Optimal Workload Allocation in Fog-Cloud Computing Toward Balanced Delay and Power Consumption

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Outline

1. Fog computing
2. Fog-cloud computing system
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4. Decomposition and solution
5. Numerical results
6. Conclusions

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What is fog computing?

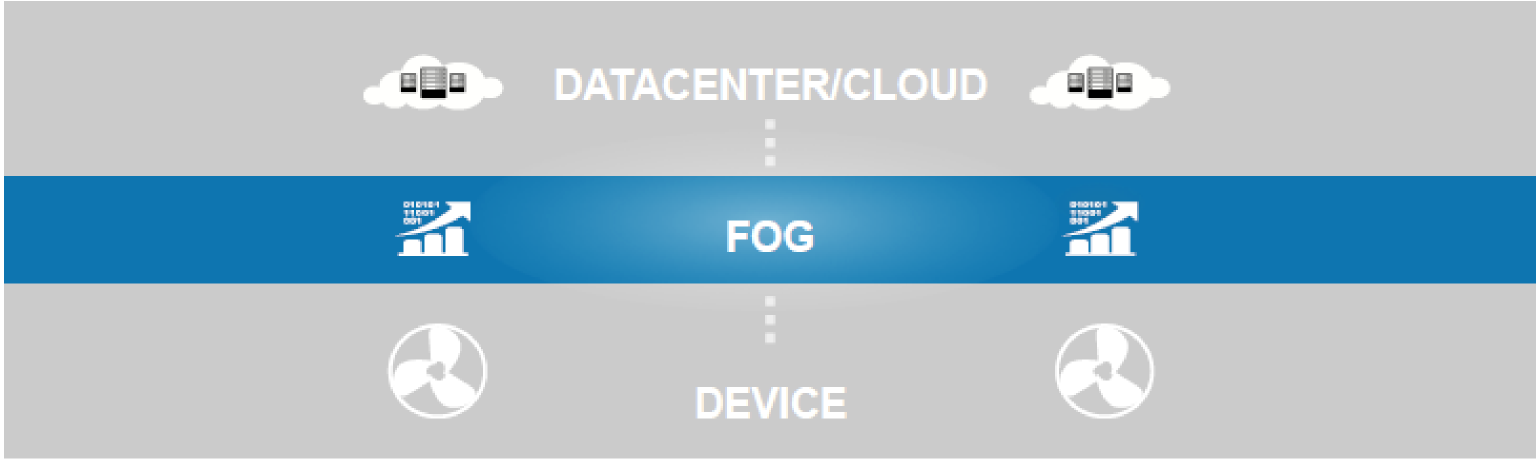
- **Fog computing** is considered as an extension of the cloud computing paradigm from the core of network to the edge of the network. It is a highly virtualized platform that provides computation, storage, and networking services between end devices and traditional cloud servers [1]. ——from cisco view.

- **Fog computing** is a scenario where a huge number of heterogeneous (wireless and sometimes autonomous) ubiquitous and de-centralized devices communicate and potentially cooperate among them and with the network to perform storage and processing tasks without the intervention of third parties. These tasks can be for supporting basic network functions or new services and applications that run in a sandboxed environment. Users leasing part of their devices to host these services get incentives for doing so [2]. ——from HP Lab's view.

[1] F. Bonomi, R. Milito, J. Zhu, and S. Addepalli, "Fog computing and its role in the internet of things," in Proceedings of the First Edition of the MCC Workshop on Mobile Cloud Computing, ser. MCC'12. ACM, 2012, pp. 13–16.
[2] L. M. Vaquero and L. Rodero-Merino, "Finding your way in the fog: Towards a comprehensive definition of fog computing," ACM SIGCOMM Computer Communication Review, 2014.

What is fog computing?

