Toward Energy and Location-Aware Resource Allocation in Next Generation Networks

IEEE International Symposium on Personal, Indoor and Mobile Radio Communications 2025, Istanbul, Türkiye

Mandar Datar[1] **Mattia Merluzzi**[1]

[1]CEA-Leti, Univ. Grenoble Alpes, F-38000 Grenoble, France
{firstname.lastname}@cea.fr

September-3, 2025

Introduction

- Today, the Information and Communication Technology (ICT) sector represents around 2-4% of global CO_2 emissions
- Global electricity demand from data centers to **triple between 2020 and 2030** [1].
- **Data intensive applications:** virtual reality (VR), augmented reality (AR), artificial intelligence (AI)
- Inevitable bonding of communication and computation aspects in wireless networks
- Energy efficiency metrics not sufficient due to the potential **rebound effects**

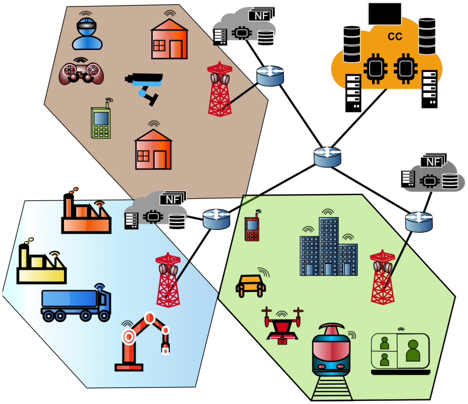
[1] Sachs, Goldman, and Co LLC. "AI, Data Centers and the Coming US Power Demand Surge." Goldman Sachs and Co. LLC, Research Report, April (2024).

(Cost-Aware) Resource allocation problem

- Need for dedicated policies such as budgeting resources (e.g., in terms of energy and/or CO_2)
- How to **efficiently** allocate **heterogeneous** resources to balance utilities and costs
- Agents with **diverse** characteristics and services
- The resource allocation problem as **a Market model**
- **Market Equilibrium** based solution

System Overview

- Communication marketplace with service providers (SPs)
- Set of SPs: $\mathcal{S} = \{1, \dots, S\}$.
- Set of resource types: $\mathcal{R} = \{\text{spectrum, CPU, RAM}\}$.
- Multiple geographical locations: $\mathcal{L} = \{1, \dots, L\}$.
- Each location is equipped with:
  - Base stations for wireless connectivity.
  - Edge Computing (EC) resources.
  - Shared cloud facilities: $\mathcal{C}$.



Network spanning different geographical regions, such as urban, residential, and industrial zones

Service Utilities and Resource Demand

- Resource allocation variable: x^s_{rlc} — amount of resource r allocated to SP s at location l from cloud/EC facility c.
- Base demand: d^s_{rlc} — minimum resource units needed to achieve unit service rate.
- Utility function:

$$u^s_{lc}(\mathbf{x}^s_{lc}) = \min_r \left\{ \frac{x^s_{rlc}}{d^s_{rlc}} \right\} \tag{1}$$

- Captures perfect complementarity of resources (bottleneck effect).

Illustration of Utility

Example:

- Base demands: $d_{\text{bw}} = 2$, $d_{\text{CPU}} = 1$
- Allocated: $x_{\text{bw}} = 4$, $x_{\text{CPU}} = 2$

$$u = \min\left\{\frac{4}{2}, \frac{2}{1}\right\} = 2$$

- Utility increases only when all resources increase proportionally.

Aggregated Utility:

$$U_l^s(\mathbf{x}_l^s) = \sum_c u_{lc}^s(\mathbf{x}_{lc}^s), \quad U^s(\mathbf{x}^s) = \sum_l U_l^s(\mathbf{x}_l^s) \tag{2}$$

Energy and Emission Constraints

- Resource use contributes to CO_2 emissions via energy consumption.
- Local demand:
$$\widehat{x}_{rl} = \text{Total demand for resource } r \text{ at location } l$$
- Cloud demand:
$$\widetilde{x}_{rc} = \text{Total demand for resource } r \text{ at cloud } c$$
- Energy limits:
$$\widehat{e}_l(\widehat{\mathbf{x}}_l) \leq E_l \quad \text{(Local)} \qquad \sum_l \widehat{e}_l(\widehat{\mathbf{x}}_l) + \sum_c \widetilde{e}_l(\widetilde{\mathbf{x}}_c) \leq E_g \quad \text{(Global)}$$

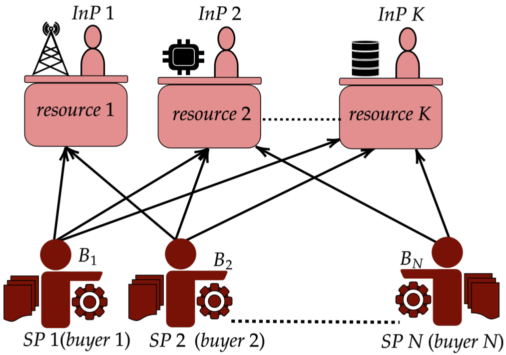
Capacity Constraints

- Each location has a finite capacity for each resource:

$$\widehat{x}_{rl} \leq X_{rl} \quad \forall r, l$$

- Cloud facilities assumed to be virtually unlimited in capacity.

