Joint Virtual Machine Placement and Migration in Dynamic Policy-Driven Data Centers

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Presentation Overview

1. Introduction
2. Related Works
3. System Model
4. Virtual Machine Migration
5. Virtual Machine Placement
6. Performance Evaluation
7. Conclusion

Introduction

What is a Dynamic Policy Driven Data Center (PDDC)?

- Data Center
  - Physical Machines (PMs)
  - Switches
  - Virtual Machines (VMs)
- Policy Driven
  - Middleboxes (MBs)
  - Policy Chains (Ordered or Unordered)
- Dynamic
  - Communication Frequencies

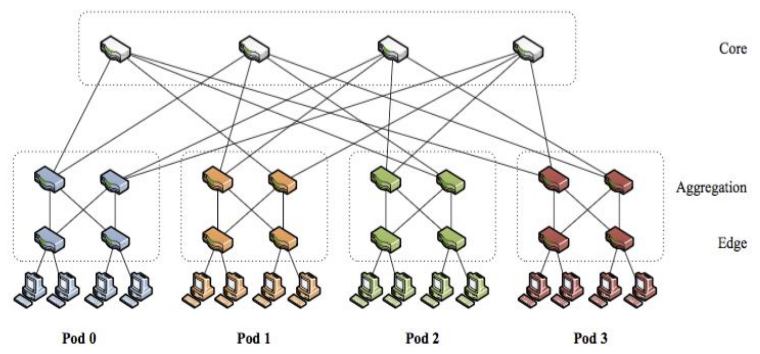
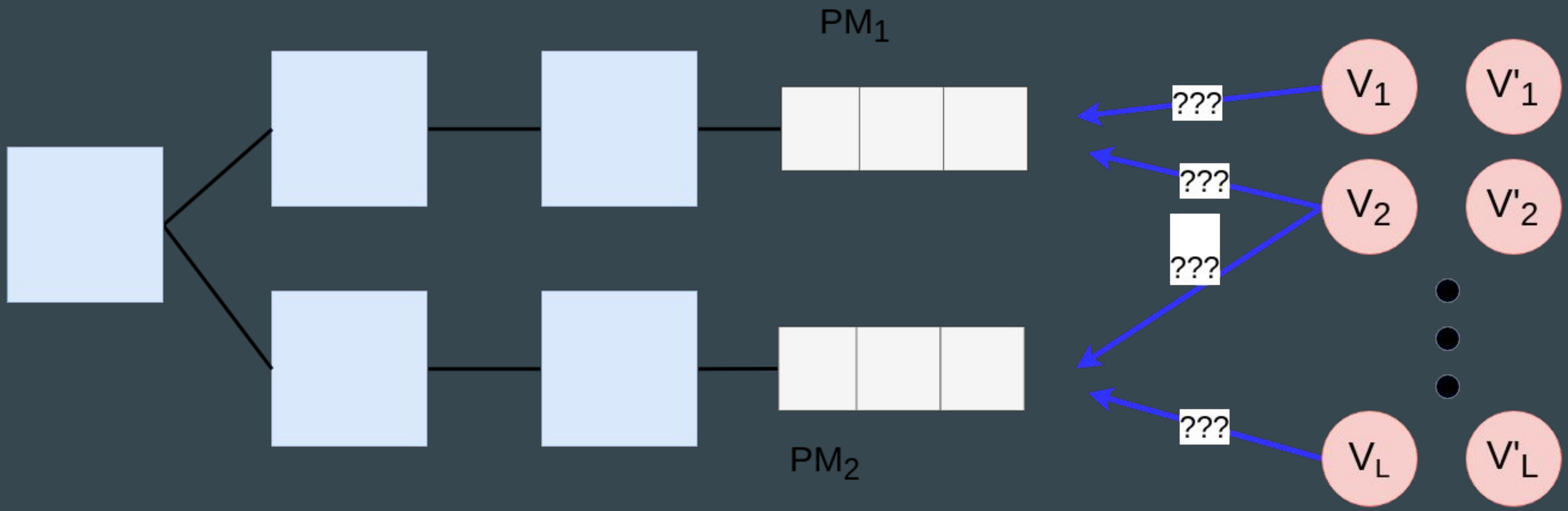
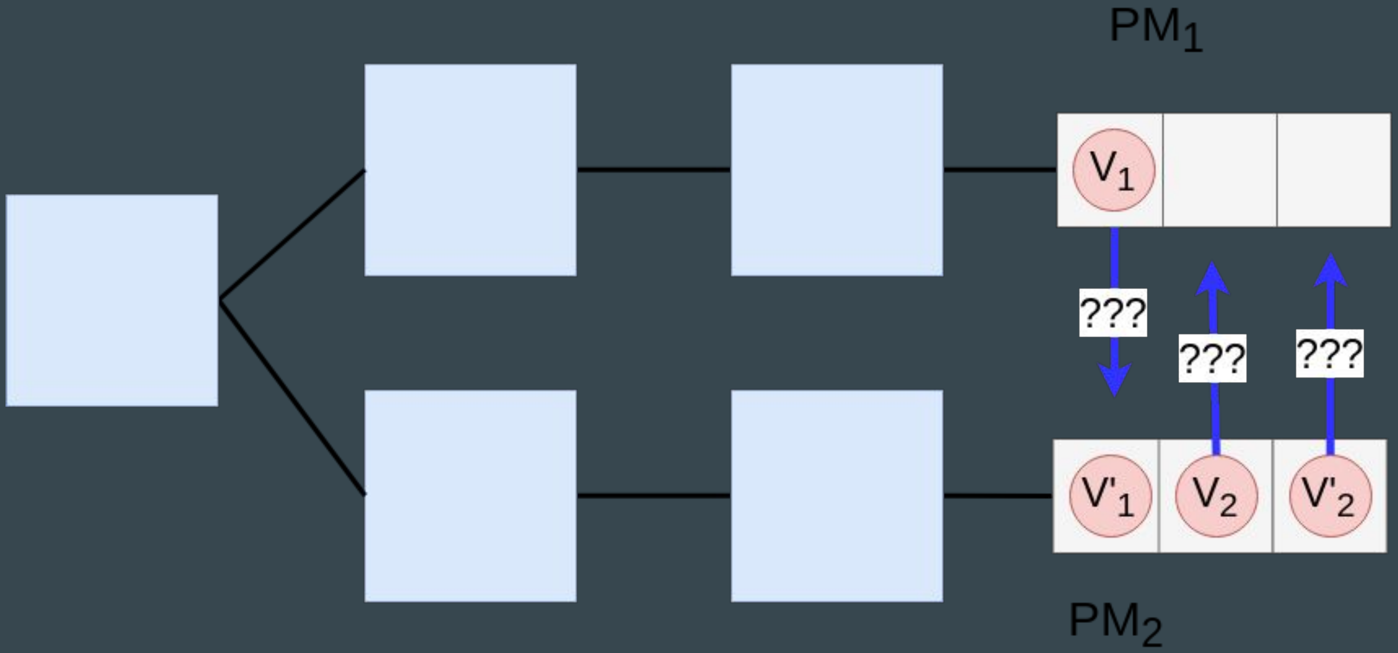


Figure 1: Sample fat tree topology.

What is VM Placement?



What is VM Migration?



Goals

Virtual Machine Placement

- Given:
  - An empty PDDC
  - Policies (Ordered or Unordered)
  - Unplaced VM Pairs with Comm. Frequency
- Output:
  - VM Placement with minimum Comm. cost
- How:
  - Optimal Algorithm
  - Placement Approximation Algorithm

Virtual Machine Migration

- Given:
  - A PDDC
  - Policies (Ordered or Unordered)
  - Placed VM Pairs with new Comm. Frequency
- Output:
  - VM Migration with minimum Comm. & Migration cost
- How:
  - MCF Algorithm
  - Migration Approximation Algorithm

Related Works

Virtual Machine Placement or Migration

- Improving the Scalability of Data Center Networks with Traffic-aware Virtual Machine Placement
    - 2010 Proceedings IEEE INFOCOM
    - X. Meng, V. Pappas, & L. Zhang
    - TrafficAware Algorithm
- PACE: Policy-Aware Application Cloud Embedding
    - 2013 Proceedings IEEE INFOCOM
    - L. E. Li et al.
- PLAN: Joint Policy- and Network-Aware VM Management for Cloud Data Centers
    - 2016 IEEE Transactions on Parallel and Distributed Systems
    - L. Cui et al.
    - PLAN Algorithm

Virtual Machine Placement and Migration

- Joint Virtual Machine Placement and Migration Scheme for Data Centers
  - 2014 IEEE Global Communications Conference
  - T. Duong-Ba, T. Nguyen, B. Bose, & T. Tran
- Traffic-Aware Virtual Machine Migration in Topology-Adaptive DCN
  - 2017 IEEE/ACM Transactions on Networking
  - Y. Cui et al.