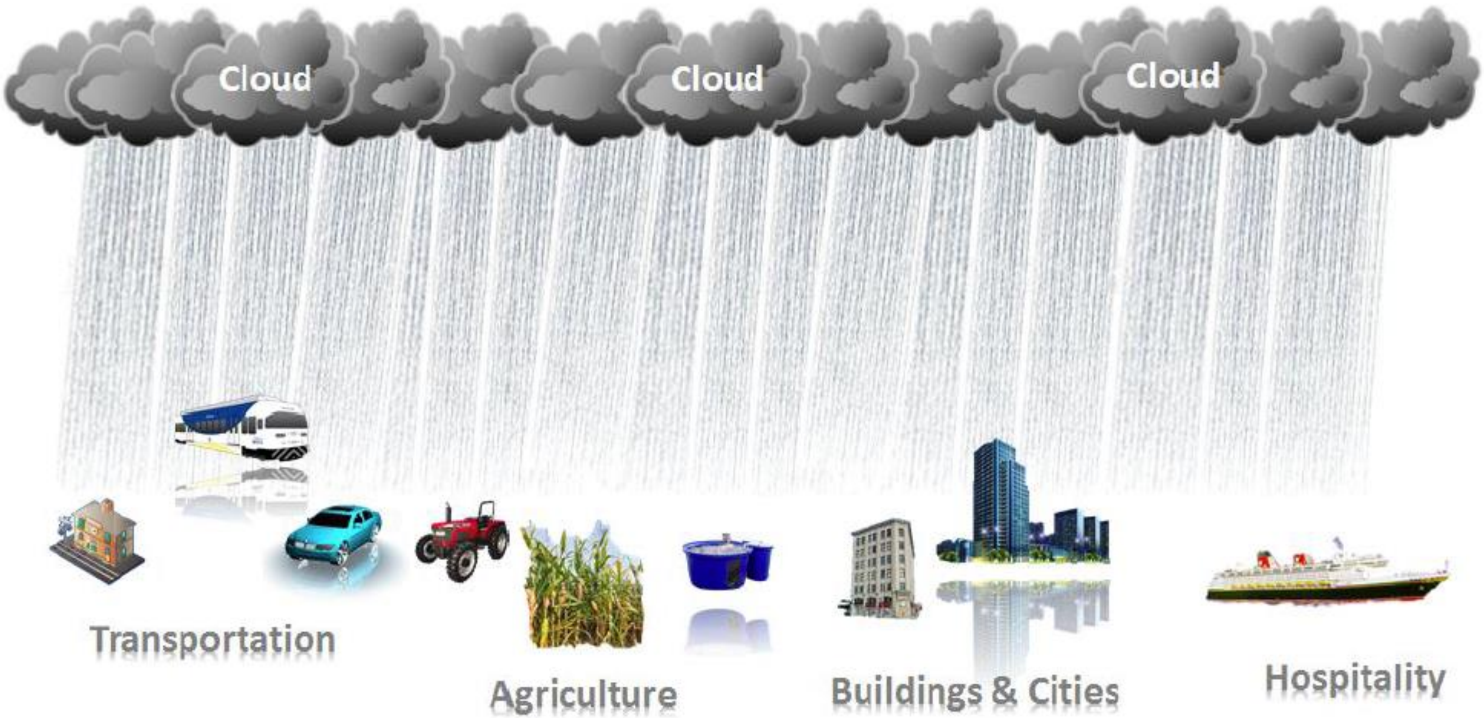
- The fog extends the cloud to be closer to the things that produce and act on IoT data. These devices, called fog nodes, can be deployed anywhere with a network connection: on a factory floor, on top of a power pole, alongside a railway track, in a vehicle, or on an oil rig. **Any device with computing, storage, and network connectivity can be a fog node.** Examples include industrial controllers, switches, routers, embedded servers, and video surveillance cameras.



[3] “Fog Computing and the Internet of Things: Extend the Cloud to Where the Things Are,” white paper, Cisco, 2015.

What is fog computing?

- The OpenFog Consortium is defining a new architecture that can address infrastructure and connectivity challenges by emphasizing information processing closer to where the data is being produced or used. OpenFog architecture intends to define the required infrastructure to enable building Fog as a Service (FaaS) to address certain classes of business challenges.



[4] “OpenFog Architecture Overview,” white paper, OpenFog Consortium Architecture Working Group, Feb.2016.

Examples of fog applications

- Fog applications are as diverse as the Internet of Things itself. What they have in common is monitoring or analyzing real-time data from network-connected things and then initiating an action. The action can involve machine-to-machine (M2M) communications or human-machine interaction (HMI).

- Examples include locking a door, changing equipment settings, applying the brakes on a train, zooming a video camera, opening a valve in response to a pressure reading, creating a bar chart, or sending an alert to a technician to make a preventive repair. The possibilities are unlimited.

[3] "Fog Computing and the Internet of Things: Extend the Cloud to Where the Things Are," white paper, Cisco, 2015.

When to consider fog computing?

- Data is collected at the extreme edge: vehicles, ships, factory floors, roadways, railways, etc.
- Thousands or millions of things across a large geographic area are generating data.
- It is necessary to analyze and act on the data in less than one second.

Fog Nodes Extend the Cloud to the Network Edge

	Fog Nodes Closest to IoT Devices	Fog Aggregation Nodes	Cloud
Response time	Milliseconds to subsecond	Seconds to minutes	Minutes, days, weeks
Application examples	M2M communication Haptics[2], including telemedicine and training	Visualization Simple analytics	Big data analytics Graphical dashboards
How long IoT data is stored	Transient	Short duration: perhaps hours, days, or weeks	Months or years
Geographic coverage	Very local: for example, one city block	Wider	Global

[3] “Fog Computing and the Internet of Things: Extend the Cloud to Where the Things Are,” white paper, Cisco, 2015.

What happens in the fog and the cloud?

Fog nodes:

- Receive feeds from IoT devices using any protocol, in real time
- Run IoT-enabled applications for real-time control and analytics, with millisecond response time
- Provide transient storage, often 1–2 hours
- Send periodic data summaries to the cloud

The cloud platform:

- Receives and aggregates data summaries from many fog nodes
- Performs analysis on the IoT data and data from other sources to gain business insight
- Can send new application rules to the fog nodes based on these insights

How to achieve the optimal workload allocation in fog-cloud computing is very important!

[3] "Fog Computing and the Internet of Things: Extend the Cloud to Where the Things Are," white paper, Cisco, 2015.

