MAN Optimization via Clog Computing for a Heterogeneous Internet of Things

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Group Meeting

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Outline

- Purpose/Motivation
- Problem Statement
- Application Profiles
- Network Parameters/Costs
- Mathematical Description
- Topology/Flow Scenarios
- Simulation Results
- Ongoing Work

Purpose/Motivation

- Will IoT simply require more physical layer core capacity? Or will traffic nature, i.e. increased heterogeneity and functional requirements require more robust traffic engineering and/or policy based/constraint-based routing?
- Application Heterogeneity:
  - Bandwidth/Latency
  - Processing
  - Storage
  - Internal vs External to MAN
- MAN should play a more active role linking the access and core layers
  - fog processing and storage capabilities/cloud providers extend services to fog
- With increased application/traffic heterogeneity in IoT, effective traffic engineering & functional placement will have a much more significant impact on network costs and performance.

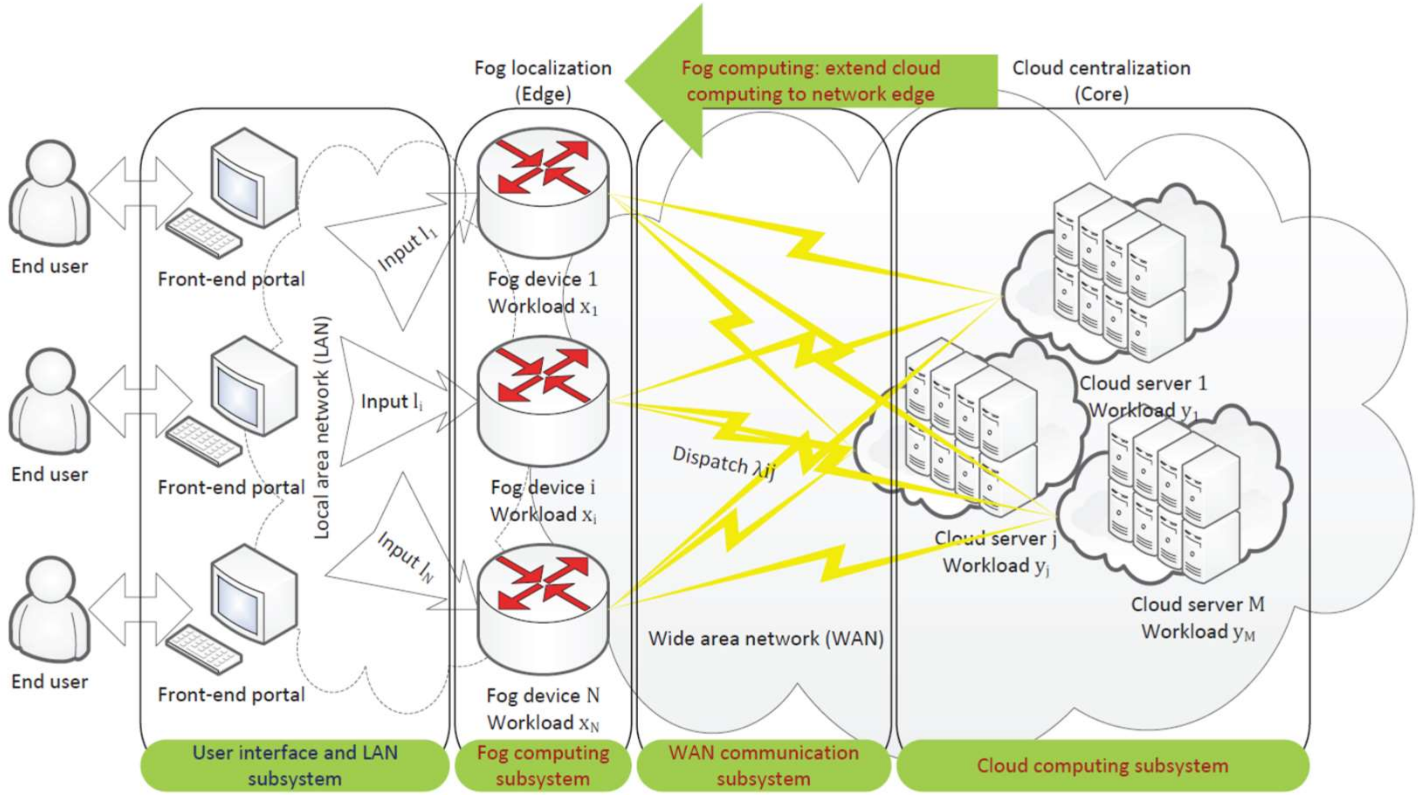
Problem Statement

- As IoT related traffic becomes increasingly heterogeneous and demands greater proportions of overall Internet traffic, it must be provisioned according to its unique performance and functional requirements, in this case: latency, throughput, processing, and storage requirements. MAN providers are in a unique position to manage and execute this function within a Hybrid Fog-Cloud environment. Thus a MAN provisioning model is proposed.

- Given core network SLAs, MAN topology/nodal capabilities, and performance requirements by app profile: minimize operational costs of MAN via 3 components:
  - Path from source to destination – intra-MAN
  - Path from source to MAN/WAN interface – external traffic
  - Processing/Storage Nodes (if applicable):
    - Fog/Cloud/Hybrid

- Goal is to model mixtures of anticipated application/traffic profiles routed through a MAN with maximum end-to-end latency via constraint-based routing principles to demonstrate what factors (application/topological parameters) have a more significant impact on total costs.

Related Work



System with four subsystems, focuses on workload and relationships between each subsystem:
LAN/input, Fog, WAN, Cloud

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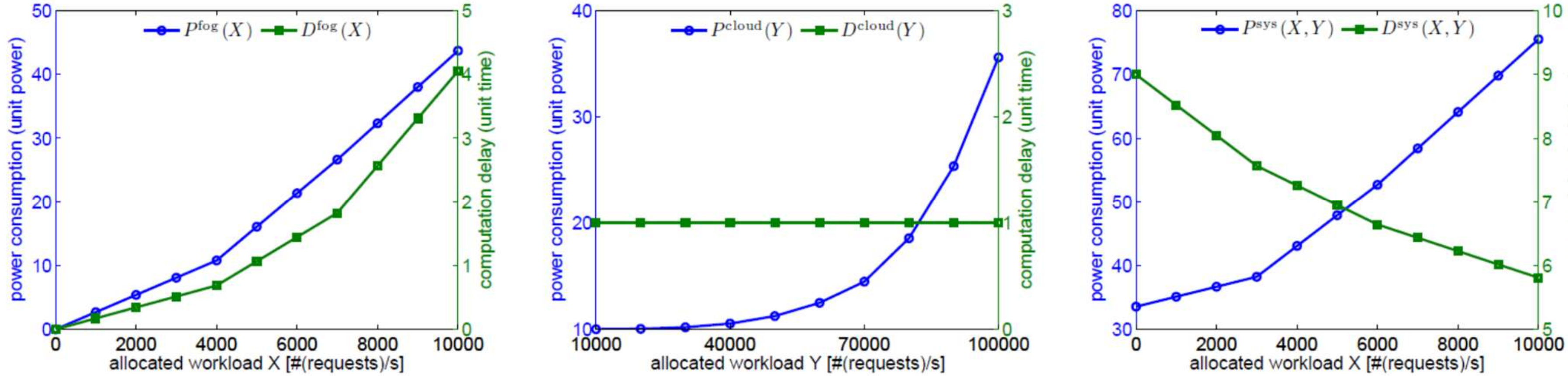
Deng, Ruilong, et al. "Optimal Workload Allocation in Fog-Cloud Computing Towards Balanced Delay and Power Consumption." (2012).

Related Work



(a) Fog computing subsystem (b) Cloud computing subsystem (c) Fog-cloud computing system

Fog subsystem:
Computation delay increases with power consumption
Cloud subsystem:
Computation delay remains relatively fixed for increased power consumption
Fog-Cloud Computing system:
Total system delay decreases with increasing power consumption

.

Deng, Ruilong, et al. "Optimal Workload Allocation in Fog-Cloud Computing Towards Balanced Delay and Power Consumption." (2012).

Mathematical Explanation

- Inputs:
  - MAN Topology: G(N,L) (and core location)
    - Node tier dictates costs and capacities for processing and storage – μ, ν, U, E
  - DC location in core
  - Costs per unit traffic: Λ - MAN, ε - WAN
  - Application Profiles:
    - α, β, κ, Δ, Θ
  - Core Network SLAs: Residual Latency by application & destination - $\theta_{a,f}$

- Objective function: Minimize total operational cost of MAN
  - Processing, Storage, WAN up/down, Capacity

- Outputs: For all node pairs, profiles, and core destinations:
  - Path
  - Processing node (if applicable)
  - Storage node (if applicable)
  - Required link capacities, WAN bandwidth up/down