System Model

Datacenter

- Fat Tree Topology
  - K-parameter determines number of PMs & switches
- PDDC:
  - Undirected Graph G(V, E)
  - $V = V_P \cup V_S$
  - E is the set all edges
- Physical Machines:
  - i-th PM has $m(i)$ resource slots
  - Each VM requires 1 slot

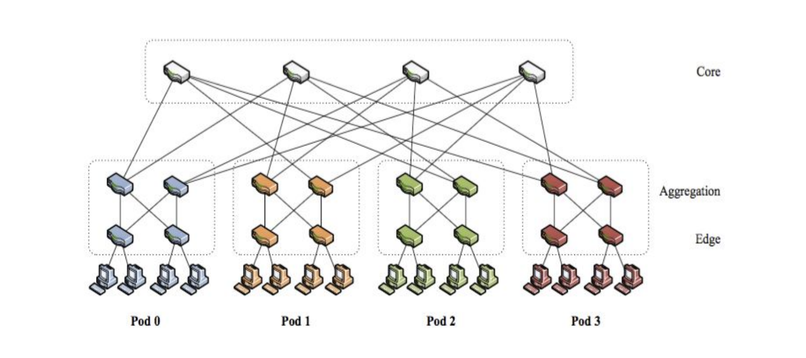
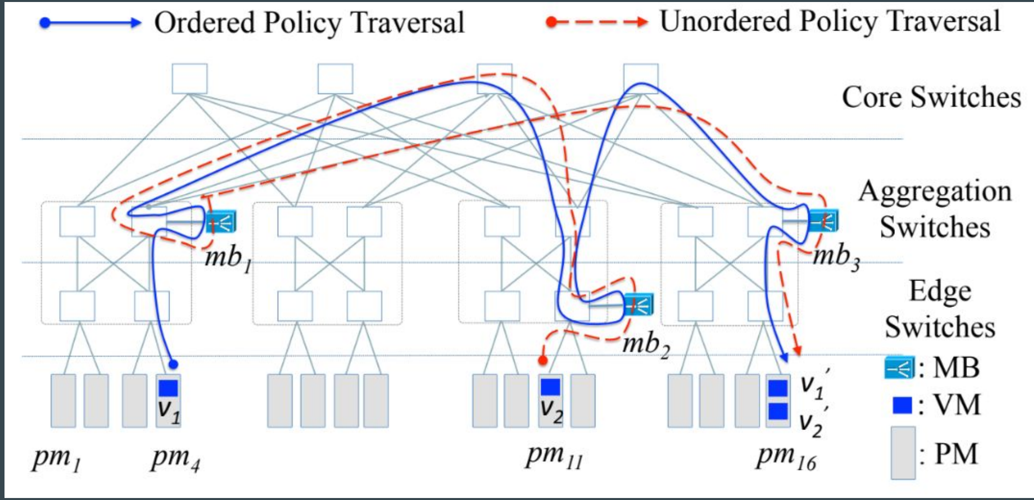


Figure 1: Sample fat tree topology.

Middleboxes

- Set of Middleboxes:
  - $M = \{ mb_1 , mb_2 , \dots , mb_m \}$
- MB Switch:
  - $mb_j \rightarrow sw(j) \in V_s$
- Bump Off the Wire Design

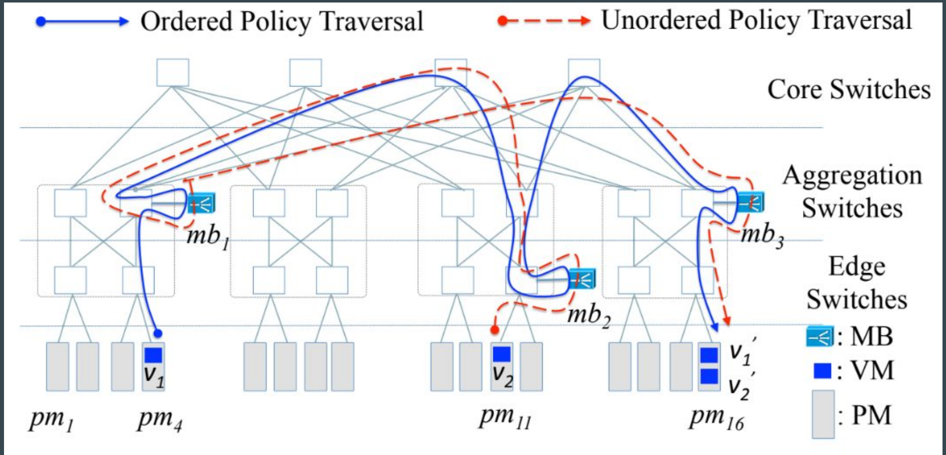


VM Pairs

- VM Pairs:
  - $P = \{ (v_1, v'_1), (v_2, v'_2), \dots, (v_L, v'_L) \}$
  - v_i = Source VM
  - v'_i = Destination VM
- Communication Frequency:
  - $\lambda = \langle \lambda_1, \lambda_2, \dots, \lambda_L \rangle$
  - Non-constant vector

Policies

- Ordered Policies
  - ($mb_1, mb_2, \ldots, mb_m$)
  - Ingress Switch = First MB visited
  - Egress Switch = Last MB visited
  - Sequential MB Dependencies
- Unordered Policies
  - { $mb_1, mb_2, \ldots, mb_m$ }
  - Independant MBs



Costs

- Distance Cost
  - $c(i, j)$
- VM Pair Communication Cost
  - (frequency) * (number of hops)
- VM Pair Migration Cost
  - $\mu * c(i, j)$

Virtual Machine Migration

Ordered Policy Goal

$$C_t(m) = \sum_{i=1}^{l} \lambda_i \cdot \sum_{j=1}^{m-1} c\big(sw(j), sw(j+1)\big) + \sum_{i=1}^{l} \Big(\mu \cdot c\big(p(v_i), m(v_i)\big) + \lambda_i \cdot c\big(m(v_i), sw(1)\big)\Big)$$

$$+ \sum_{i=1}^{l} \Big(\mu \cdot c\big(p(v_i'), m(v_i')\big) + \lambda_i \cdot c\big(sw(m), m(v_i')\big)\Big)$$

Ordered Policy Goal

$$C_t(m) = \boxed{\sum_{i=1}^{l} \lambda_i \cdot \sum_{j=1}^{m-1} c\big(sw(j), sw(j+1)\big)} + \boxed{\sum_{i=1}^{l} \Big(\mu \cdot c\big(p(v_i), m(v_i)\big) + \lambda_i \cdot c\big(m(v_i), sw(1)\big)\Big)}$$

$$\boxed{+ \sum_{i=1}^{l} \Big(\mu \cdot c\big(p(v_i'), m(v_i')\big) + \lambda_i \cdot c\big(sw(m), m(v_i')\big)\Big)}$$

