type, latency, capacity, bandwidth etc.

Rack-level memory power and cost increases with new hardware generations

![Memory as a % of total rack Power/Cost](chart)

- Gen 0: 14.6%
- Gen 1: 19.8%
- Gen 2: 19.7%
- Gen 3: 20.7%
- Gen 4: 28.8%
- Gen 5: 33.3%

- Memory as homogeneous
- Power and Cost increases with new hardware generations
CXL-based Heterogeneous Memory

Flexible CPU and memory bus

- different memory capacity to bandwidth ratio
- combine different generation of DIMMs
- use cheaper and low power memory alternatives
- utilize near memory accelerators
CXL-Memory Characteristics

Byte addressable in same physical address space
- transparent allocation with cache-line granular access

Memory bandwidth is like DDR channels
- NUMA BW is better than a dual socket system

Close to NUMA latency on dual socket systems
- adds ~100ns latency over normal DRAM access
Performance Drops with Large CXL-Memory

Cache Application
86.00
91.00
14%

Web Application
82.00
84.00
18%

Data Warehouse
92.00
90.00
10%
1. Effective placement of hot pages
   - faster page allocation
   - apt hot page detection
   - lightweight page movement
   - sensitivity towards different page types

2. Workload characterization
   - page temperature and re-access time
   - application’s expected behavior
Effective memory management for tiered-memory system

- lightweight demotion to slow memory tier
- efficient hot page promotion to fast memory tier
- optimized page allocation path to reduce latency
- workload aware page allocation policy

Without modifying any

- applications, or
- hardware

source code available at [https://lwn.net/Articles/876993/](https://lwn.net/Articles/876993/)
Every node maintains a watermark to determine load

- reclamation triggers when number of free pages goes below the watermark
- new pages get allocated to remote node
- reclamation stops when free pages goes above the watermark
- new allocations again happen on local node
Demotion in TPP - Migrate to Slow Tiers

Maintains a separate demotion page list
- scans inactive pages first
- if not enough, move to active pages

Tries to migrate scanned pages to slow memory tier
- failed pages follows default reclamation path
Optimized Allocation Path in TPP

Decouples page allocation and reclamation logic

- reclamation triggers when x% memory is left
- allocation happens on local node as long as allocation watermark is satisfied

User-space interface to control reclamation watermark

- `vm.demote_scale_factor` (by default, set to 2% of local node’s capacity)
Effective Promotion of Trapped Hot Pages

Samples only CXL-node

- promoting local node pages is meaningless

Considers page activeness during promotion

- NUMA hint may come from *infrequently accessed page*
- such pages become demote candidate after being promoted
- include *active LRU* heuristics in promotion
- move *inactive hinted page to active LRU* and wait for next fault
- anon and file promotion rate varies on respective LRU activities
User Interface

TPP appears as a new AutoNUMA mode

- `echo x > /proc/sys/kernel/numa_balancing`
  - 0x0: NUMA_BALANCING_DISABLED
  - 0x1: NUMA_BALANCING_NORMAL
  - 0x2: NUMA_BALANCING_MEMORY_TIERING

- If there is a single CPU-attached memory node, automatically falls back to NUMA_BALANCING_MEMORY_TIERING mode
Evaluate

Deploy and evaluate on **Meta cluster in production** w/ CXL-Memory expander ASIC

- Caching applications
- Social media application
- Data warehouse & analytics
Better Allocation and Promotion with TPP

Decoupling allocation and reclamation logic helps handle bursts more effectively

- **1.6x** better allocation rate at 95th percentile
- promotion can be **30x** faster than default Linux
Performs Great w/ 80% CXL-Memory

**Cache Application**
- Default: 86.00
- AutoNUMA: 91.00
- TPP: 99.50

**Web Application**
- Default: 82.00
- AutoNUMA: 84.00
- TPP: 99.00

**Data Warehouse**
- Default: 92.00
- AutoNUMA: 90.00
- TPP: 97.00

13%

17%

7%
Effective memory management for tiered-memory system

- lightweight demotion
- **30x** faster hot page promotion
- **1.6x** optimized page allocation
- workload aware page allocation policy

**Without modifying any**

- applications, or
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Thank You!

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