Fisher Market



$$\mathcal{M} := \left\langle \mathcal{S}, \left(\mathbf{x}^s \in \mathbb{R}^K\right)_{s\in\mathcal{S}}, \left(U^s\right)_{s\in\mathcal{S}}, \left(B^s\right)_{s\in\mathcal{S}}, \mathbf{p} \in \mathbb{R}^K \right\rangle,$$

- Buyer set: $\mathcal{S}$
- Budgets: B^s for each $s \in \mathcal{S}$
- Resources set: $\mathcal{K}$ (with $K = |\mathcal{K}|$)
- Allocations: $\mathbf{x}^s = (x_1^s, x_2^s, \ldots, x_K^s) \in \mathbb{R}^K$, for $s \in \mathcal{S}$
- Utility functions: $U^s(\mathbf{x}^s)$
- Price vector: $\mathbf{p} = (p_{rlc})_{r,l,c}$

A special case of the Arrow-Debreu market[2] where there are no firms; instead, buyers possess a single type of commodity, which serves as a fixed budget.

[2] Arrow, Kenneth J., and Gerard Debreu. "Existence of an equilibrium for a competitive economy." In The Foundations of Price Theory Vol 5, pp. 289-316. Routledge, 2024.

Carbon credits

- each agent $s \in \mathcal{S}$ is allocated a budget B^s,
- represents artificial currency or *carbon credits*
- budget, determined by a regulatory authority or the agents themselves
- may depend on factors such as the agent's service priority, or its efforts to reduce carbon emissions

Market Equilibrium

A competitive equilibrium (CE) in the market $\mathcal{M}$ is a pair $(\mathbf{p}^*, \mathbf{x}^*)$ that represents the equilibrium prices and allocation, if the following two conditions hold:

C1 Given the price vector, every SP s spends its budget such that it receives resource bundle $\mathbf{x}^{s*}$ that maximizes its utility.

$$\mathbf{x}^{s*} \in \arg\max \left\{ U^s(\mathbf{x}^s) \middle| \sum_{r,l,c} p^*_{rlc} x^s_{rlc} \leq B_s \right\} \quad \forall s \in \mathcal{S} \tag{C1.1}$$

C2 If the total energy consumption due to resources usage meets the capacity, it is positively priced; otherwise, the corresponding resource has zero price, i.e., we have:

$$p^*_{rlc} = \lambda \nabla_{\widetilde{x}_{rc}} \widetilde{e}_c(\widetilde{x}^*_c) \quad \forall r \in \mathcal{R},\ \forall l \in \mathcal{L},\ \forall c \in \mathcal{C} \setminus \{0\}, \tag{C2.1}$$

$$p^*_{rl0} = \gamma_{rl} + (\lambda + \mu_l) \nabla_{\widehat{x}_{rc}} \widehat{e}_\ell(\widehat{x}^*_l) \quad \forall r \in \mathcal{R},\ \forall l \in \mathcal{L}, \tag{C2.2}$$

$$\gamma_{rl}(\widehat{x}^*_{rl} - X_{rl}) = 0 \quad \forall r \in \mathcal{R},\ \forall l \in \mathcal{L}, \tag{C2.3}$$

$$\mu_l \left(\widehat{e}^l(\mathbf{x}^*) - E_\ell \right) = 0 \quad \forall l \in \mathcal{L} \tag{C2.4}$$

$$\lambda \left(\sum_l \widehat{e}_l(\widehat{\mathbf{x}}^*_l) + \sum_c \widetilde{e}_c(\widetilde{\mathbf{x}}^*_c) - E_g \right) = 0 \tag{C2.5}$$

Extended-Esenberg-Gale optimization program

$$
\begin{aligned}
\underset{\mathbf{x}}{\text{maximize}} \quad & \sum_s B^s \log\left(\sum_l \sum_c u_{lc}^s(\mathbf{x}_{lc}^s)\right) \\
\text{subject to} \quad & u_{lc}^s(\mathbf{x}_{lc}^s) = \min_r \left\{ \frac{x_{rlc}^s}{\overline{d}_{rlc}^s} \right\}, \forall s, \forall l \in \mathcal{L}, \forall c \in \mathcal{C}, \\
(\gamma_{rl}) \quad & \widehat{x}_{rl} - X_{rl} \leq 0, \forall r \in \mathcal{R}, \forall l \in \mathcal{L}, \\
(\mu_l) \quad & \widehat{e}_l(\widehat{\mathbf{x}}_l) \leq E_l, \forall l \in \mathcal{L}, \\
(\lambda) \quad & \sum_l \widehat{e}_l(\widehat{\mathbf{x}}_l) + \sum_c \widetilde{e}_c(\widetilde{\mathbf{x}}_c) \leq E_g, \\
& x_{rlc}^s \geq 0, \forall s, \forall r \in \mathcal{R}, \forall l \in \mathcal{L}, \forall c \in \mathcal{C}.
\end{aligned}
\tag{3}
$$