MB Traversal Cost

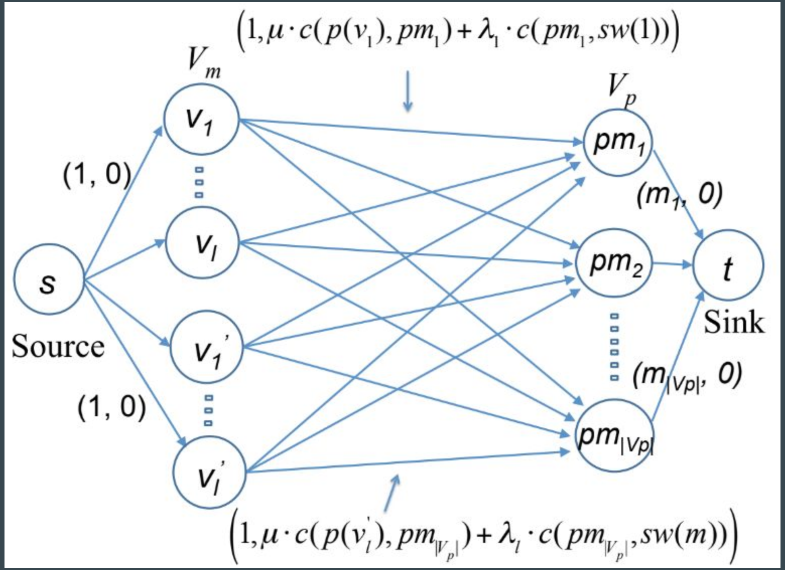
Migration and Ingress Cost

Migration and Egress Cost

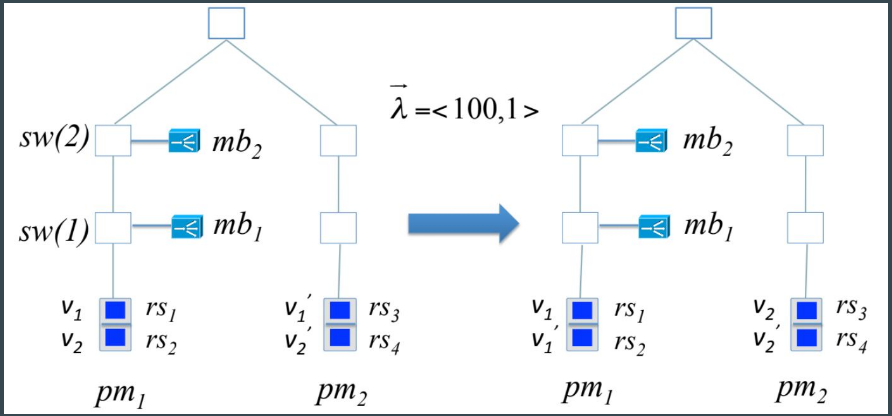
Ordered Policy Solution - MCF Algorithm

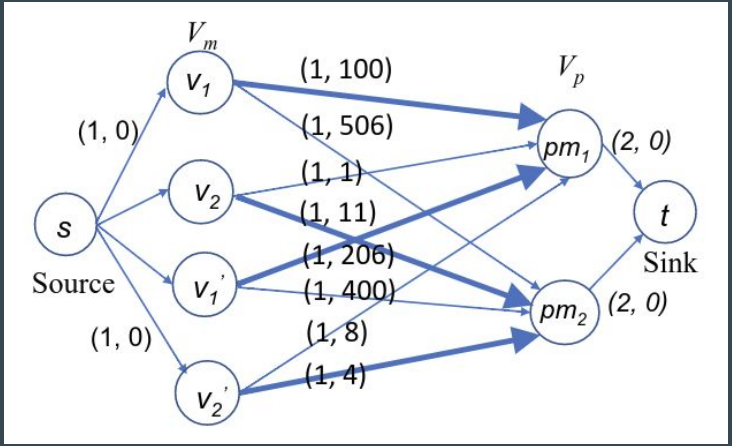
1. Add Source & Sink Node: $V' = \{s\} \cup \{t\} \cup V_m \cup V_p$
2. Connect Source/Sink to VMs/PMs:
   $E' = \{(s,v) : v \in V_m\} \cup \{(v, pm_j : v \in V_m, pm_j \in V_p\} \cup \{(pm_j, t) : pm_j \in V_p\}$
3. Source to VM: capacity 1, cost 0 & PM to Sink: capacity m_j, cost 0
4. Source VM to PM edges: capacity 1, cost:
   $\mu \cdot c\big(p(v_i), pm_j\big) + \lambda_i \cdot c\big(pm_j, sw(1)\big)$
   Destination VM to PM edges: capacity 1, cost:
   $\mu \cdot c\big(p(v_i'), pm_j\big) + \lambda_i \cdot c\big(pm_j, sw(m)\big)$
5. Supply = 2L, Demand = 2L

Ordered Policy Solution - MCF Algorithm



Ordered Policy Solution - MCF Algorithm





Unordered Policy Goal

$$C_t(m, \vec{\pi}) = \sum_{i=1}^{l} \Big(\mu \cdot c\big(p(v_i), m(v_i)\big) + \mu \cdot c\big(p(v_i'), m(v_i')\big) \Big)$$

$$\sum_{i=1}^{l} \lambda_i \cdot \Big(\sum_{j=1}^{m-1} c\big(sw(\pi^i(j)), sw(\pi^i(j+1))\big) + c\big(m(v_i), sw(\pi^i(1))\big)$$

$$+c\big(sw(\pi^i(m)), m(v_i')\big) \Big)$$

Unordered Policy Goal

$$C_t(m, \vec{\pi}) = \boxed{\sum_{i=1}^{l} \Big(\mu \cdot c\big(p(v_i), m(v_i)\big) + \mu \cdot c\big(p(v_i'), m(v_i')\big) \Big)}$$

$$\sum_{i=1}^{l} \lambda_i \cdot \Big(\boxed{\sum_{j=1}^{m-1} c\big(sw(\pi^i(j)), sw(\pi^i(j+1))\big)} + \boxed{c\big(m(v_i), sw(\pi^i(1))\big)}$$

$$\boxed{+c\big(sw(\pi^i(m)), m(v_i')\big)} \Big)$$

Migration Cost

Cost to First MB

Variable MB Cost

Cost to Last MB

Unordered Policy Solution - Approximation

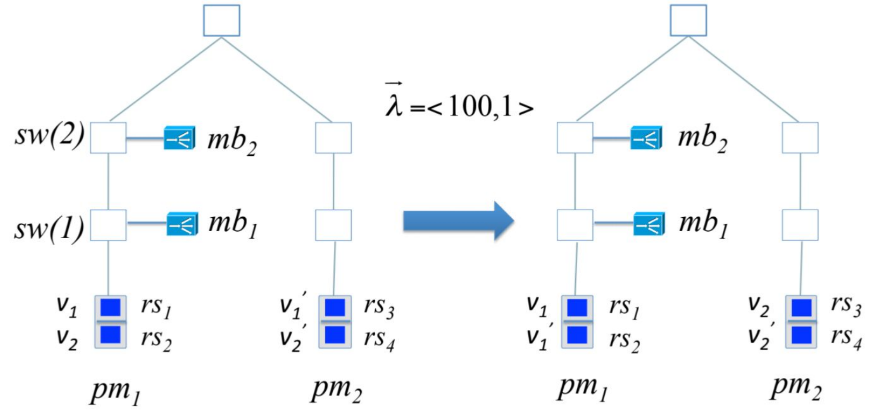
Algorithm 1: VM^{2}P Algorithm for Unordered Policy.

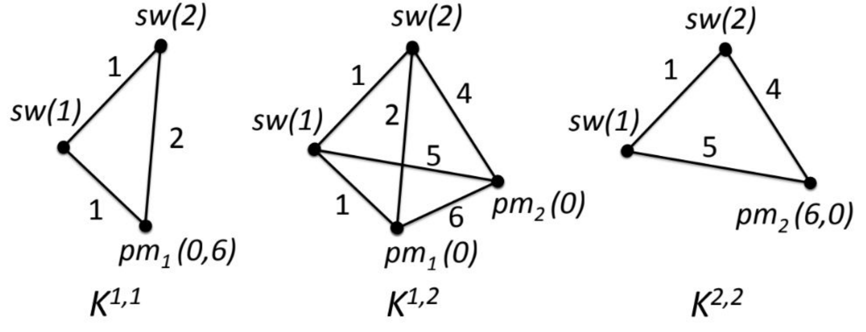
Input: A PDDC with unordered policy $\{mb_1, mb_2, ..., mb_m\}$, VM pairs P with placement p, $V_p = \{pm_i\}$, $m(i)$.

Output: A migration m and its total energy cost $C_t(m, \overrightarrow{\pi})$.

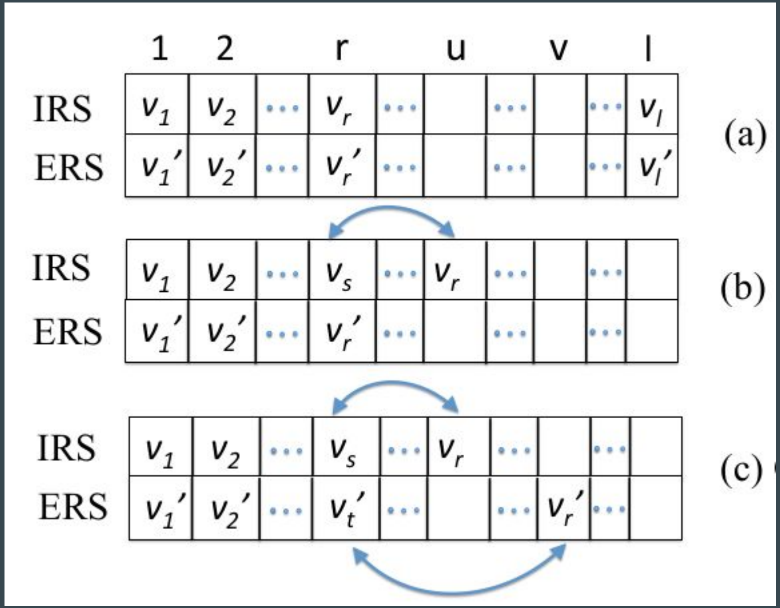
0. $m = \phi$, $C_t(m, \overrightarrow{\pi}) = 0$, $k = 0$
1. **while** $(k \leq l)$ //not all VM pairs are migrated yet
2. $a = 1$, $b = 1$, $c_{min} = \infty$;
3. **for** $(i = 1; i \leq |V_p|; i++)$
4. **if** $(m(pm_i) == 0)$ **break**;
5. **for** $(j = i; j \leq |V_p|; j++)$
6. **if** $(m(pm_j) == 0)$ **break**;
7. **if** $(i == j \wedge m(s_j) \leq 1)$ **break**;
8. $V_K^{i,j} = \{pm_i, pm_j, sw(1), sw(2), ...sw(m)\}$;
9. Construct complete graph $K^{i,j} = (V_K^{i,j}, E_K^{i,j})$;
10. Compute a minimum spanning tree MST for $K^{i,j}$;
11. Compute a walk W from pm_i to pm_j on MST by visiting all vertices using each edge *at most twice*, and calculate the cost $c_{i,j}$ of W;
12. $c(pm_i) = \mu \cdot c(p(v_i), pm_i)$, $c(pm_j) = \mu \cdot c(p(v_i^{'}), pm_j)$;
13. $c_{i,j} = \lambda_k \cdot c_{i,j} + c(pm_i) + c(pm_j)$;
14. **if** $(c_{i,j} < c_{min})$ $a = i$, $b = j$, $c_{min} = c_{i,j}$;
15. **end for;**
16. **end for;**
17. $m = m \cup \{(pm_a, pm_b)\}$;
18. $C_t(m, \overrightarrow{\pi})$ += c_{min};
19. $m(pm_a)--$, $m(pm_b)--$;
20. $k++$; // the next VM pair
21. **end while;**
22. **RETURN** m and $C_t(m, \overrightarrow{\pi})$.