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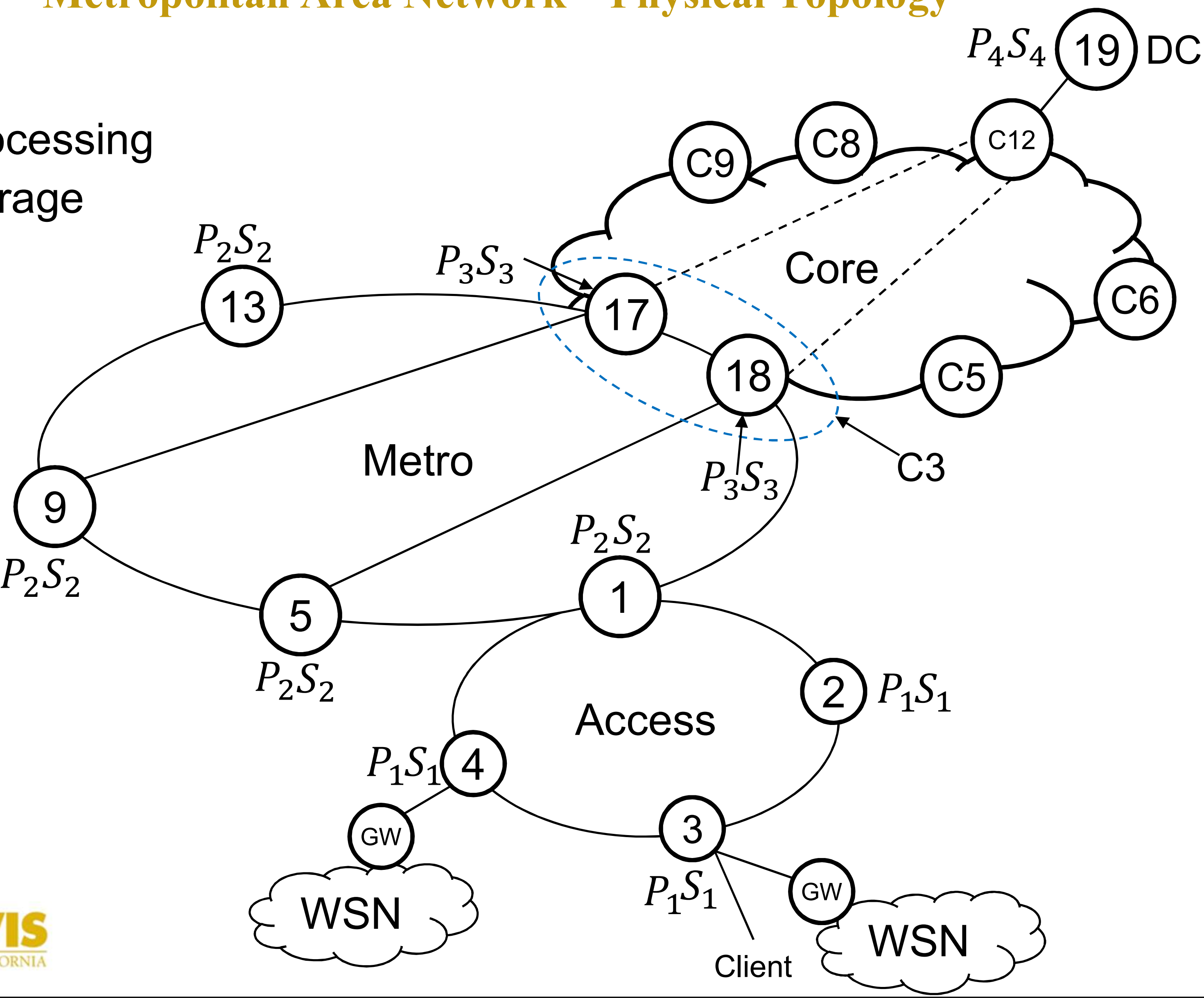
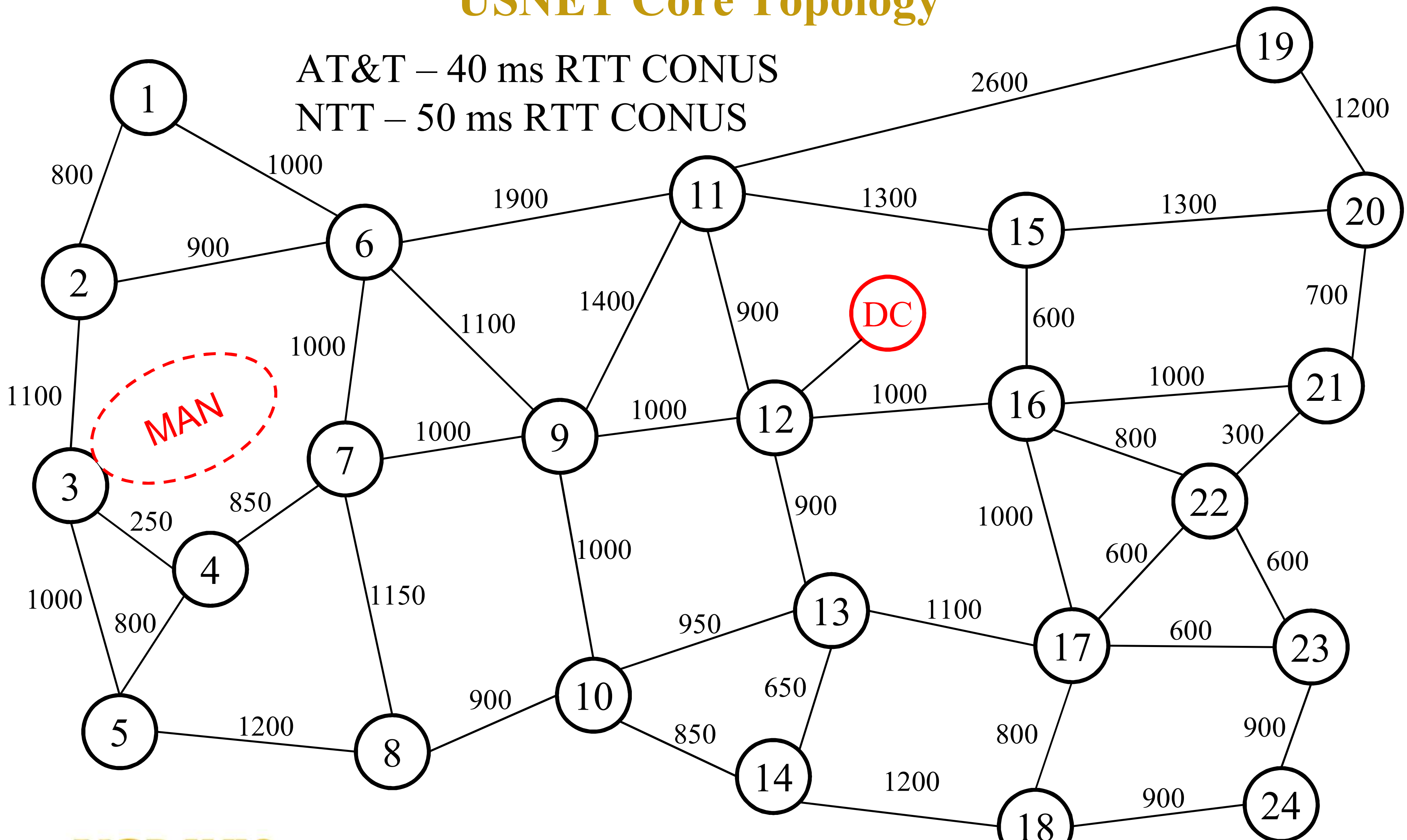
Metropolitan Area Network – Physical Topology

P_t: Tier **t** processing
S_t: Tier **t** storage



USNET Core Topology

AT&T – 40 ms RTT CONUS
NTT – 50 ms RTT CONUS



All Distances in km

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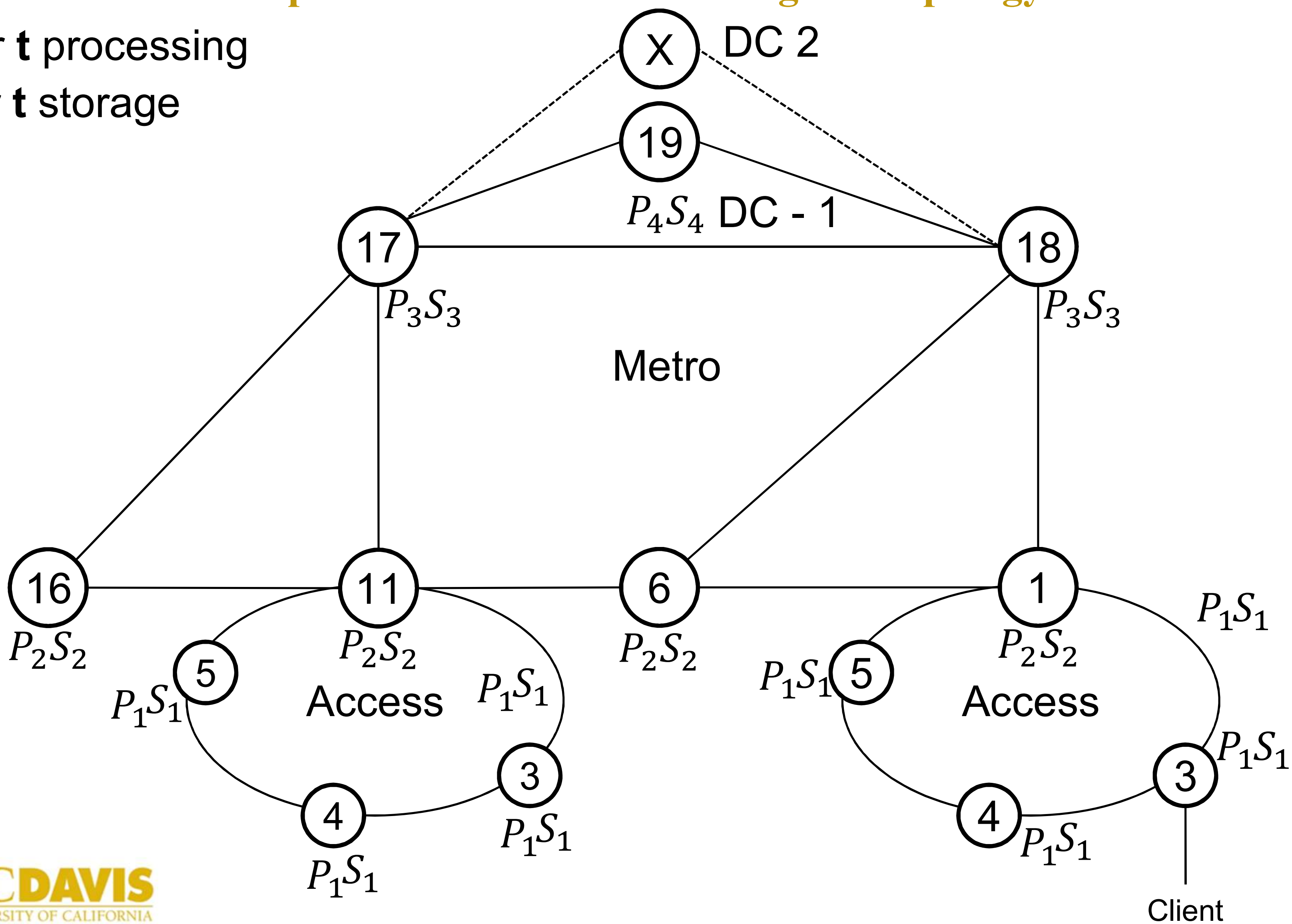
http://www.us.ntt.net/support/sla/network.cfm
http://www.att.com/gen/general?pid=6622