Main Contribution of This Paper

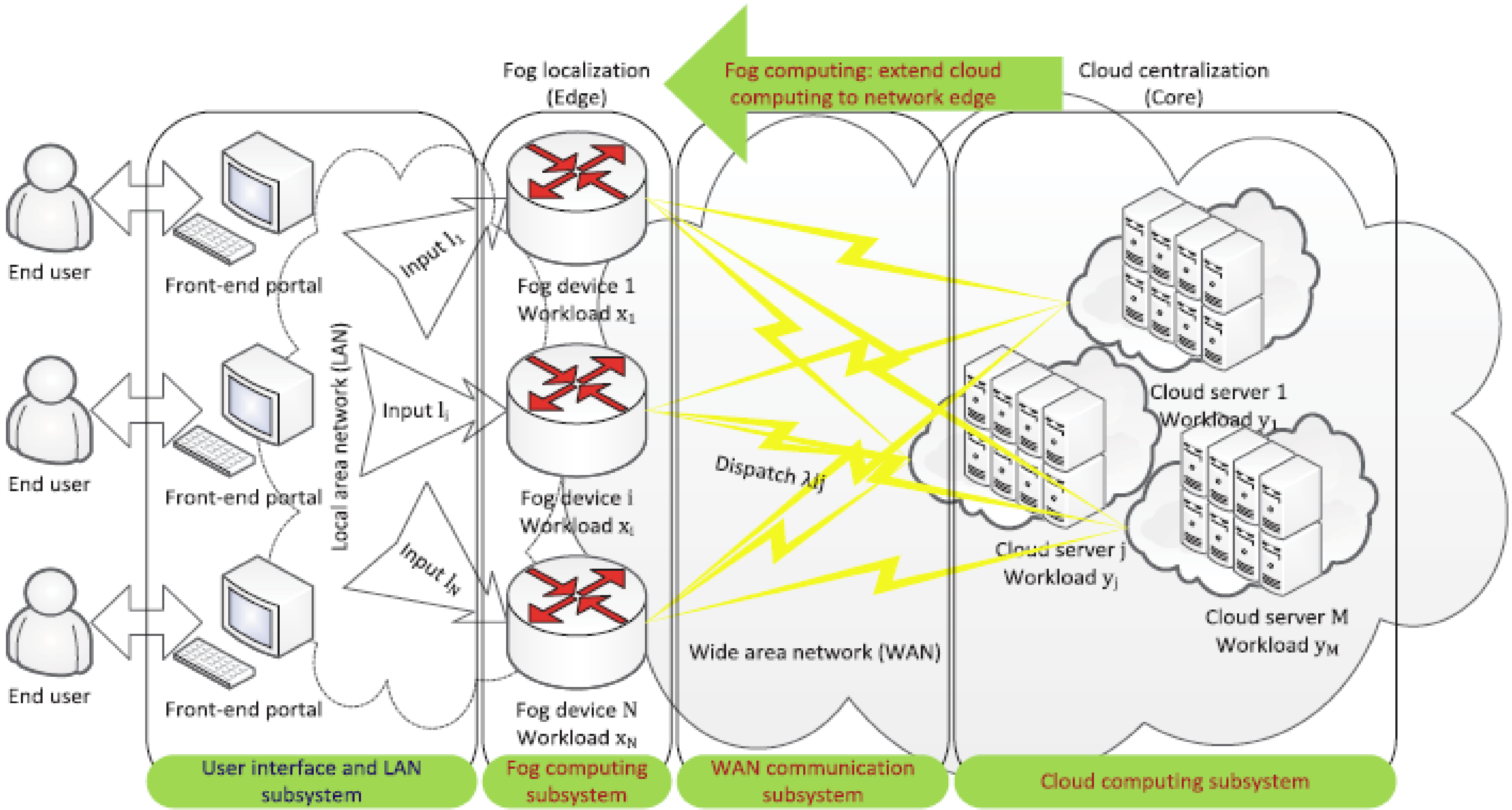
In this work, the tradeoff between power consumption and transmission delay in the fog-cloud computing system is investigated.

They formulate a workload allocation problem which suggests the optimal workload allocations between fog and cloud toward the minimal power consumption with the constrained service delay.

The problem is then tackled using an approximate approach by decomposing the primal problem into three sub-problems of corresponding subsystems.

They conduct extensive simulations to demonstrate that the fog can complement the cloud with much reduced communication latency.

Fog-cloud computing system



Overall architecture of a fog-cloud computing system with four subsystems and their interconnections/interactions.

System model

Symbol	Definition	Unit[a]
i, N, $\mathcal{N}$	index, number, set of fog devices	n/a
j, M, $\mathcal{M}$	index, number, set of cloud servers	n/a
l_i	traffic arrival rate to fog device i	$\sharp$(requests)$/s$
x_i	workload assigned to fog device i	$\sharp$(requests)$/s$
λ_{ij}	traffic rate dispatched from fog device i to cloud server j	$\sharp$(requests)$/s$
y_j	workload assigned to cloud server j	$\sharp$(requests)$/s$
L	total input from all front-end portals	$\sharp$(requests)$/s$
X	workload allocated for fog computing	$\sharp$(requests)$/s$
Y	workload allocated for cloud computing	$\sharp$(requests)$/s$
P	power consumption	unit power
D	delay	unit time
$\overline{D}$	system delay constraint	unit time
v_i	service rate at fog device i	$\sharp$(requests)$/s$
f_j	machine CPU frequency at cloud server j	$\sharp$(cycles)$/s$
σ_j	binary: on/off state of cloud server j	n/a
n_j	integer: machine number at cloud server j	n/a
d_{ij}	communication delay from fog device i to cloud server j	unit time
η_i	weighting factor at fog device i	n/a
$\overline{D}_j$	delay threshold at cloud server j	unit time

[a]The unit of a quantity may be omitted in the rest of the paper if it is specified here.