Unordered Policy Solution - Approximation





Sketch of Optimal Proof



Virtual Machine Placement

Ordered Policy Goal

$$C_t(m) = \sum_{i=1}^{l} \lambda_i \cdot \sum_{j=1}^{m-1} c\big(sw(j), sw(j+1)\big) +$$

$$\sum_{i=1}^{l} \Big(\lambda_i \cdot c\big(m(v_i), sw(1)\big) + \lambda_i \cdot c\big(sw(m), m(v_i')\big) \Big)$$

Ordered Policy Goal

$$C_t(m) = \boxed{\sum_{i=1}^{l} \lambda_i \cdot \sum_{j=1}^{m-1} c\big(sw(j), sw(j+1)\big)} +$$

$$\boxed{\sum_{i=1}^{l} \Big(\lambda_i \cdot c\big(m(v_i), sw(1)\big) + \lambda_i \cdot c\big(sw(m), m(v_i')\big) \Big)}$$

MB Traversal Cost

Ingress and Egress Cost

Ordered Policy Solution - Optimal

Algorithm 2: VMP^2 Algorithm for Ordered Policy.

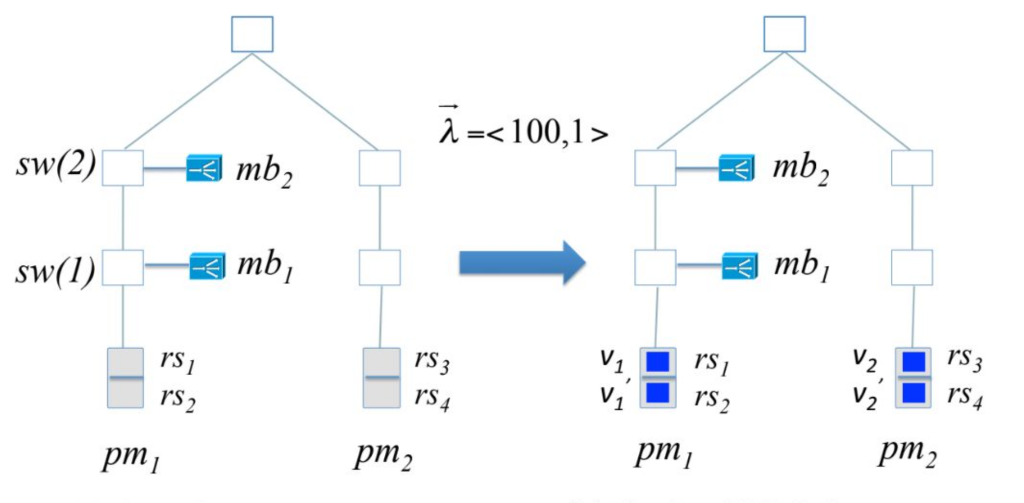
Input: A PDDC with ordered policy $(mb_1, mb_2, ..., mb_m)$, VM pairs P, $V_p = \{pm_i\}$, $m(i)$.

Output: A placement p and the total comm. cost $C_c(p)$.

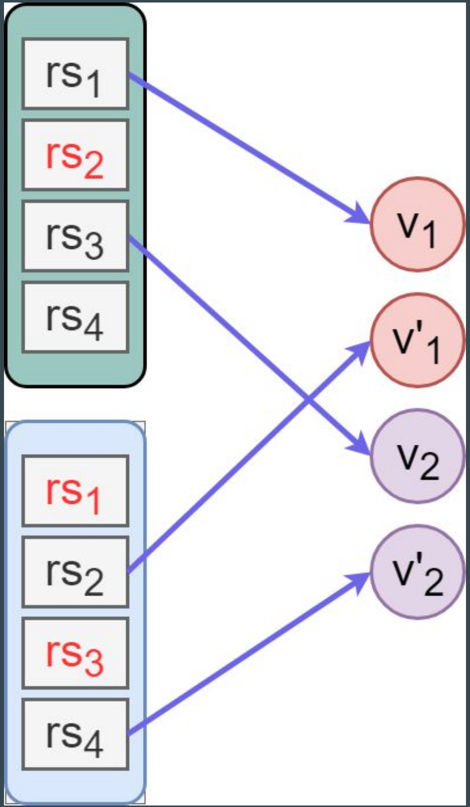
Notations: $\mathcal{I}[i].id$, $\mathcal{I}[i].dist$, $\mathcal{E}[i].id$, $E[i].dist$: ID and cost of the i^{th} resource slot in $\mathcal{I}$ and $\mathcal{E}$.

0. $i = 1$, $j = 1$, $k = 1$, $C_c(p) = 0$,
$\mathcal{I}= \phi$ (empty set), $\mathcal{E}= \phi$, $p = \phi$;
1. Assign all resource slots in the PDDC unique IDs;
2. Sort them in ascending order of their costs to ingress switch $sw(1)$ (and egress switch $sw(m)$), store the first $2l$ resource slots and their costs in an array A (and B);
3. **while** $(k \leq l)$
4.   **while** $(A[i].id \in \mathcal{E})$ $i++$;
5.   **while** $(B[j].id \in \mathcal{I})$ $j++$;
6.   **if** $(A[i].id \neq B[j].id)$
7. $\mathcal{I}[k].id = A[i].id, \mathcal{I}[k].dist = A[i].dist$;
8. $\mathcal{E}[k].id = B[j].id, \mathcal{E}[k].dist = B[j].dist$;
9. i++; j++;
10.   **else**
11.   **while** $(A[i+1].id \in \mathcal{E})$ i++;
12.   **while** $(B[j+1].id \in \mathcal{I})$ j++;
13.   **if** $(A[i+1].dist \leq B[j+1].dist)$
14. $\mathcal{I}[k].id = A[i+1].id, \mathcal{I}[k].dist = A[i+1].dist$;
15. $\mathcal{E}[k].id = B[j].id, \mathcal{E}[k].dist = B[j].dist$;
16. i += 2; j++;
17.   **else**
18. $\mathcal{I}[k].id = A[i].id, \mathcal{I}[k].dist = A[i].dist$;
19. $\mathcal{E}[k].id = B[j+1].id, \mathcal{E}[k].dist = B[j+1].dist$;
20. i++; j += 2;
21.   **end if;**
22.   **end if;**
23. k++;
24. **end while;**
25. $a = \sum_{j=1}^{m-1} c\big(sw(j), sw(j+1)\big)$;
26. **for** $(1 \leq i \leq l)$
27.   Place v_i at resource slot $\mathcal{I}[i].id$;
28.   Place $v_i^{'}$ at resource slot $\mathcal{E}[i].id$;
29. $p = p \cup \{(\mathcal{I}[i].id, \mathcal{E}[i].id)\}$;
30. $C_c(p)$ += $\lambda_i * (\mathcal{I}[i].dist + a + \mathcal{E}[i].dist)$;
31. **end for;**
32. **RETURN** p and $C_c(p)$.