Metropolitan Area Network – Logical Topology

P_t: Tier **t** processing

S_t: Tier **t** storage



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Application Profile

- Each application profile contains a unique combination of parameters:
- α: Computational complexity per unit of traffic
- β: Ratio of processed to raw data at processing node
- κ: Average flow size – must be processed as a single entity
- Λ: Minimum storage time
- Θ: Uni-directional latency budget from access/GW to access/GW

App Profile	α (CPU/Mbps)	β	κ (Mb)	Λ (hrs)	Θ (ms)
1- VR	0.01	0.2	3	0	50
2 - Indust Data	0.009	0.1	2	10	70
3 – Data Backup	0	0	0.5	4	210
4 - P-P interactive	0.007	0.3	0.4	0	50
5 - Encrypted Data	0.008	1.2	0.2	5	120
6 – P-P streaming	0	0	.001	0	130
7 – Medical	0.003	0.2	2	0.1	80
8 – Env Data	0.006	0.3	1	100	130
9 -	0	0	5	3	180

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http://www.cisco.com/c/en/us/solutions/collateral/enterprise-networks/enterprise-network-functions-virtualization-nfv/datasheet-c78-736768.html

Network Parameters

- Each application profile contains a unique combination of parameters
- μ: Per unit cost of computational power
- ν: Per unit cost of storage capacity
- Λ: Per unit cost of MAN link capacity
- $\varepsilon_{up}, \varepsilon_{down}$: Per unit WAN bandwidth cost (up/down)
- τ: Processing time constant (Normalized to DC)

Tier	μ ($/CPU/Mo)	ν ($/GB/Mo)	Λ ($/Mbps/Mo)	$\varepsilon_{up}, \varepsilon_{down}$ ($/Mbps)	τ (/CPU)
1 – Access CO	40	0.0042	0.005	.05/.01	3
2 – Metro CO	35	0.004	0.005	05/.01	2
3 – Core CO	30	0.0035	0.005	05/.01	1.5
4 - DC	25	0.0025	0.005	05/.01	1

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https://cloud.google.com/compute/pricing

https://cloud.google.com/storage/pricing#pricing-example-simple

Mathematical Formulation

Inputs:

$v_{a,f}^{s,m}$: Offered traffic of application profile a, between node pair (s, m), destined for node f (f in core or metro)

$\theta_{a,f,m}$: Residual latency budget of traffic destined for core node f of application profile a,processed at node m

$A = A_p \cup A_s \cup A_{sp} \cup A_n$

A_s : Set of all application profiles requiring storage only

A_p : Set of all application profiles requiring processing only

A_{sp} : Set of all application profiles requiring processing and storage

A_n : Set of all application profiles requiring neither processing nor storage

Mathematical Formulation (cont.)

Inputs:

N_c: set of nodes directly attached to core network
N_g: set of nodes that generate traffic (sources of data)g
N_{DC}: set of data center nodes
$N = N_c \cup N_g \cup N_{DC}$
$N_p = N_g \cup N_{DC}$: Set of all nodes capable of processing
$N_s = N_g \cup N_{DC}$: Set of all nodes capable of storage
$N_l = N_g$ Set of local nodes capable of processing (excluding DC)

F_c : Set of distant core nodes

$\eta_{s,d}$: set of all admissible paths between node pair (s, d)
$\delta_k^{s,d}$: Total prop delay on the k^{th} adm path between node pair (s, d)
$\zeta_k^{s,d}$: Total trans delay on the k^{th} adm path between node pair (s, d)
U_m : processing capacity of node m, in CPUs
E_f: storage capacity of node f, in Gbit

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Mathematical Formulation (cont.)

Variables:

$A_p : x_{a,f}^{s,m} = 1$ if traffic of app profile a, destined for node f, generated at source node s, is processed at node m

$A_s : x_{a,f}^{s,m} = 1$ if traffic of app profile a, generated at node s, is stored at node f, $m = f$

$A_{sp} : x_{a,f}^{s,m} = 1$ if traffic of app profile a, generated at source node s, is processed at node m and stored at node f

$A_p, A_{sp} : r_{a,k,f}^{s,m} = 1$ if traffic of application profile **a** is routed over the k^{th} admissible path between node pair (s, m), destined for node f

$A_s : r_{a,k,f}^{s,m} = 1$ if traffic of application profile **a** is routed over the k^{th} admissible path between node pair (s, m), $m = f$

$A_n : r_{a,k,f}^{s,m} = 1$ if traffic of application profile a is routed over the k^{th} admissible path between node pair (s, m), internal: $m = f$,external: $m \in N_c$

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Mathematical Formulation (cont.)

Variables:

$A_p, A_{sp}, A_s : r^{s,m}_{a,k,f} = 1$ if traffic of application profile a is routed over the k^{th} admissible path between node pair (s, m), $m \in N_p, A_s : m \in N_s$

$A_p, A_{sp} : r'^{s,m}_{a,k,f} = 1$ if traffic of application profile a is routed over the k^{th} admissible path between node pair (m, f), $m \in N_p, f \in N_g, A_{sp} : f \in N_s$

$A_p, A_{sp} : r''^{s,m,d}_{a,k,f} = 1$ if traffic of application profile a is routed over the k^{th} admissible path between node pair (m, d),destined for core node f, $m \in N_p, f \in F_c, d \in N_c$

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Mathematical Formulation (cont.)

Objective Function:

$$min(Cost_p + Cost_s + Cost_u + Cost_d + Cost_{cap})$$

$$Cost_p = \sum_{m \in N_p} \gamma_m \sum_{a \in A_p \cup A_{sp}} \alpha_a \sum_{s \in N_g} \sum_{f \in N \cup F_c} x_{a,f}^{s,m} v_{a,f}^{s,m} \text{ Processing}$$

$$Cost_s = \underbrace{\sum_{a \in A_s} \Delta_a \sum_{m=f \in N_p} \nu_f \sum_{s \in N_g} x_{a,f}^{s,m} v_{a,f}^{s,m}}_{\text{source to storage}} + \underbrace{\sum_{a \in A_{sp}} \Delta_a \beta_a \sum_{f \in N_p} \nu_f \sum_{s \in N_g} \sum_{m \in N_p} x_{a,f}^{s,m} v_{a,f}^{s,m}}_{\text{proc to storage, source to proc/storage}}$$

Storage

$$Cost_d = \epsilon_{down} \Big[\sum_{a \in A_p} \beta_a \sum_{s \in N_g} \sum_{f \in N_g} \sum_{m \in N_{DC}} x_{a,f}^{s,m} v_{a,f}^{s,m} + \sum_{a \in A_{sp}} \beta_a \sum_{s \in N_g} \sum_{f \in N_l} \sum_{m \in N_{DC}} x_{a,f}^{s,m} v_{a,f}^{s,m} \Big]$$

Downstream

Mathematical Formulation (cont.)

Objective Function (cont.):

$$Cost_u = \epsilon_{up}\Big[\underbrace{\sum_{a\in A_p} \beta_a \sum_{m\in N_l} \sum_{s\in N_g} \sum_{f\in F_c} x_{a,f}^{s,m} v_{a,f}^{s,m}}_{\text{local processing to destination}} + \underbrace{\sum_{a\in A_{sp}} \beta_a \sum_{m\in N_l} \sum_{s\in N_g} \sum_{f\in N_{DC}} x_{a,f}^{s,m} v_{a,f}^{s,m}}_{\text{local proc, storage at DC}} +$$

$$\underbrace{\sum_{a\in A_n} \sum_{m\in N_c} \sum_{s\in N_g} \sum_{f\in F_c} v_{a,f}^{s,m}}_{\text{Tx to destination}} + \underbrace{\sum_{a\in A_p} \sum_{s\in N_g} \sum_{f\in N\cup F_c} x_{a,f}^{s,m} v_{a,f}^{s,m}}_{\text{Proc at DC, back to metro/dest}} +$$

$$\underbrace{\sum_{a\in A_{sp}} \beta_a \sum_{s\in N_g} \sum_{f\in N_l} \sum_{m\in N_{DC}} x_{a,f}^{s,m} v_{a,f}^{s,m}}_{\text{Proc at DC, stored in metro}} + \underbrace{\sum_{a\in A_s} \sum_{s\in N_g} \sum_{m=f\in DC} x_{a,f}^{s,m} v_{a,f}^{s,m}}_{\text{Stored in DC}} \Big] \text{ Upstream}$$

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Mathematical Formulation (cont.)

Objective Function (cont.):

$$\sum_{a\in A_n\cup A_s}\sum_{s\in N_g}\left[\sum_{m=f\in N_s}\sum_{k\in R_{i,j}} r^{s,m}_{a,k,f} v^{s,m}_{a,f} + \sum_{f\in F_c}\sum_{m\in N_c}\sum_{k\in R_{i,j}} r^{s,m}_{a,k,f} v^{s,m}_{a,f}\right] = C_1$$

$$\sum_{a\in A_p\cup A_{sp}}\sum_{s\in N_g}\sum_{m\in N_p}\sum_{f\in N\cup F_c}\sum_{k\in R_{i,j}} r^{s,m}_{a,k,f} v^{s,m}_{a,f} = C_2$$

$$\sum_{a\in A_p\cup A_{sp}}\beta_a\sum_{s\in N_g}\sum_{f\in N_g\cup N_s}\sum_{m\in N_p}\sum_{k\in R_{i,j}} r'^{s,m}_{a,k,f} v^{s,m}_{a,f} = C_3$$

$$\sum_{a\in A_p}\beta_a\sum_{s\in N_g}\sum_{f\in F_c}\sum_{m\in N_g}\sum_{d\in N_c}\sum_{k\in R_{i,j}} r''^{s,m,d}_{a,k,f} v^{s,m}_{a,f} = C_4$$

$$\Lambda\sum_{(i,j)\in L_m} C_1 + C_2 + C_3 + C_4 = Cost_{cap}$$

Capacity

Mathematical Formulation (cont.)