System model

Power consumption of fog device

For the fog device i, the computation power consumption P_i^{fog} can be modeled by a function of the computation amount x_i, which is a monotonic increasing and strictly convex function.

$$P_i^{\text{fog}} \triangleq a_i x_i^2 + b_i x_i + c_i$$

where $a_i > 0$ and b_i, $c_i \geq 0$ are predetermined parameters

Computing delay of fog device

Assuming a queueing system, for the fog device i with the traffic arrival rate x_i and service rate v_i, the computation delay (waiting time plus service time) D^{fog}_i is

$$D_i^{\text{fog}} \triangleq \frac{1}{v_i - x_i}$$

System model

Power Consumption of Cloud Server

Each cloud server hosts a number of similar computing machines. The configurations (e.g., CPU frequency) are assumed to be equal for all machines at the same server. Thus, each machine at the same server has the same power consumption. We approximate the power consumption value of each machine at the cloud server *j* by a function of the machine CPU frequency f_j : $A_j f_j^p + B_j$

where A_j and B_j are positive constants, and *p* varies from 2.5 to 3 [5]. Thus, the power consumption P_{cloud}^j of the cloud server j can be obtained by multiplying the on/off state σ_j, the on-state machine number n_j, and each machine power consumption value.

$$P_j^{\text{cloud}} \triangleq \sigma_j n_j \left(A_j f_j^p + B_j \right)$$

[5] L. Rao, X. Liu, M. D. Ilic, and J. Liu, "Distributed coordination of Internet data centers under multiregional electricity markets," Proc. IEEE, vol. 100, no. 1, pp. 269–282, Jan. 2012..

System model

Computation Delay of Cloud Server

The M/M/n queueing model is employed to characterize each cloud server. For the cloud server j with the on/off state σ_j and n_j turned-on machines, when each machine has the traffic arrival rate y_j and service rate f_j/K, respectively, the computation delay D^{cloud}_j is given by

$$D_j^{\text{cloud}} \triangleq \sigma_j \left[\frac{C(n_j, y_j K/f_j)}{n_j f_j/K - y_j} + \frac{K}{f_j} \right]$$

Communication Delay for Dispatch

Let d_{ij} denote the delay of the WAN transmission path from the fog device i to the cloud server j. Thus, when the traffic rate dispatched from the fog device i to the cloud server j is λ_{ij}, the corresponding communication delay D^{comm}_{ij} is

$$D_{ij}^{\text{comm}} \triangleq d_{ij}\lambda_{ij}$$

Constraints

Workload Balance Constraint

Let L denote the total request input from all front-end portals. The traffic arrival rate from all front-end portals to the fog device i is denoted by l_i. Thus,

$$L \triangleq \sum_{i \in \mathcal{N}} l_i$$

$$\begin{cases} X \triangleq \sum_{i \in \mathcal{N}} x_i \\ Y \triangleq \sum_{j \in \mathcal{M}} y_j \end{cases}$$

Besides, let X and Y denote the workload allocated for fog computing and cloud computing, respectively. Then workload balance constraints:

$$l_i - x_i = \sum_{j \in \mathcal{M}} \lambda_{ij} \qquad \forall i \in \mathcal{N}. \quad (1)$$

for each fog device

$$\sum_{i \in \mathcal{N}} \lambda_{ij} = y_j \qquad \forall j \in \mathcal{M} \quad (2)$$

for each cloud server

$$L = X + Y$$

for fog-cloud computing system

Constraints

Fog Device Constraint

For the fog device i, there is a limit on the processing ability due to physical constraints. Let $x^{max}{}_i$ denote the computation capacity of the fog device i. In addition, the workload x_i assigned to the fog device i should be no more than the traffic arrival rate l_i to that device. From the above, we have

$$0 \leq x_i \leq \min\{x_i^{\max}, l_i\} \qquad \forall i \in \mathcal{N} \qquad (3)$$

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Constraints

Cloud Server Constraint

For the cloud server j, $\quad y_j \geq 0 \qquad \forall j \in \mathcal{M} \qquad (4)$

Besides, there is a limit on the computation rate of each machine due to physical constraints. Let f^{min}_j and f^{max}_j denote the lower and upper bound on the machine CPU frequency, respectively

$$f_j^{\min} \leq f_j \leq f_j^{\max} \qquad \forall j \in \mathcal{M} \qquad (5)$$

In addition, for the cloud server j, the number of machines n_j has an upper bound n^{max}_j . Thus, for the integer variable n_j,

$$n_j \in \left\{0, 1, 2, \ldots, n_j^{\max}\right\} \qquad \forall j \in \mathcal{M} \qquad (6)$$