Ordered Policy Solution - Optimal



(a) k =2 fat-tree PDDC (b) Optimal VM placement



Unordered Policy Goal

$$c^{p,\pi^i} = \sum_{i=1}^{l} \left(\boxed{\lambda_i \cdot c\big(p(v_i), sw(\pi^i(1))\big)} + \lambda_i \cdot \sum_{j=1}^{m-1} \left(\boxed{c\big(sw(\pi^i(j), sw(\pi^i(j+1))\big)} \right) + \boxed{\lambda_i \cdot c\big(sw(\pi^i(m)), p(v_i')\big)} \right)$$

Cost to First MB

Variable MB Traversal Cost

Cost to Last MB

Unordered Policy Solution - Approximation

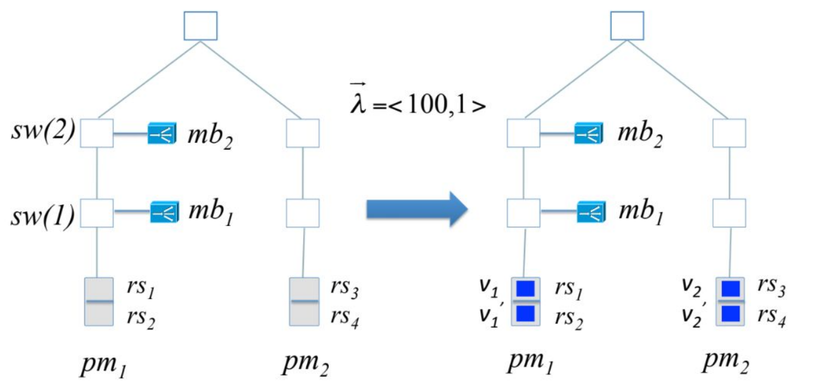
Algorithm 3: VMP^2 Algorithm for Unordered Policy.

Input: A PDDC with unordered policy $\{mb_1, mb_2, ..., mb_m\}$,
VM pairs P, $V_p = \{pm_i\}$, $m(i)$.

Output: A placement p and the total comm. cost $C_c(p, \overrightarrow{\pi})$.

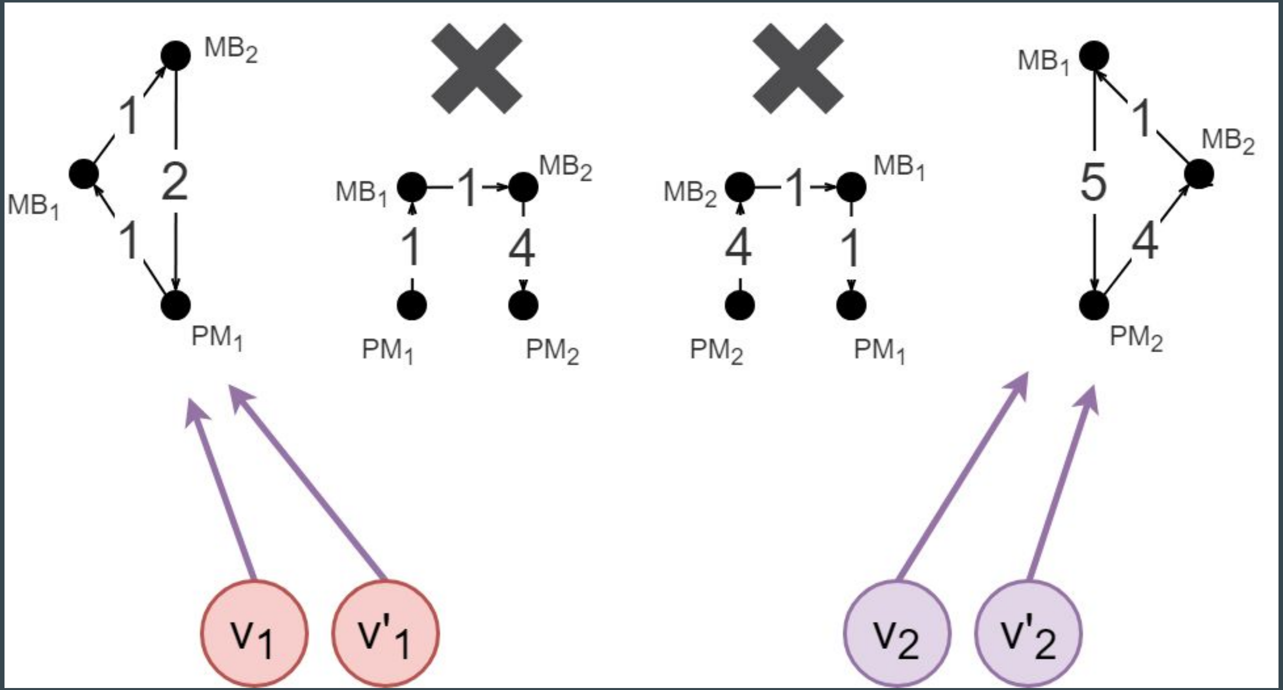
0. $X = \phi$; // stores each PM pair and the cost of the walk
1. **for** $(i = 1; i \leq |V_p|; i++)$
2. **for** $(j = i; j \leq |V_p|; j++)$
3. $V_K^{i,j} = \{pm_i, pm_j, sw(1), sw(2), ...sw(m)\}$;
4. Construct complete graph $K^{i,j} = (V_K^{i,j}, E_K^{i,j})$;
5. Compute a minimum spanning tree MST for $K^{i,j}$;
6. Compute a walk W from pm_i to pm_j on MST by visiting all vertices using each edge *at most twice*, and calculate the cost $c(i,j)$ of W.
7. $X = X \cup \{(i, j, c(i,j))\}$;
8. **end for;**
9. **end for;**
10. Sort X in non-descending order of $c(i,j)$.
Let $X = \{(s_1, t_1, c(s_1, t_1)), (s_2, t_2, c(s_2, t_2)), ...\}$;
11. $i = 1$, $j = 1$; // the i^{th} VM pair $(v_i, v_i^{'})$ is placed at the j^{th} PM pair (s_i, t_j) in X;
$p = \phi$, $C_c(p, \overrightarrow{\pi}) = 0$;
12. **while** $(i \leq l)$ //not all VM pairs are placed yet
13. **while** $\left(m(s_j) \geq 1 \wedge m(t_j) \geq 1\right)$
14. Place v_i at PM s_j, place $v_i^{'}$ at PM t_j;
15. $p = p \cup \{(s_j, t_j)\}$;
16. $C_c(p, \overrightarrow{\pi}) += \lambda_i * c(s_j, t_j)$;
17. $m(s_j)--$, $m(t_j)--$;
18. $i++$;
19. **if** $(i > l)$ **break**;
20. **end while;**
21. $j++$; // the next available PM pairs
22. **end while;**
23. **RETURN** p and $C_c(p, \overrightarrow{\pi})$.