Constraints:

$$\sum_{m \in N_p} x_{a,f}^{s,m} = 1, \forall \; (a \in A_p, s \in N_g, f \in N \cup F_c)$$

$$\sum_{f = m \in N_s} x_{a,f}^{s,m} = 1, \forall \; (a \in A_s, s \in N_g)$$

$$\sum_{m \in N_p} \sum_{f \in N_s} x_{a,f}^{s,m} = 1, \forall \; (a \in A_{sp}, s \in N_g)$$

$$\sum_{a \in A_p} \alpha_a \sum_{s \in N_g} \sum_{f \in N \cup F_c} x_{a,f}^{s,m} v_{a,f}^{s,m} \leq U_m \quad \forall m \in N_p$$

Processing

$$\sum_{a \in A_s} \Delta_a \sum_{s \in N_g} x_{a,f}^{s,m} v_{a,f}^{s,m} + \sum_{a \in A_{sp}} \Delta_a \beta_a \sum_{s \in N_g} \sum_{m \in N_p} x_{a,f}^{s,m} v_{a,f}^{s,m} \leq E_f, \; \forall f \in N_s$$

Storage

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Mathematical Formulation (cont.)

Constraints (cont.): Solenoidality

$$\sum_{k} r_{a,k,f}^{s,m} = 1, \forall (a \in A_n, s, f \in N_g, m = f)$$

$$\sum_{m \in N_c} \sum_{k} r_{a,k,f}^{s,m} = 1, \forall (a \in A_n, s \in N_g, f \in F_c)$$

$$\sum_{k} r_{a,k,f}^{s,m} = x_{a,f}^{s,m}, \forall (a \in A_p \cup A_{sp} \cup A_s, s \in N_g, m \in N_p, f \in N \cup F_c)$$

$$\sum_{k} r'^{s,m}_{a,k,f} = x_{a,f}^{s,m}, \forall (a \in A_p \cup A_{sp}, s \in N_g, m \in N_p, f \in N_s \cup N_g)$$

$$\sum_{d \in N_c} \sum_{k} r''^{s,m,d}_{a,k,f} = x_{a,f}^{s,m}, \forall (a \in A_p, s \in N_g, m \in N_g, f \in F_c)$$

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Mathematical Formulation (cont.)

source to dest

Constraints (cont.): Latency

$$\sum_{k \in \eta_{s,m}} r^{s,m}_{a,k,f}(\delta^{s,m}_k + \zeta^{s,m}_k) + \sum_{d \in N_c} \sum_{k \in \eta_{s,d}} r^{s,d}_{a,k,f}(\delta^{s,d}_k + \zeta^{s,d}_k) \leq \theta_{a,f}$$

$$\forall (a \in A_n, s, m \in N_g, f \in N \cup F_c)$$

$$\gamma_m = \alpha_a \kappa_a x^{s,m}_{a,f} \tau_m \longleftarrow \text{Processing delay at node m}$$

$$\sum_{m \in N_p} \Big[\sum_{k \in \eta_{s,m}} r^{s,m}_{a,k,f}(\delta^{s,m}_k + \zeta^{s,m}_k) + \gamma_m + \sum_{k' \in \eta_{m,f}} r'^{s,m}_{a,k',f}(\delta^{m,f}_{k'} + \zeta^{m,f}_{k'}) \Big] \leq \Theta_a$$

$$\forall (A \in A_p, s, f \in N_g)$$

$$\sum_{m \in N_p} \Big[\sum_{k \in \eta_{s,m}} r^{s,m}_{a,k,f}(\delta^{s,m}_k + \zeta^{s,m}_k) + \gamma_m +$$

$$\sum_{d \in N_c} \sum_{k'' \in \eta_{m,d}} r''^{s,m,d}_{a,k'',f}(\delta^{m,d}_{k''} + \zeta^{m,d}_{k''}) \Big] \leq \sum_{m \in N_p} x^{s,m}_{a,f} \theta_{a,f,m} \; \forall (A \in A_p, s \in N_g, f \in F_c)$$

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Mathematical Formulation (cont.)

Constraints (cont.): Latency

$$\sum_{f\in N_s}\sum_{m\in N_p}\left[\sum_{k\in\eta_{s,m}} r^{s,m}_{a,k,f}(\delta^{s,m}_k+\zeta^{s,m}_k)+\gamma_m+\sum_{k'\in\eta_{m,f}} r'^{s,m}_{a,k',f}(\delta^{m,f}_{k'}+\zeta^{m,f}_{k'})\right]\leq\Theta_a$$

$$\forall(A\in A_{sp}\cup A_s,\, s\in N_g)$$

Processing delay: $\gamma_m=\alpha_a\kappa_a x^{s,m}_{a,f}\tau_m$

$$sec=\left(\frac{CPU}{Mbps}\right)(Mb)\left(\frac{1}{CPU}\right)$$

Processing Capacity: $U_m=\alpha_a x^{s,m}_{a,f}v^{s,m}_{a,f}$

$$CPU=\left(\frac{CPU}{Mbps}\right)(Mbps)$$

Storage Capacity: $E_f=\Delta_a x^{s,m}_{a,f}v^{s,m}_{a,f}$, β_a if necessary

$$GB=(sec)\left(\frac{Mbit}{sec}\right)\left(\frac{GB}{Mbit}\right)$$

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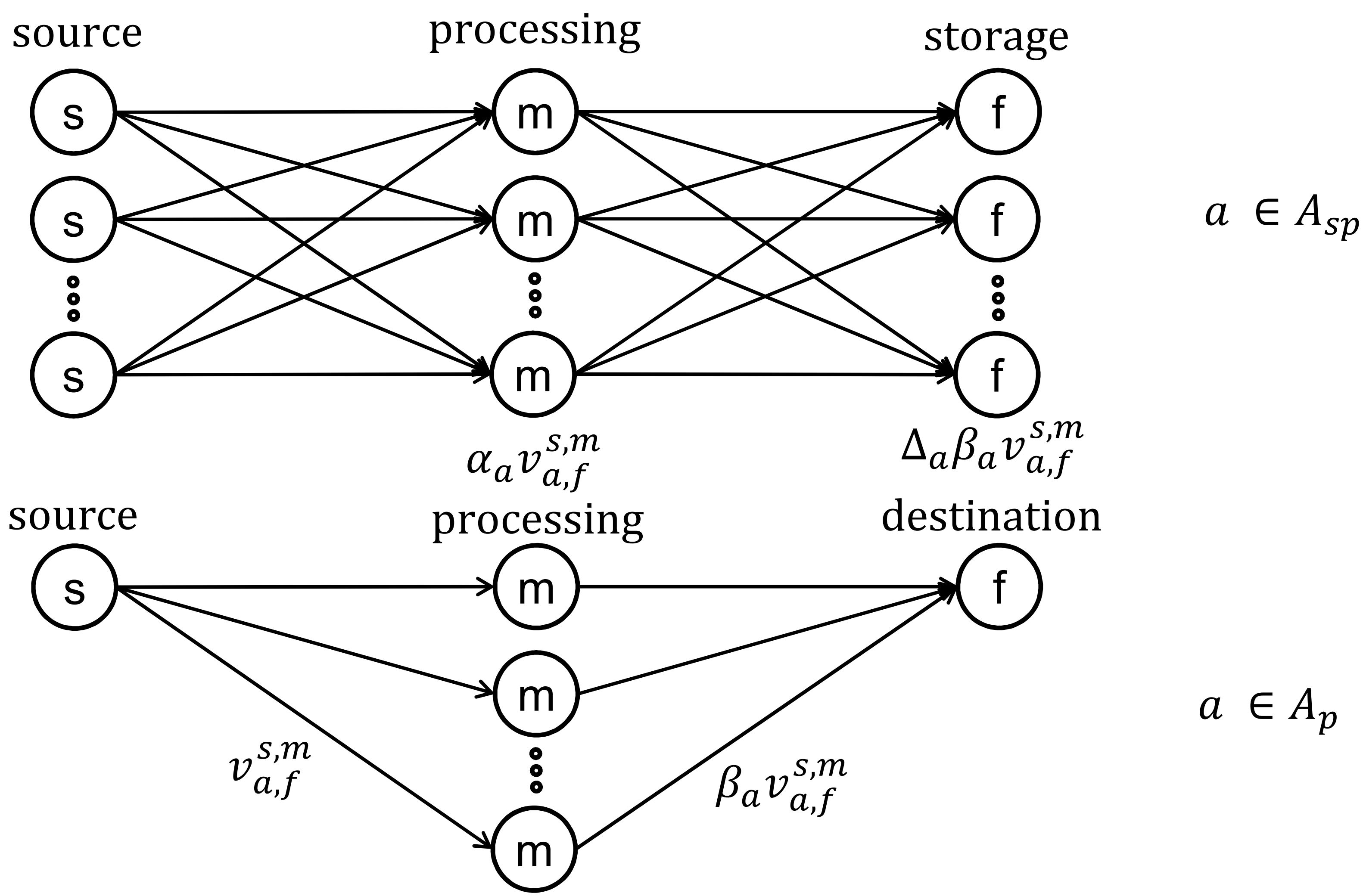
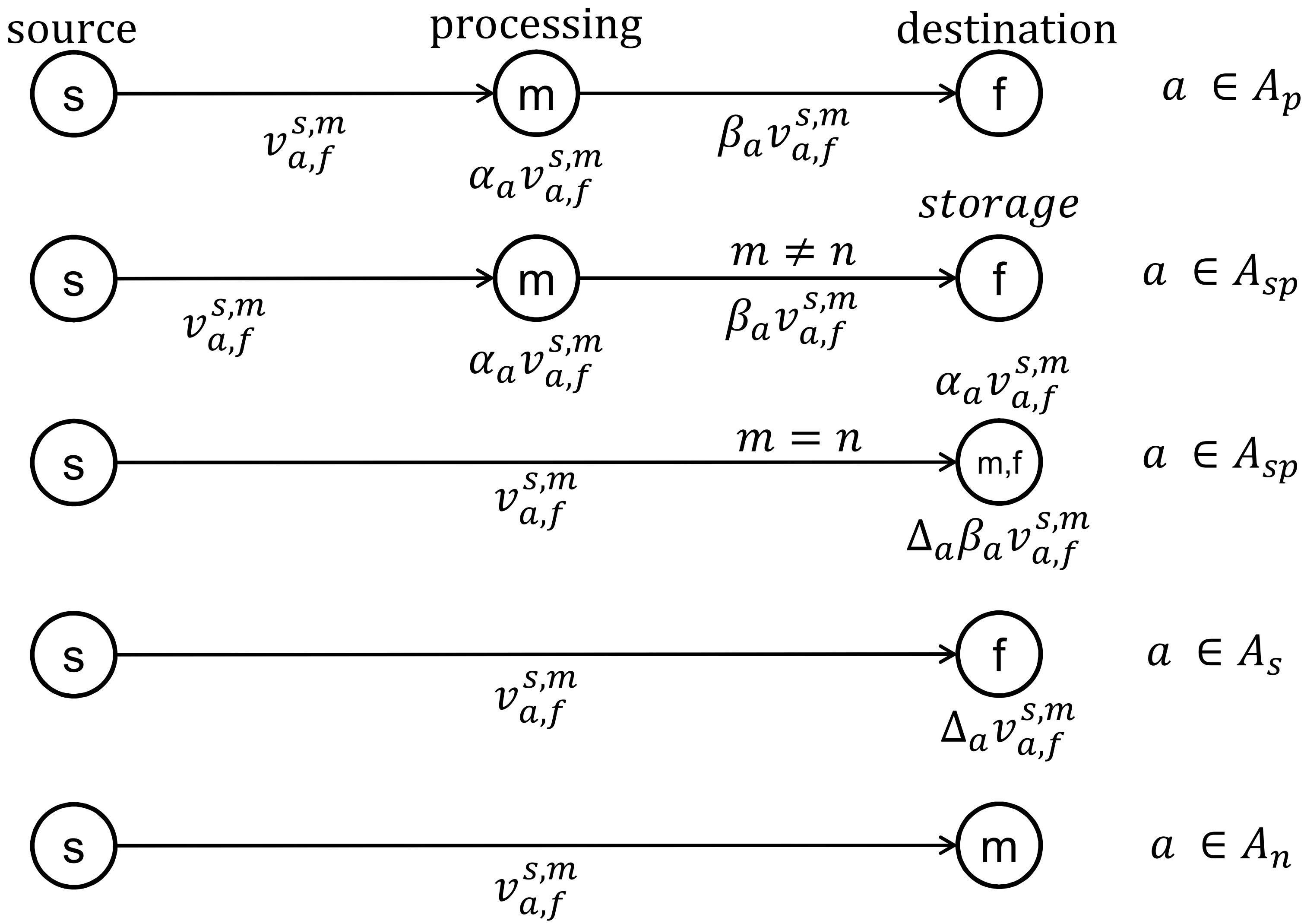
Functional Scenarios