Finally, the binary variable σ_j denote the on/off state of the cloud server j.

$$\sigma_j \in \{0, 1\} \qquad \forall j \in \mathcal{M} \qquad (7)$$

Constraints

WAN Communication Bandwidth Constraint

For simplicity, the traffic rate λ_{ij} is assumed to be dispatched from the fog device i to the cloud server j through one transmission path. Furthermore, these transmission paths do not overlap with each other. There is a limitation $\lambda^{max}{}_{ij}$ on the bandwidth capacity of each path. Thus, the bandwidth constraint of the WAN communication is

$$0 \leq \lambda_{ij} \leq \lambda_{ij}^{\max} \qquad \forall i \in \mathcal{N}; \quad \forall j \in \mathcal{M} \qquad (8)$$

Problem Formulation

Towards the power consumption-delay tradeoff in fog-cloud computing, on one hand, it is important and desirable to minimize the aggregated power consumption of all fog devices and cloud servers. The power consumption function of the fog-cloud computing system is defined as

$$P^{\mathrm{sys}} \triangleq \sum_{i \in \mathcal{N}} P_i^{\mathrm{fog}} + \sum_{j \in \mathcal{M}} P_j^{\mathrm{cloud}}$$

On the other hand, it is equally important to guarantee the quality of service (e.g., latency requirements) of end users. The end-user delay consists of the computation (including queueing) delay and communication delay. Therefore, the delay function of the fog-cloud computing system is defined as

$$D^{\mathrm{sys}} \triangleq \sum_{i \in \mathcal{N}} D_i^{\mathrm{fog}} + \sum_{j \in \mathcal{M}} D_j^{\mathrm{cloud}} + \sum_{i \in \mathcal{N}} \sum_{j \in \mathcal{M}} D_{ij}^{\mathrm{comm}}$$

Problem Formulation

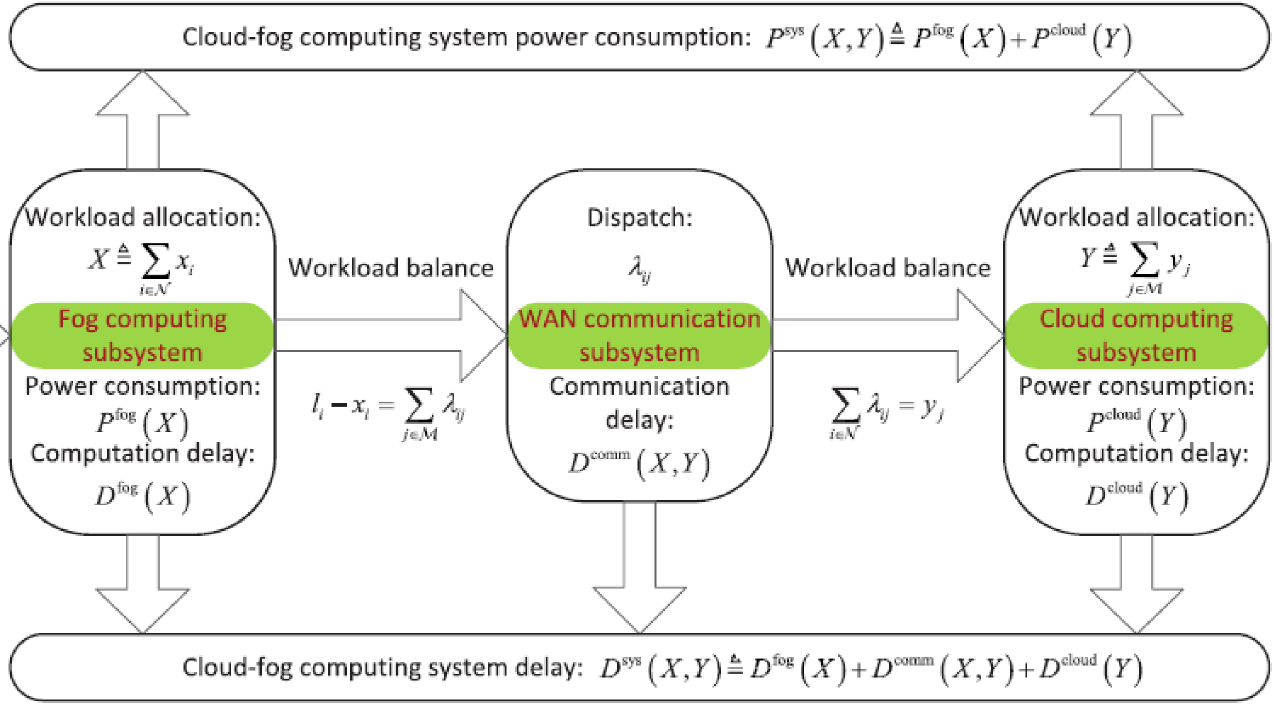
The problem of minimizing the power consumption of the fog-cloud computing system while guaranteeing the required delay constraint D for end users.

$$\min_{x_i, y_j, \lambda_{ij}, f_j, n_j, \sigma_j} \quad P^{\text{sys}}$$

$$\text{s.t.} \quad \begin{cases} D^{\text{sys}} \le \overline{D} \\ (1)\text{–}(8). \end{cases}$$

The decision variables are the workload x_i assigned to the fog device i, the workload y_j assigned to the cloud server j, the traffic rate λ_{ij} dispatched from the fog device i to the cloud server j, as well as the machine CPU frequency f_j, the machine number n_j, and the on/off state σ_j at the cloud server j. The objective of workload allocation in the fog-cloud computing system is to tradeoff between: **1) the system power consumption and 2) the end-user delay**.