Unordered Policy Solution - Approximation



(a) k =2 fat-tree PDDC (b) Optimal VM placement

Unordered Policy Solution - Approximation

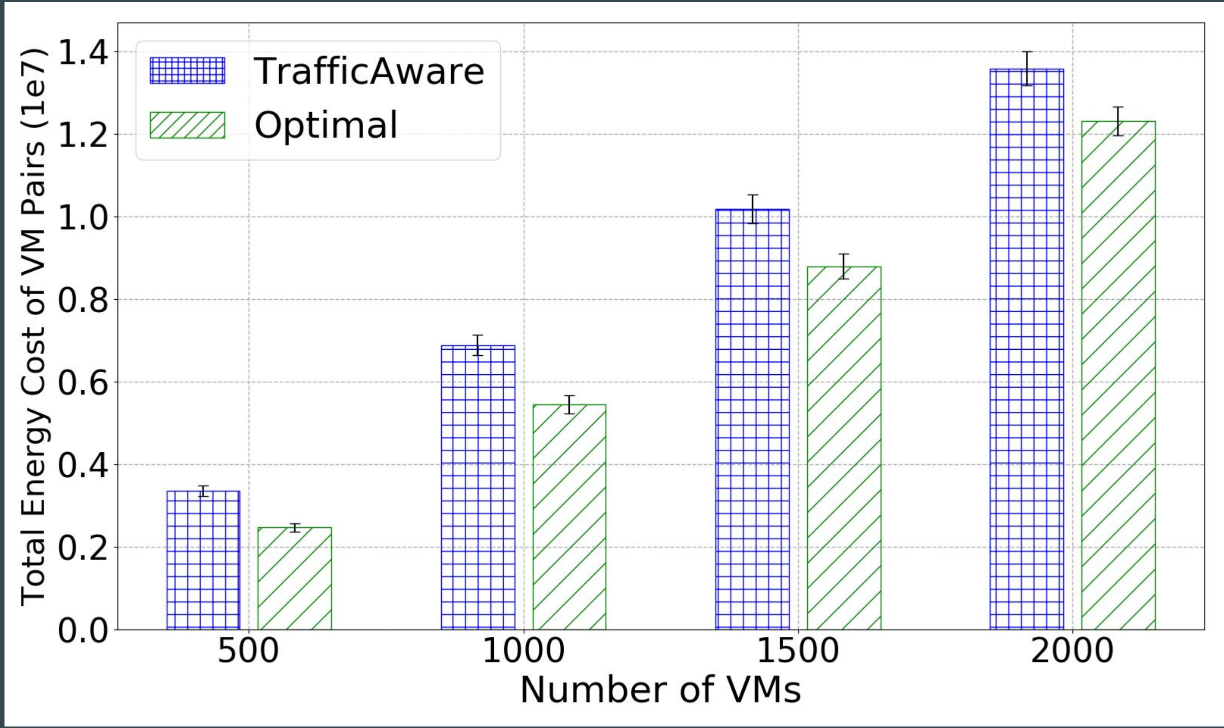


Performance Evaluation

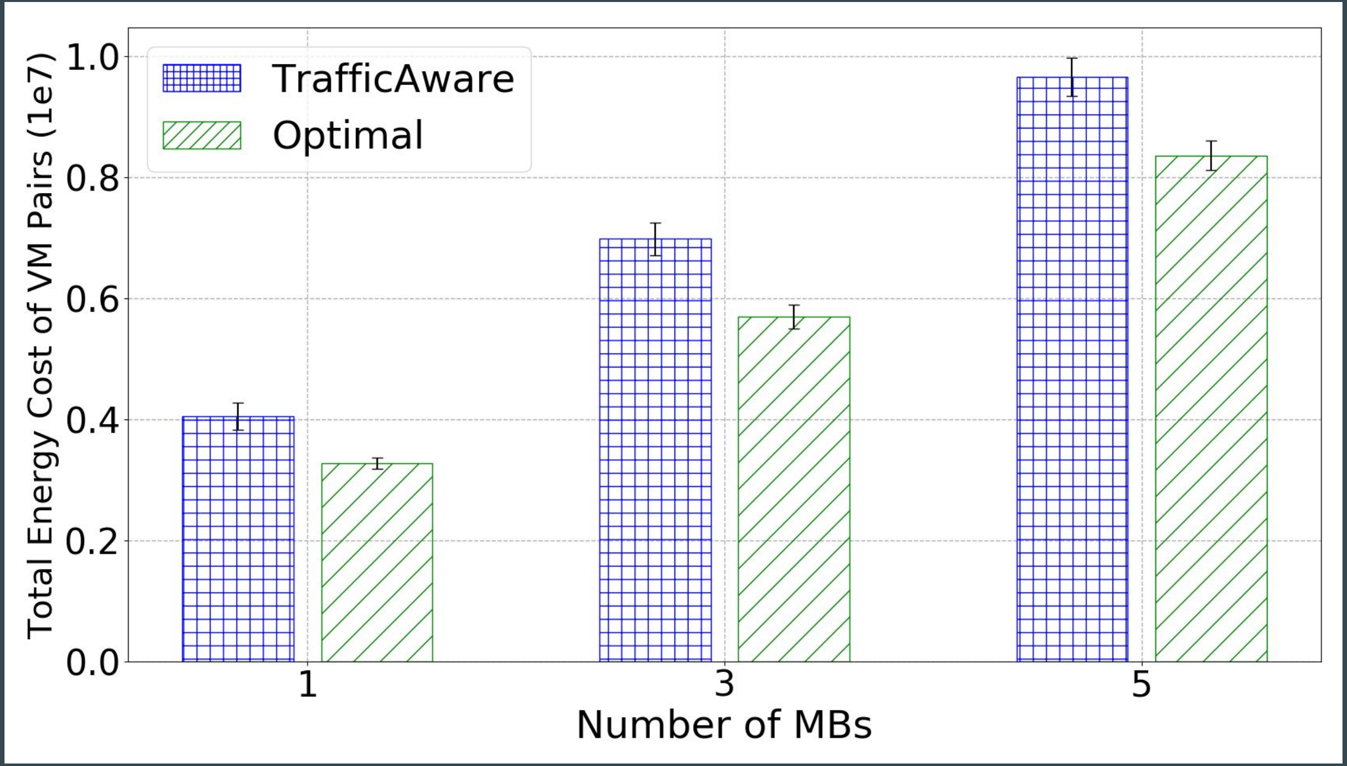
Common Simulation Parameters

- Fat Tree Topology (k = 8)
  - 128 Physical Machines
  - Frequency Range [1, 1000]
- Varying One of the Following (Placement):
  - Number of VM Pairs
  - Number of MBs
  - Number of Resource Slots
- Varying Mu Parameter (Migration)

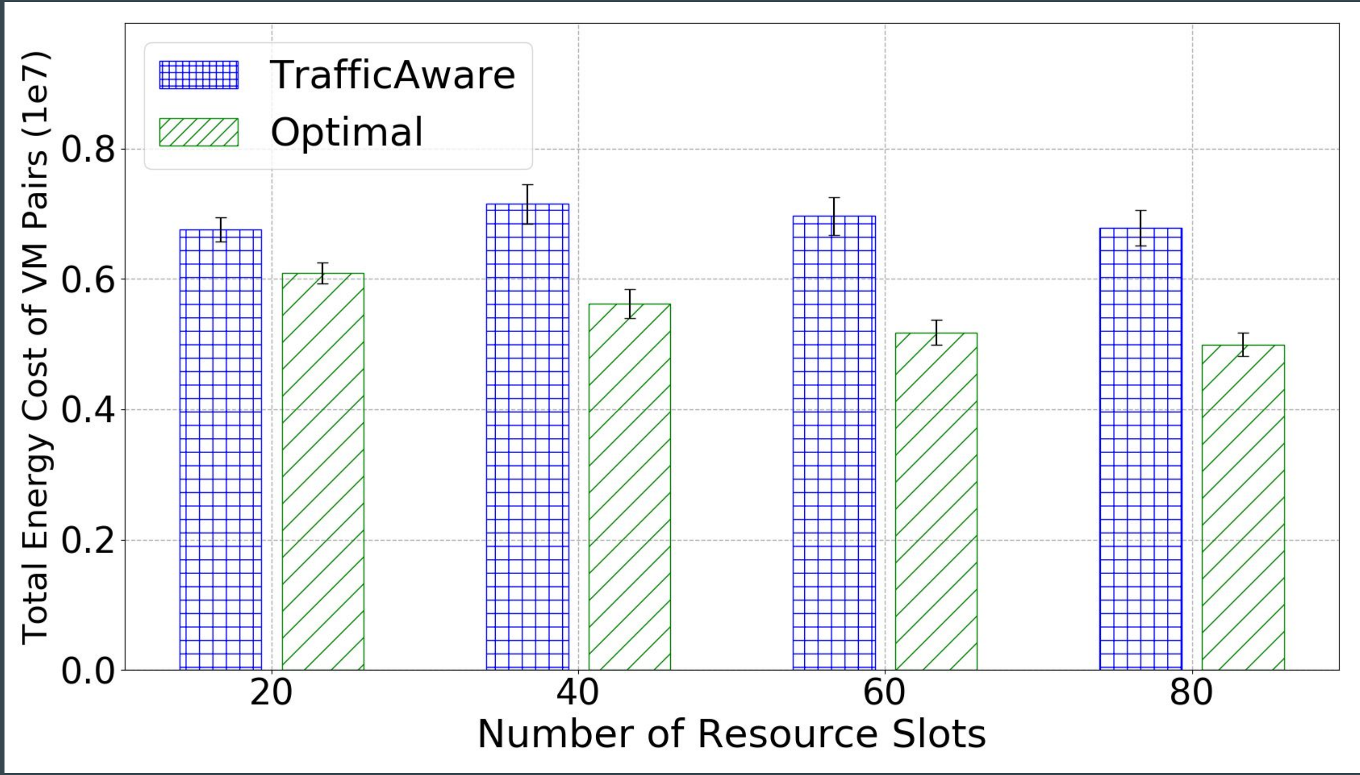
Ordered Placement - VM Simulation (rc = 40, mb = 3)