Functional Scenarios



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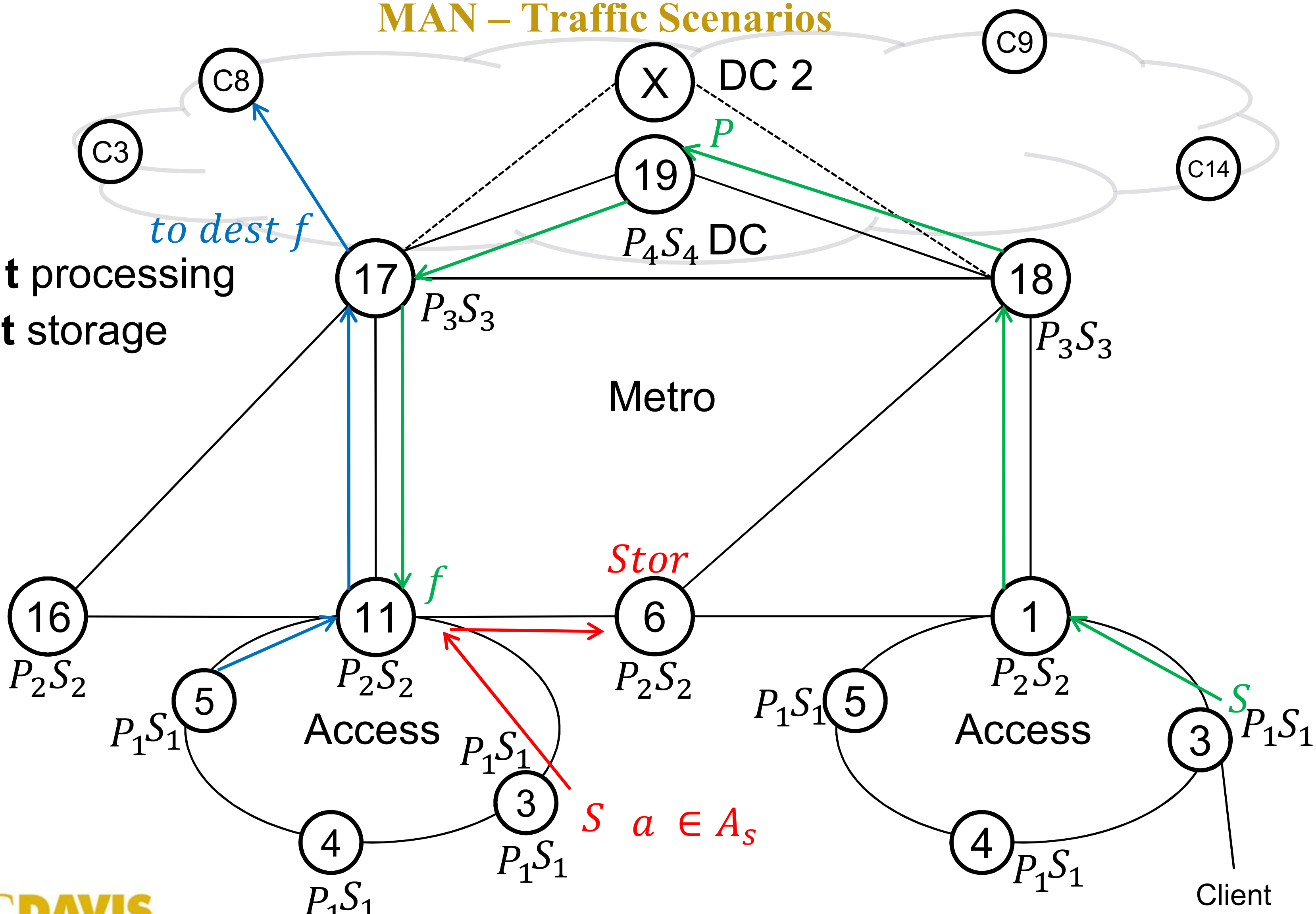
MAN – Traffic Scenarios



P_t: Tier **t** processing
S_t: Tier **t** storage

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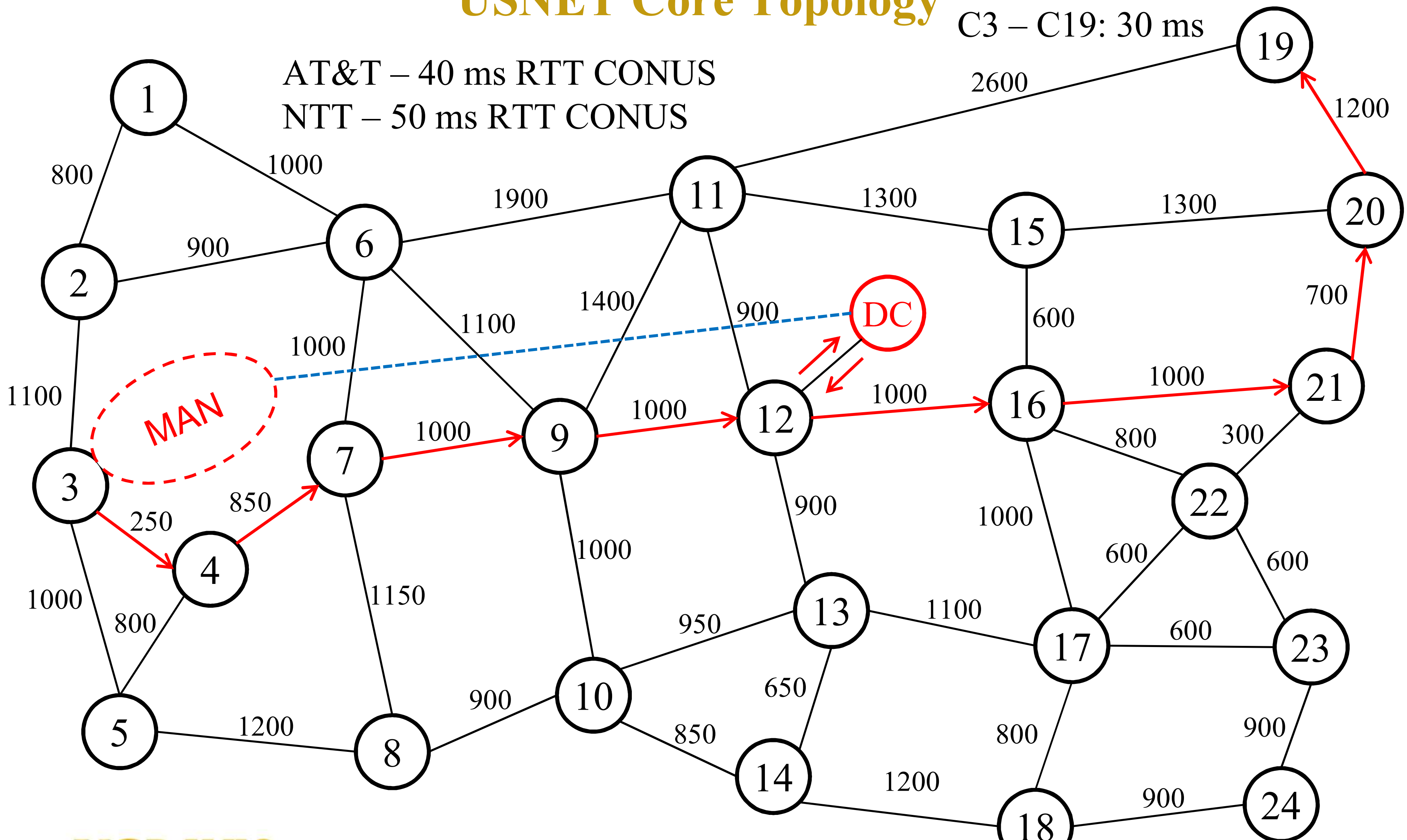
USNET Core Topology