Decomposition and solution



framework of power consumption-delay tradeoff by workload allocation in a fog-cloud computing system

Note that in primal problem (PP), the decision variables come from different subsystems and are tightly coupled with each other, which makes the relationship between the workload allocation and the power consumption-delay tradeoff not clear. To address this issue, we develop an approximate approach to decompose PP into three SPs of corresponding subsystems.

A. Power Consumption-Delay Tradeoff for Fog Computing

We consider to tradeoff between the power consumption and computation delay in the fog computing subsystem. That is, we have the SP1

$$\min_{x_i} \sum_{i\in\mathcal{N}} \left(a_i x_i^2 + b_i x_i + c_i + \frac{\eta_i}{v_i - x_i} \right)$$
$$\text{s.t.} \begin{cases} \sum_{i\in\mathcal{N}} x_i = X \\ (3) \end{cases}$$

where the adjustable parameter η_i is a weighting factor to tradeoff between the power consumption and computation delay at the fog device i. After we obtain the optimal workload x^*_i assigned to the fog device i, we can calculate the power consumption and computation delay in the fog computing subsystem, respectively.

$$\begin{cases} P^{\text{fog}}(X) = \sum_{i\in\mathcal{N}} \left[a_i (x_i^*)^2 + b_i x_i^* + c_i \right] \\ D^{\text{fog}}(X) = \sum_{i\in\mathcal{N}} \frac{1}{v_i - x_i^*}. \end{cases}$$

B. Power Consumption-Delay Tradeoff for Cloud Computing

At the cloud server j, for the delay-sensitive requests, their response delay should be bounded by a certain threshold that is specified as the service level agreement, since the agreement violation would result in loss of business revenue. We assume that the response delay should be smaller than an adjustable parameter D_j, which can be regarded as the delay threshold that identifies the revenue/penalty region at the cloud server j.

$$D_j^{\text{cloud}} \leq \overline{D}_j.$$

We consider to tradeoff between the power consumption and computation delay in the cloud computing subsystem. That is, we have the SP2

$$\min_{y_j, f_j, n_j, \sigma_j} \sum_{j \in \mathcal{M}} \sigma_j n_j \left(A_j f_j^p + B_j \right) \qquad \text{s.t.} \begin{cases} \sum_{j \in \mathcal{M}} y_j = Y \\ D_j^{\text{cloud}} \leq \overline{D}_j & \forall j \in \mathcal{M} \\ (4)-(7). \end{cases}$$

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B. Power Consumption-Delay Tradeoff for Cloud Computing

After we obtain the optimal workload y^*_j assigned to the cloud server j and the optimal solution f^*_j , n^*_j , and σ^*_j , we can calculate the power consumption and computation delay in the cloud computing subsystem, respectively, as

$$\begin{cases} P^{\text{cloud}}(Y) = \sum_{j \in \mathcal{M}} \sigma_j^* n_j^* \left[A_j \left(f_j^* \right)^p + B_j \right] \\ D^{\text{cloud}}(Y) = \sum_{j \in \mathcal{M}} D_j^{\text{cloud}*} = \sum_{j \in \mathcal{M}} \sigma_j^* \overline{D}_j. \end{cases}$$

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C. Communication Delay Minimization for Dispatch

We consider the traffic dispatch rate λ_{ij} to minimize the communication delay in the WAN subsystem. That is, we have the SP3

$$\min_{\lambda_{ij}} \sum_{i \in \mathcal{N}} \sum_{j \in \mathcal{M}} d_{ij} \lambda_{ij}$$
$$\text{s.t.} \quad (1), \quad (2), \quad \text{and } (8).$$

After we obtain the optimal traffic rate λ^*_{ij} dispatched from the fog device i to the cloud server j, we can calculate the communication delay in the WAN subsystem as

$$D^{\text{comm}}(X, Y) = \sum_{i \in \mathcal{N}} \sum_{j \in \mathcal{M}} d_{ij} \lambda^*_{ij}.$$

D. Putting it All Together

Based on the above decomposition and the solution to three SPs, on one hand, the power consumption of the fog-cloud computing system is rewritten as

$$P^{\text{sys}}(X, Y) \triangleq P^{\text{fog}}(X) + P^{\text{cloud}}(Y)$$

which means that the system power consumption comes from the fog devices and cloud servers. On the other hand, the delay of the fog-cloud computing system is rewritten as

$$D^{\text{sys}}(X, Y) \triangleq D^{\text{fog}}(X) + D^{\text{cloud}}(Y) + D^{\text{comm}}(X, Y)$$

which means that the system delay comes from the computation delay of the fog devices and cloud servers, as well as the communication delay of the WAN. After solving the above three SPs, we can approximately solve PP by considering the following approximate problem

$$\min_{X,Y} \; P^{\text{sys}}(X, Y) \qquad \text{s.t.} \; \begin{cases} D^{\text{sys}}(X, Y) \leq \overline{D} \\ X + Y = L \end{cases}$$