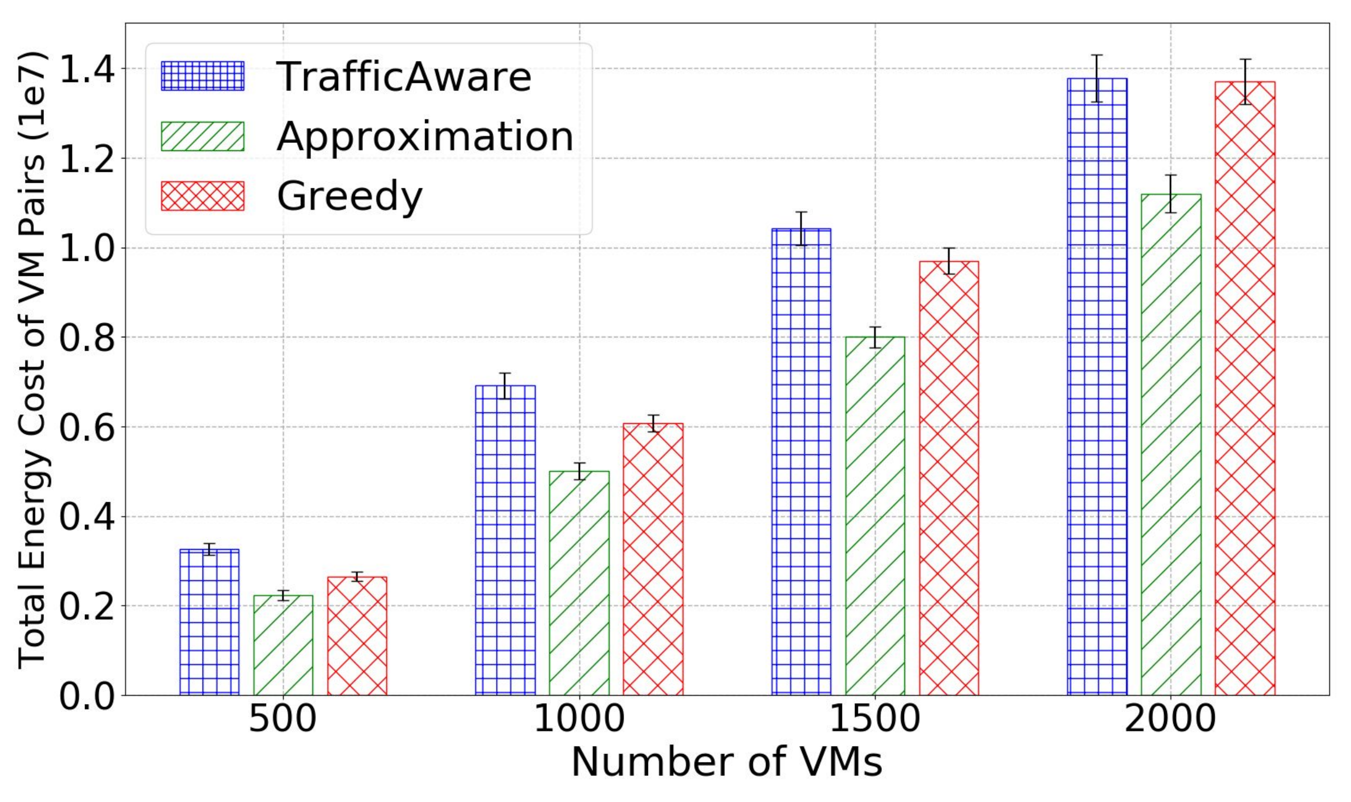
Ordered Placement - MB Simulation (rc = 40, l = 1000)



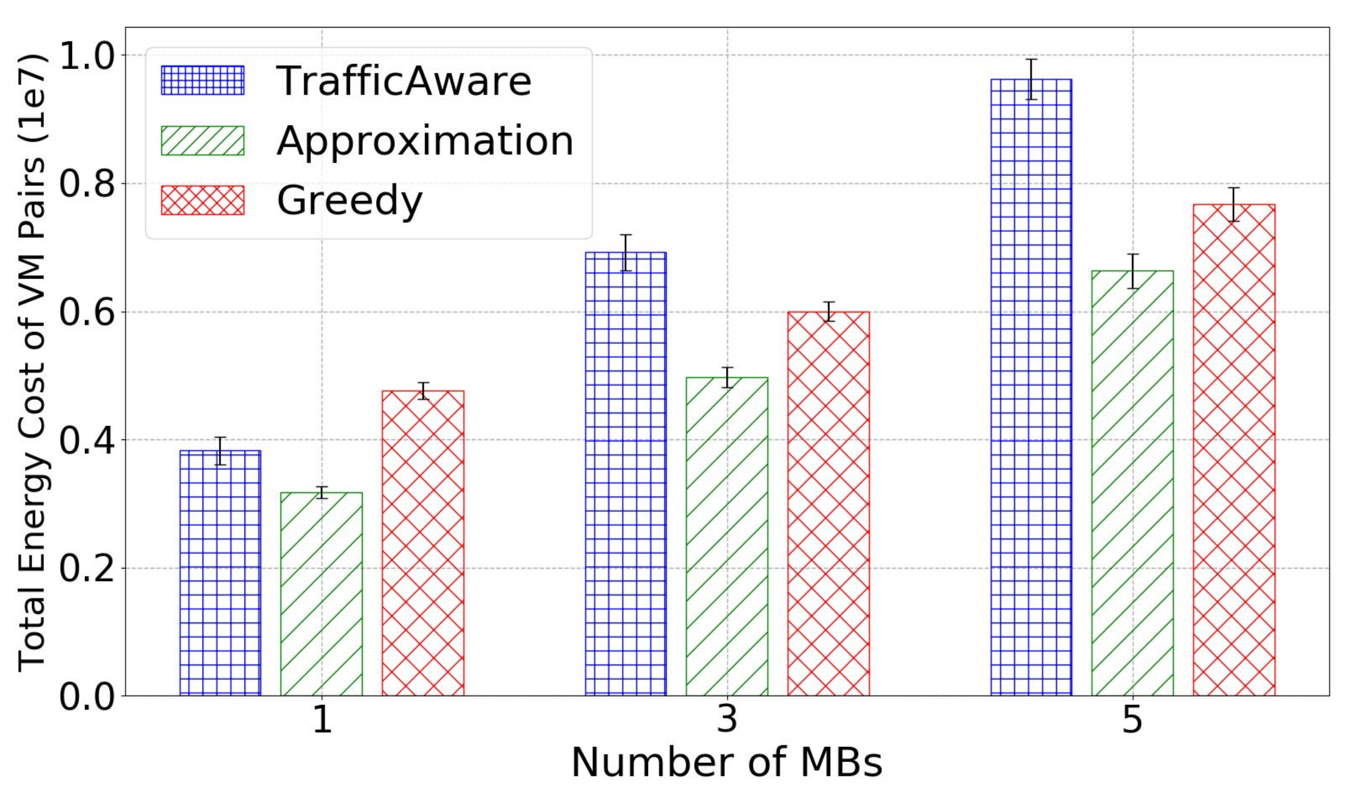
Ordered Placement - RC Simulation (I = 1000, mb = 3)



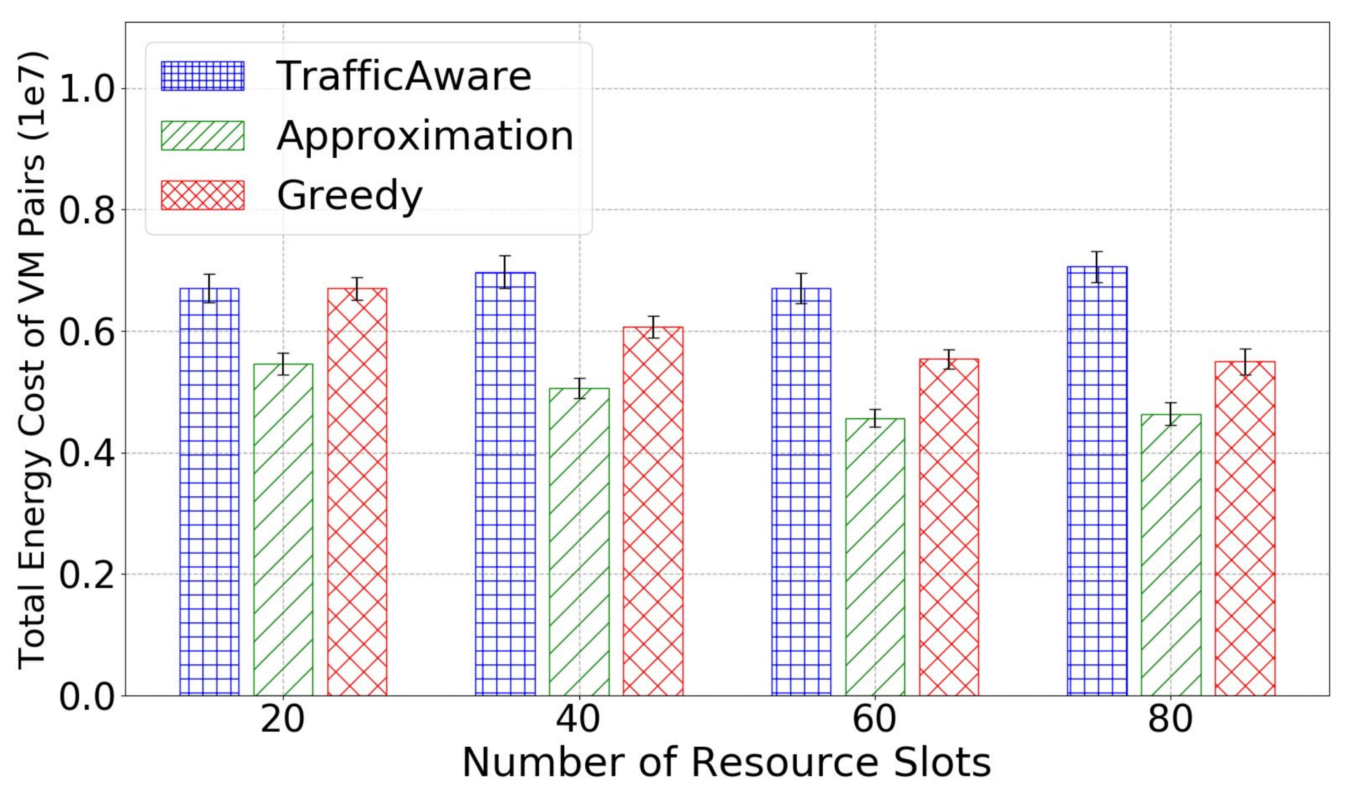
Unordered Placement - VM Simulation (rc = 40, mb = 3)