DC – C19: 20 ms
C3 – C19: 30 ms

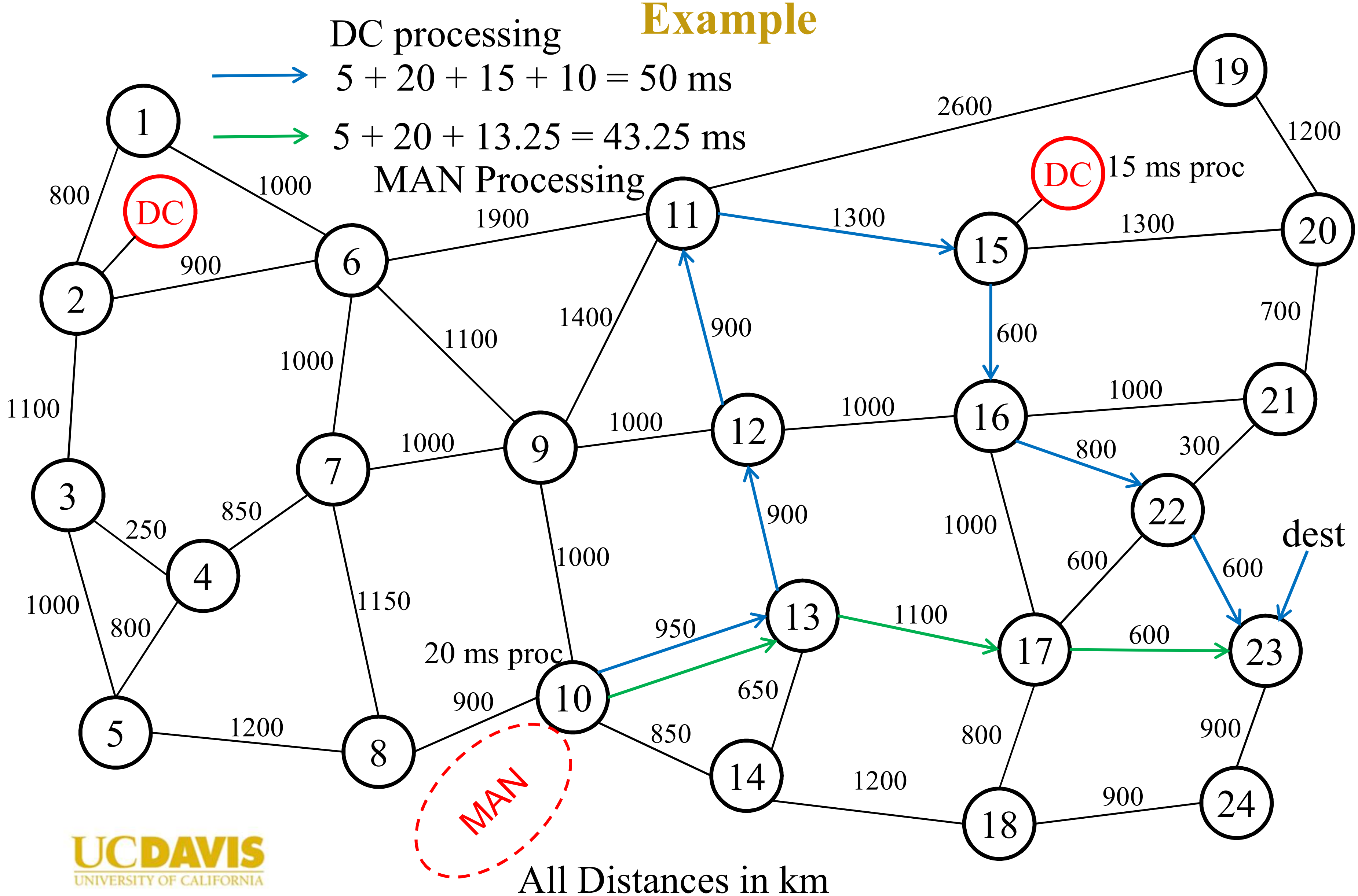
AT&T – 40 ms RTT CONUS
NTT – 50 ms RTT CONUS



All Distances in km

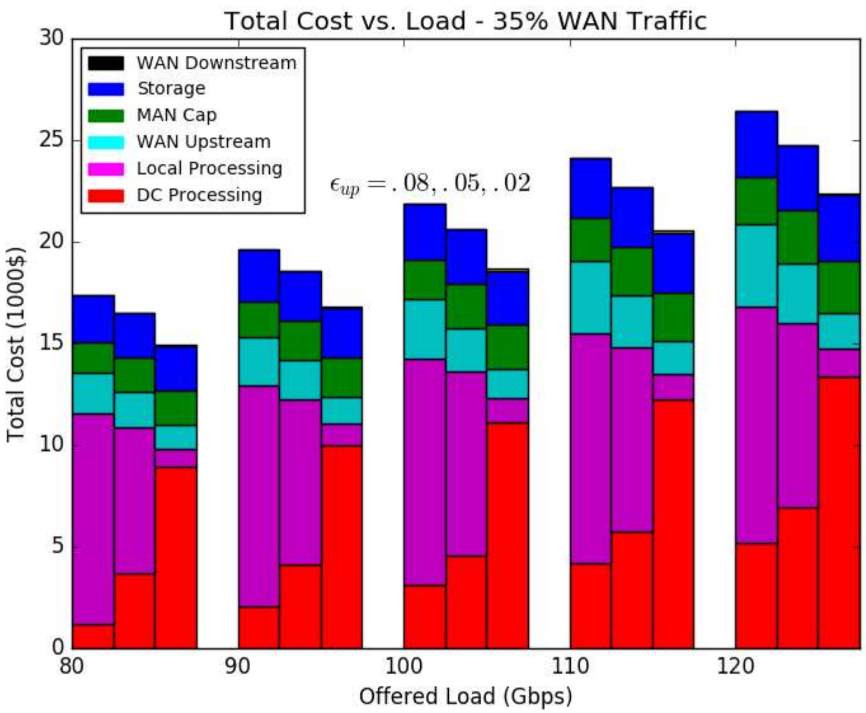
http://www.us.ntt.net/support/sla/network.cfm
http://www.att.com/gen/general?pid=6622

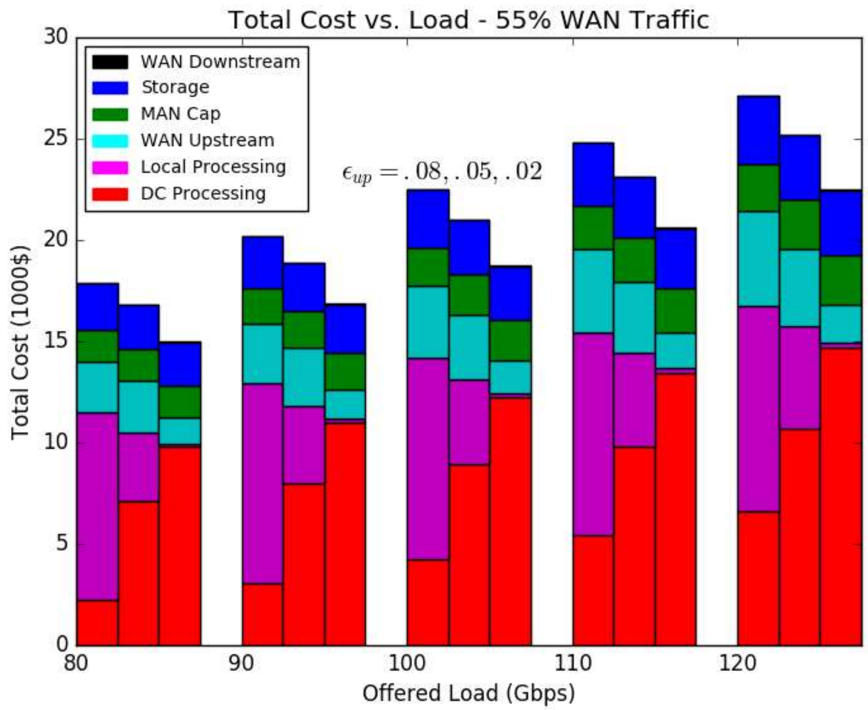
Example



DC processing
5 + 20 + 15 + 10 = 50 ms
5 + 20 + 13.25 = 43.25 ms
MAN Processing
DC
DC
15 ms proc
20 ms proc
MAN
dest
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
800
1000
900
1100
250
850
1000
800
1200
1900
1000
1100
1000
1150
900
1400
1000
1000
900
900
950
850
650
1300
600
1000
1100
1200
1000
800
600
800
2600
1200
1300
700
1000
300
600
600
900
900
All Distances in km

Simulation Results





- WAN upstream increases slightly with more external traffic
- At lower WAN upstream per unit costs, DC processing almost 100% of total processing costs