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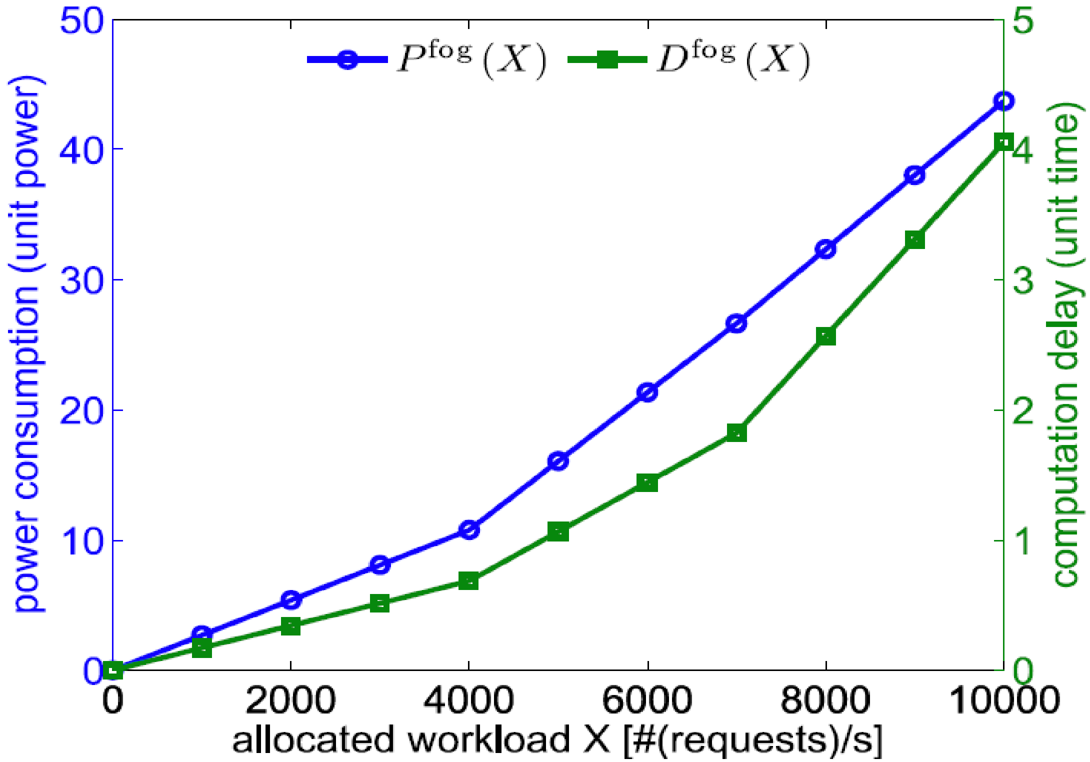
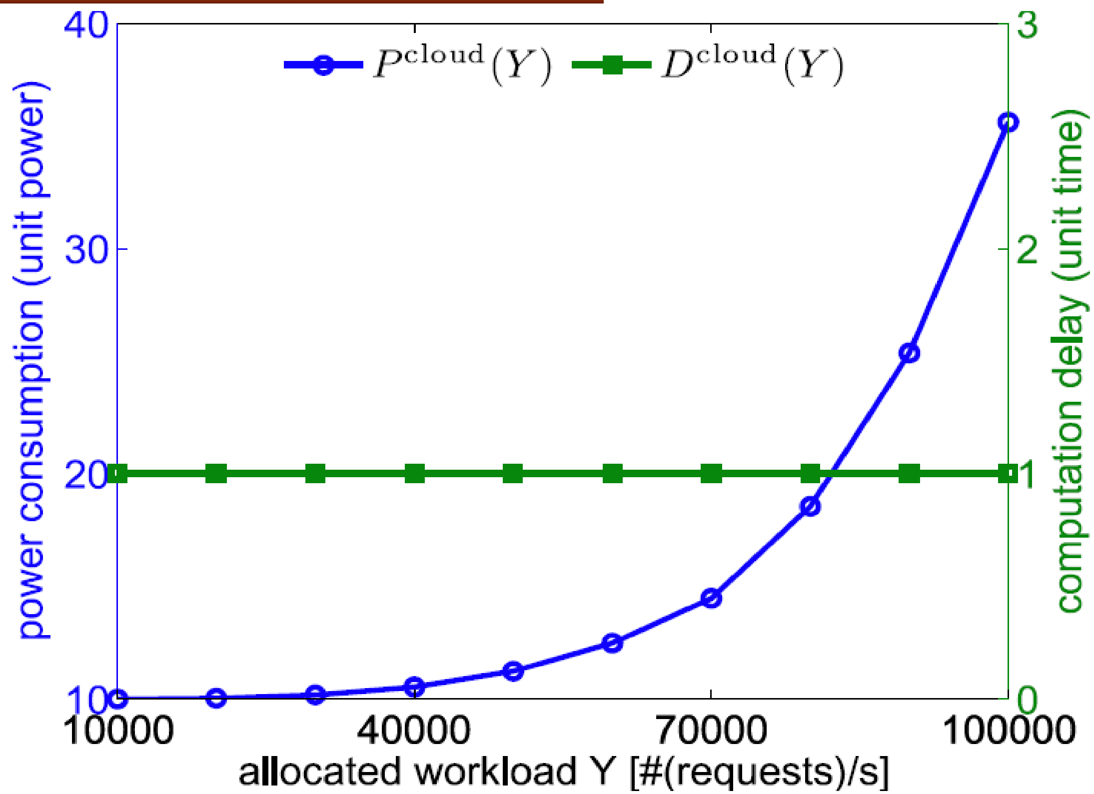
Numerical results (five fog devices and three cloud servers)