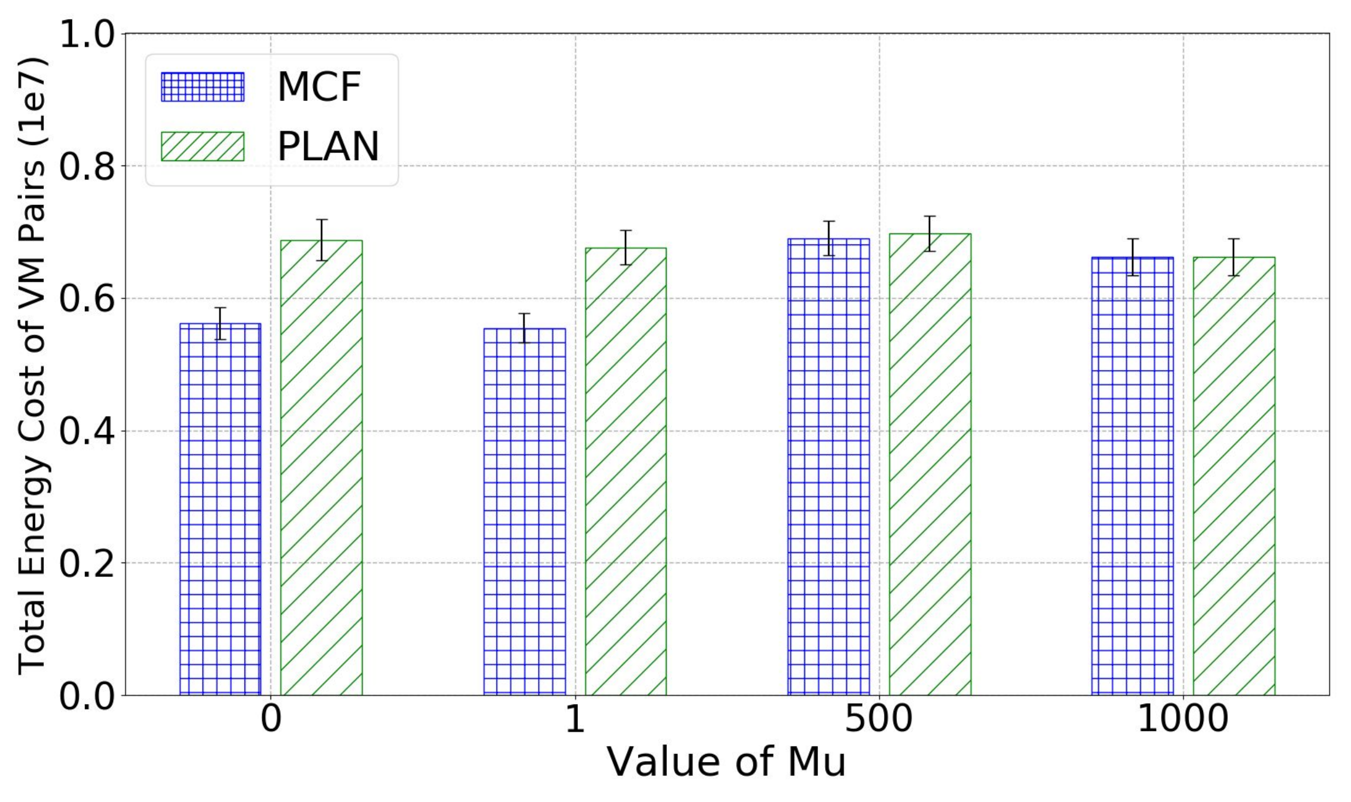
Unordered Placement - MB Simulation (rc = 40, l = 1000)



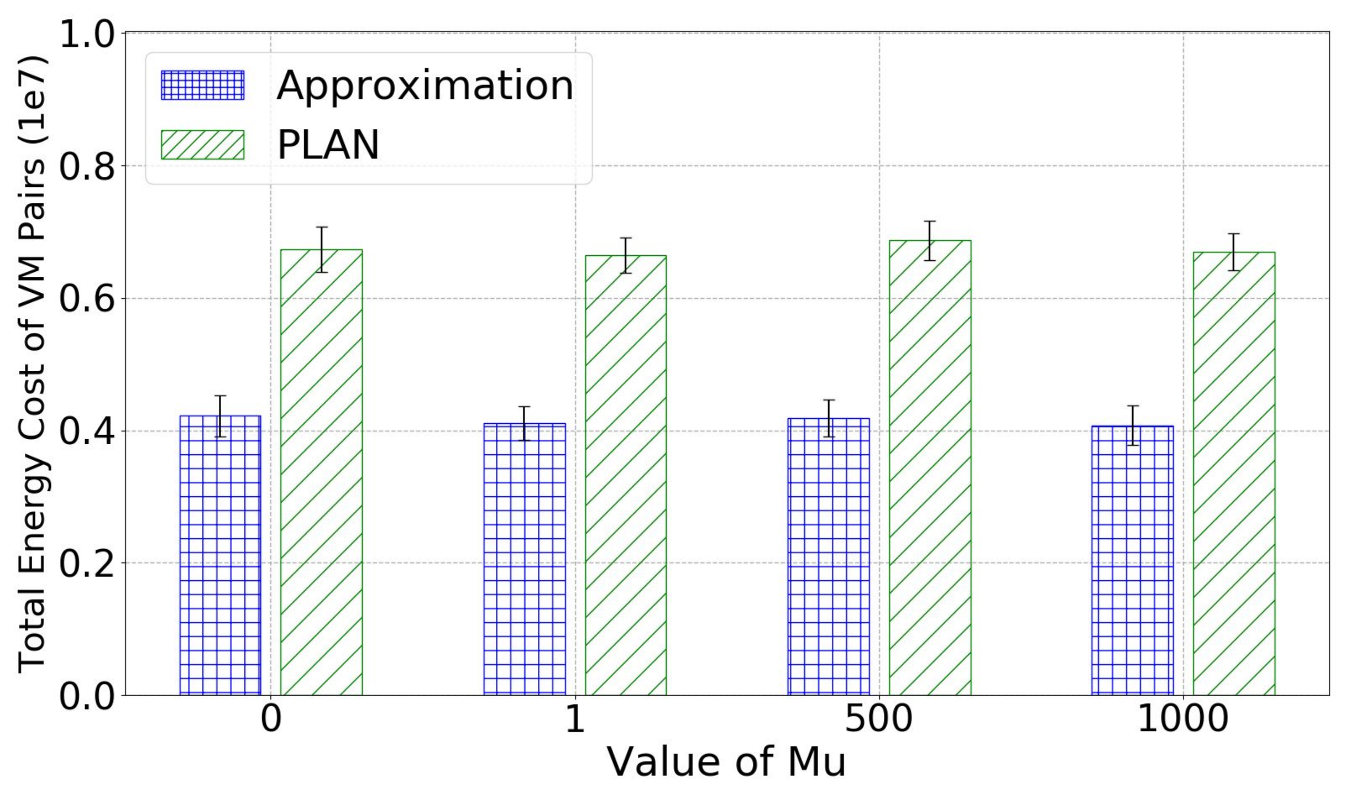
Unordered Placement - RC Simulation (l = 1000, mb = 3)



Ordered Migration - (I = 1000, mb = 3, rc=40)



Unordered Migration - (I = 1000, mb = 3, rc=40)



Conclusion

Conclusion

- Placement Special Case of Migration
- Ignoring PDDC constraints leads to Inefficiencies
- Future Work:
    - Testing in Real Networks
    - Variable ‘sized’ VMs
    - Network Function Virtualization (NFVs)