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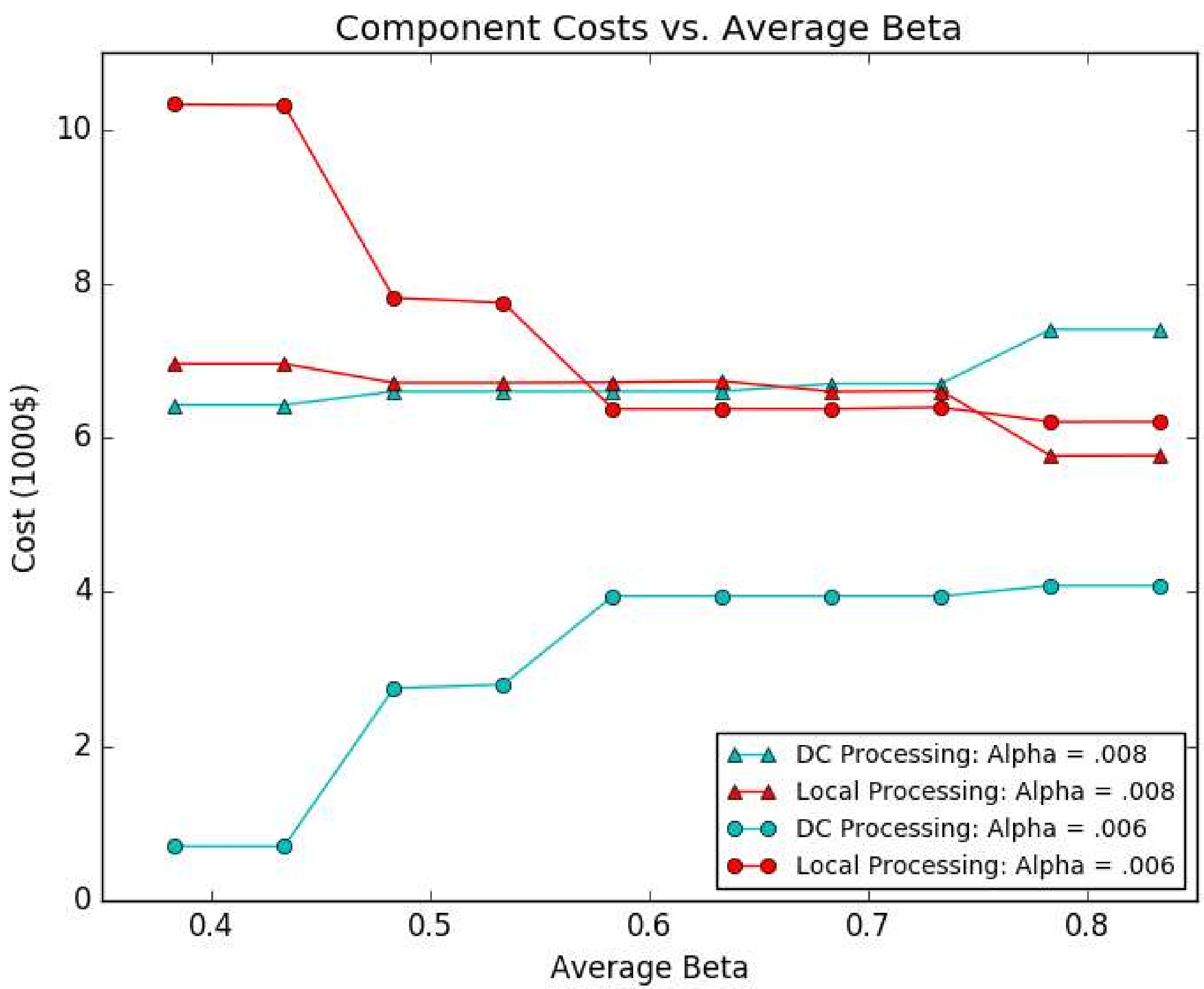
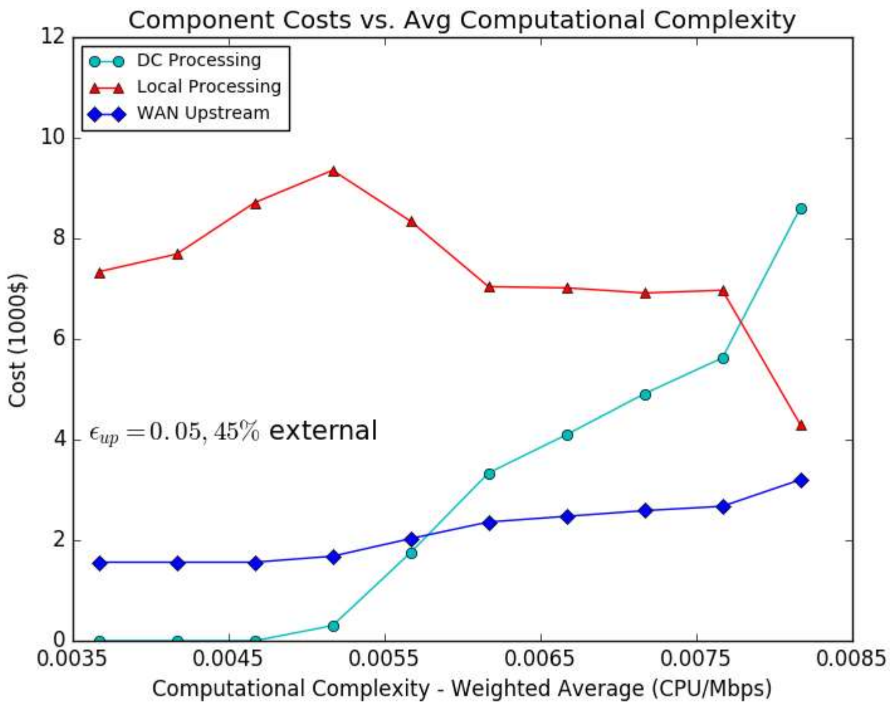
Simulation Results

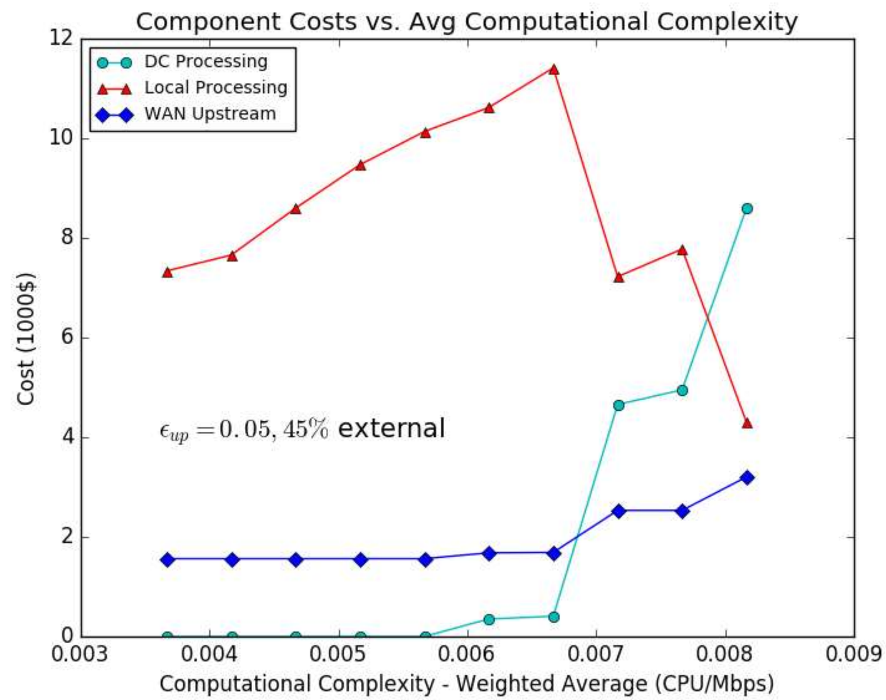


With average $\alpha = 0.006$, local and DC processing begin to converge with increasing β; with average $\alpha = 0.008$, costs are similar at smaller β, begin to slightly diverge with increasing β.

Simulation Results

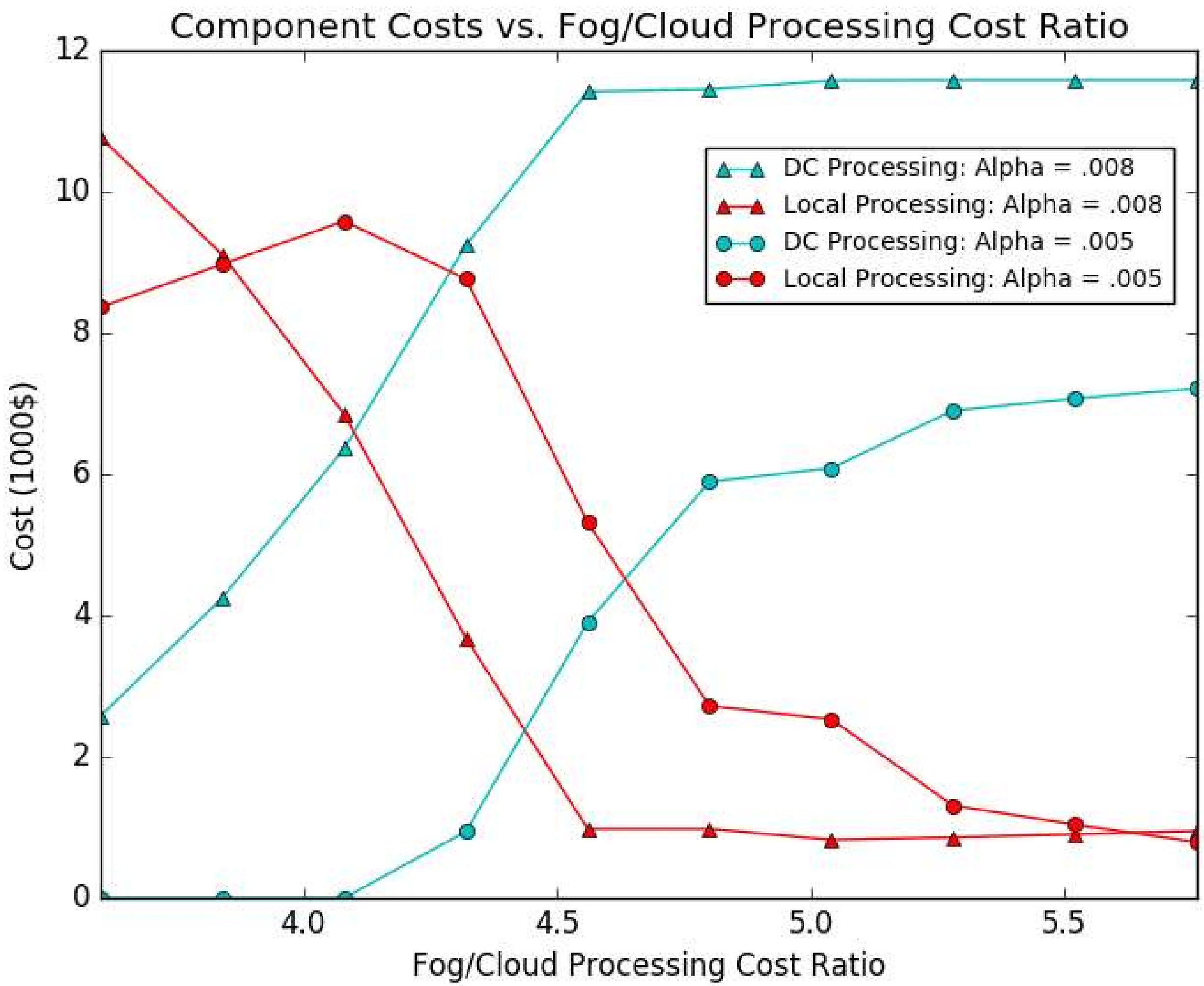


Core CO Capacity: 100 CPU



Core CO Capacity: 200 CPU

Simulation Results



With greater average α, local and DC processing costs intersect and reach steady state at lower fog/cloud cost ratios.