Fog computing subsystem

They vary the workload X allocated for fog computing from 0 to 10^4, to evaluate how they affect the power consumption $P^{fog}(X)$ and computation delay $D^{fog}(X)$ in the subsystem. It is seen that both power consumption and computation delay increase with the workload allocated for fog computing.

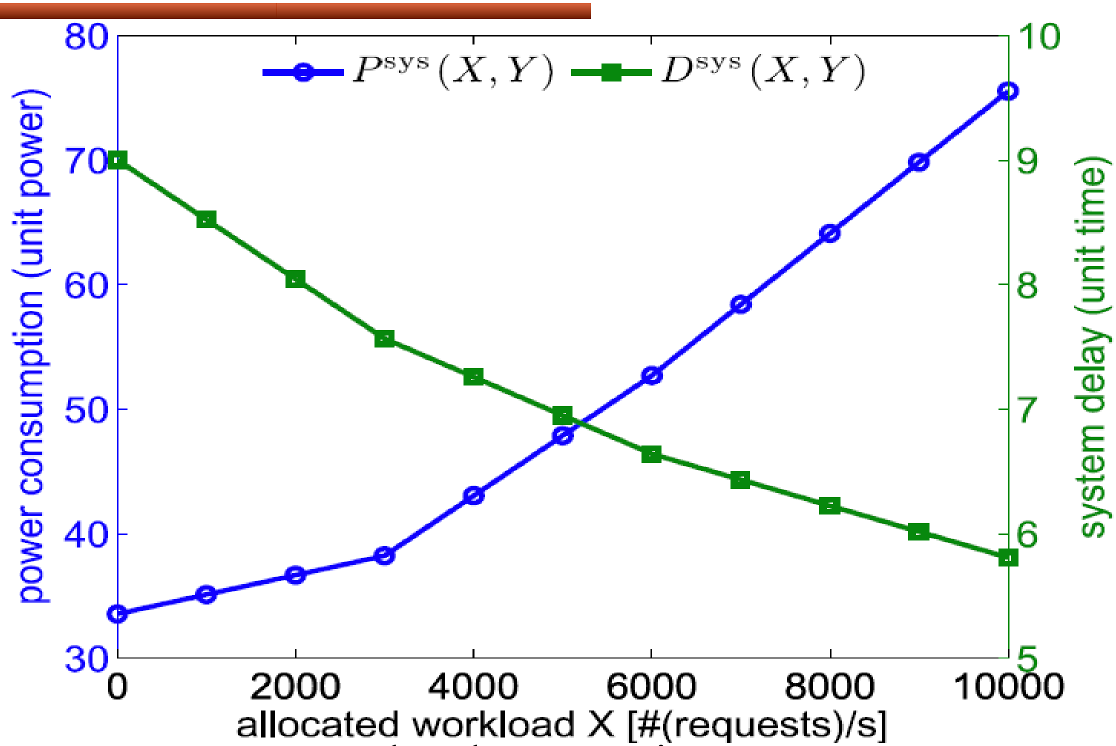
Numerical results (five fog devices and three cloud servers)



Cloud computing subsystem

Then, they vary the workload Y allocated for cloud computing from 10^4 to 10^5, to evaluate how they affect the power consumption $P^{cloud}(Y)$ and computation delay $D^{cloud}(Y)$ in the subsystem. The result shows that the computation delay stays steady while the power consumption increases with the workload allocated for cloud computing.

Numerical results (five fog devices and three cloud servers)



Fog-cloud computing system.

Finally, based on the above x^*_i and y^*_j , we further solve SP3 and obtain the communication delay $D^{comm}(X, Y)$ in the WAN subsystem. Based on these we calculate the system power consumption $P^{sys}(X, Y)$ and delay $D^{sys}(X, Y)$. we note that the power consumption of fog devices dominates the system power consumption, while the communication delay of WAN dominates the system delay.

Conclusions

A systematic framework to investigate the power consumption-delay tradeoff issue in the fog-cloud computing system.

The workload allocation problem is formulated and approximately decomposed into three SPs, which can be, solved within corresponding subsystems.

Simulation and numerical results are presented to show the fog's complement to the cloud.

For the future work, a unified cost model may be built to achieve the optimal workload allocation between fog and cloud.

Thank you for your attention!

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