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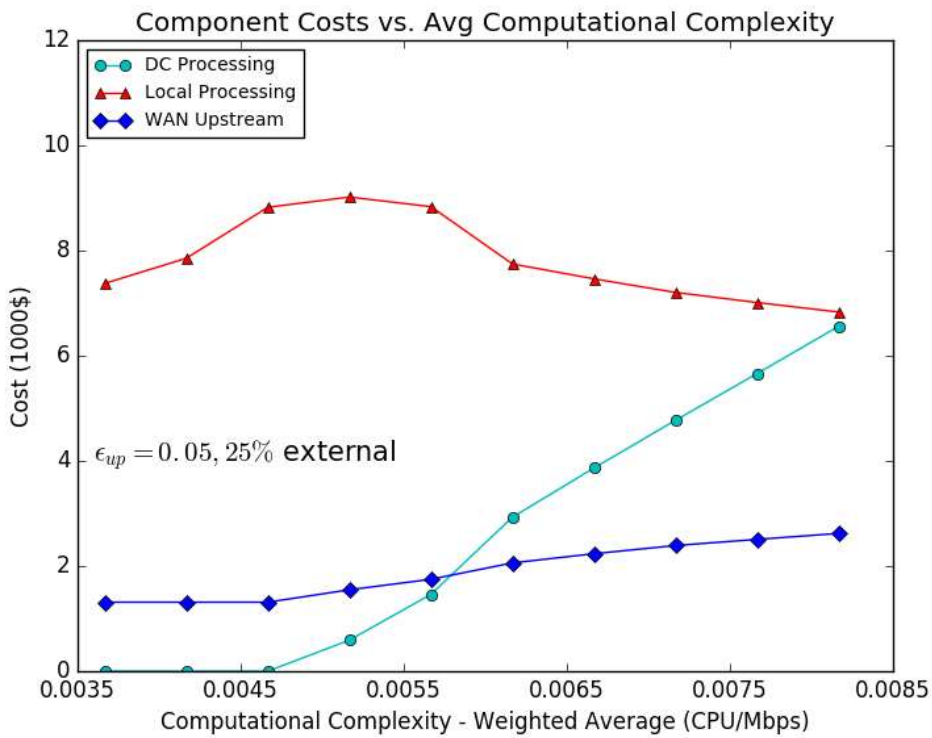
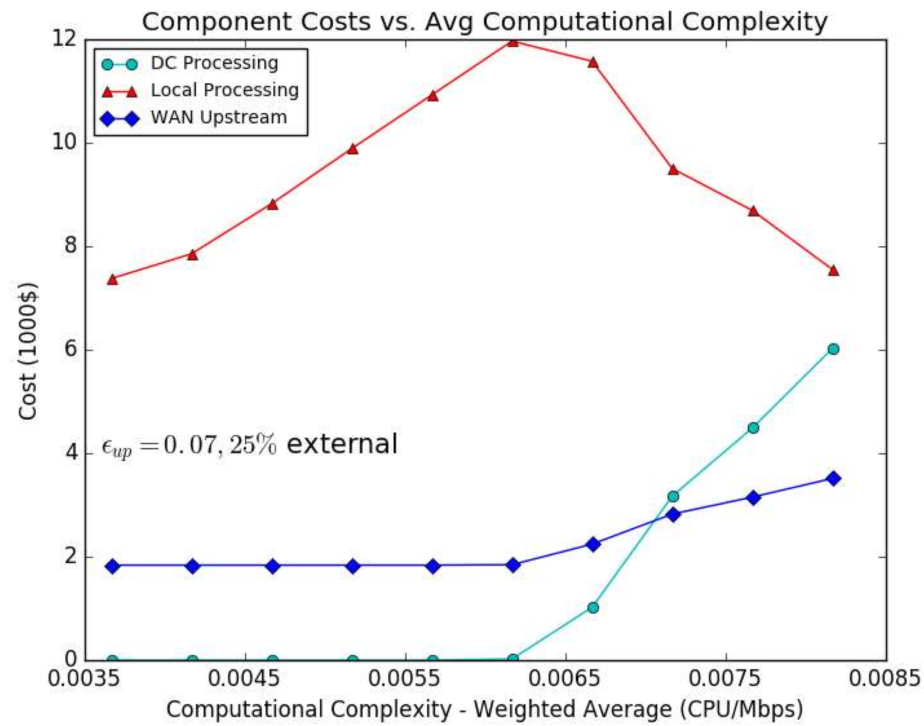
Simulation Results





More expensive WAN bandwidth causes a higher peak and sharper decline in local processing with increasing computational complexity

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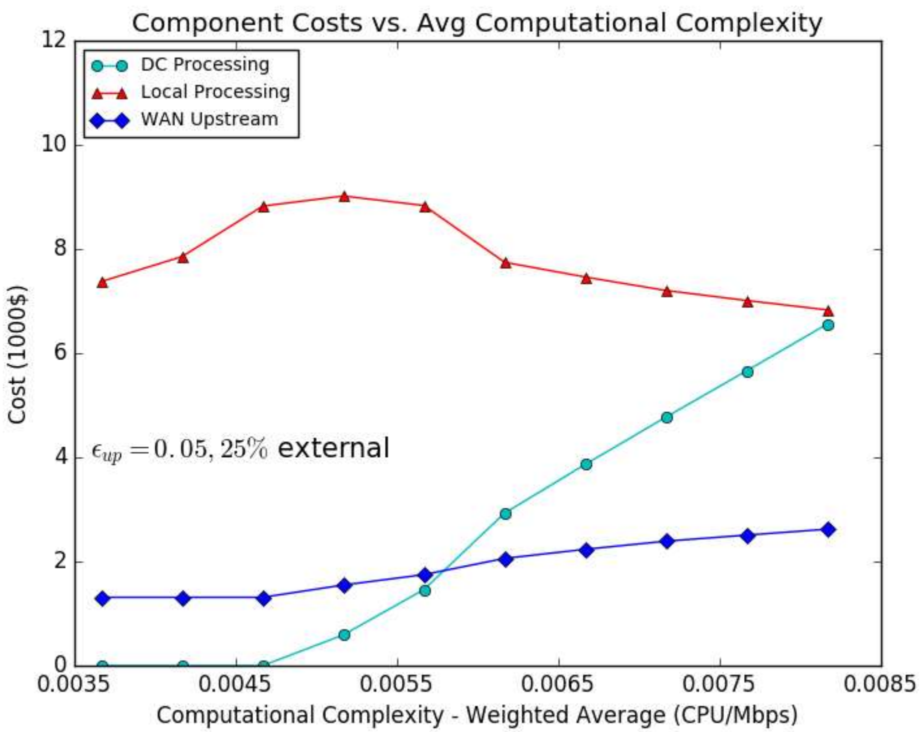
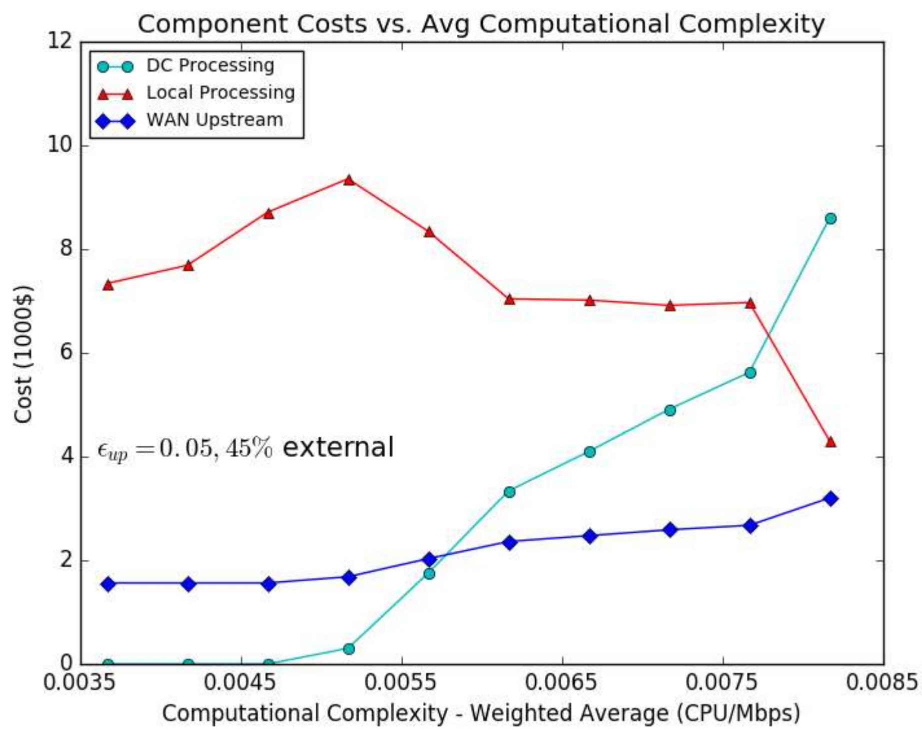
Simulation Results





External traffic is more affected by latency constraints, and thus have more abrupt changes in processing costs from fog to cloud or vice versa

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Ongoing Work

- Reconfigure core network: multiple DCs, with strategic placement such that latency constraints have greater impact in processing/storage locations

- Dynamic Simulation:
  - Apply static optimal solution and conduct performance evaluation
  - Poisson, Power Law, and periodic offered traffic

- Extension: Storage locations can be viewed as potential multicast sources that are accessible from clients distributed across the world
  - Can extend problem to better decide storage locations or possibly move storage analysis from metro to distributed across core

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