Proposition

Consider a market where each agent's utility is defined as in (1)–(2). Suppose that the functions $\widehat{e}_l(\widehat{\mathbf{x}}_l)$ and $\widetilde{e}_c(\widetilde{\mathbf{x}}_c)$ are convex and increasing in $\widehat{\mathbf{x}}_l$ and $\widetilde{\mathbf{x}}_c$, respectively, for all $l \in \mathcal{L}$ and $c \in \mathcal{C}$. Then, the market equilibrium (ME) can be obtained by solving the optimization problem (3). Also, the optimal allocation $\mathbf{x}^*$ and the associated dual variables $\mathbf{p}^*$ (corresponding to constraints (C2.1)–(C2.5)) together constitute a market equilibrium.

The fairness and efficiency

- The proposed allocation scheme maximizes the Nash welfare

$$\arg\max_{\mathbf{x}\in\mathcal{X}} \Pi_s U_s(\mathbf{x}^s)^{B^s} = \arg\max_{\mathbf{x}\in\mathcal{X}} \sum_{s\in\mathcal{S}} B^s \log\left(U^s(\mathbf{x}^s)\right) \tag{4}$$

- achieves the proportional fairness

$$\sum_s B^s \frac{U^s(\mathbf{x^{s*}}) - U^s(\mathbf{x^s})}{U^s(\mathbf{x^{s*}})} \leq 0 \tag{5}$$

Numerical Results

Table: The base demand vector of service classes

User Applications	VCPU	RAM (GB)	NB (Mbps)
BW-Intensive	2-4	8-12	300-492
CPU-Intensive	30-36	6-8	50-70
RAM-Intensive	2-4	28-32	50-70
Balanced	2-4	3.5-4	50-70

Numerical Results

- Energy function, $e_k(\overline{x}_k) = (\overline{x}_k)^{\beta_k}$, where $\beta_k \geq 1$.
- Restrictions on energy consumption at two levels:
  1. Total energy consumption limit across all resources,
  2. Local energy consumption restriction: radio resource and the MEC facility
- Socially optimal allocation

$$\begin{aligned} \underset{\mathbf{x}}{\text{maximize}} \quad & \sum_s B^s U^s(\mathbf{x}^s) \\ \text{subject to} \quad & \text{Constraints in (3)} \end{aligned} \tag{6}$$

Numerical Experiments

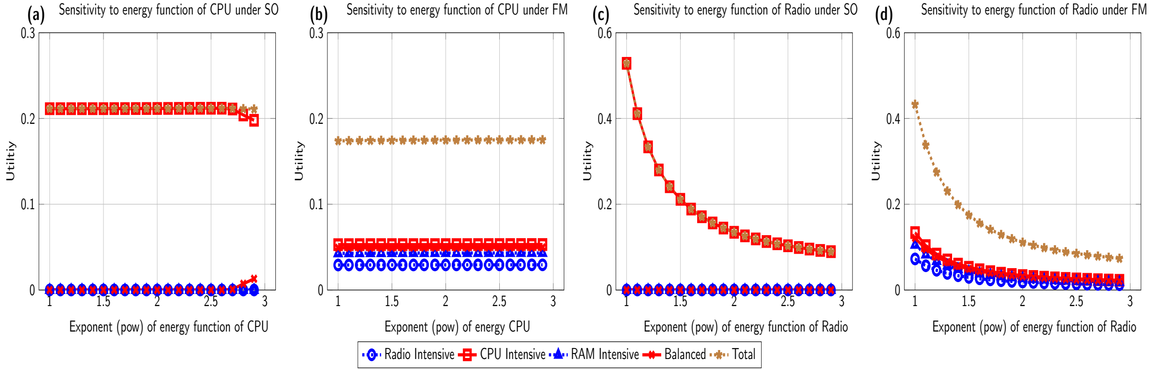


Figure: Impact of different energy functions on agents' utility. (a) and (b): Sensitivity to the CPU energy function under Social Optimum (SO) and Fisher Market (FM)-based allocation, respectively. (c) and (d): Sensitivity to the Radio energy function under SO and FM-based allocation, respectively.

Numerical Experiments

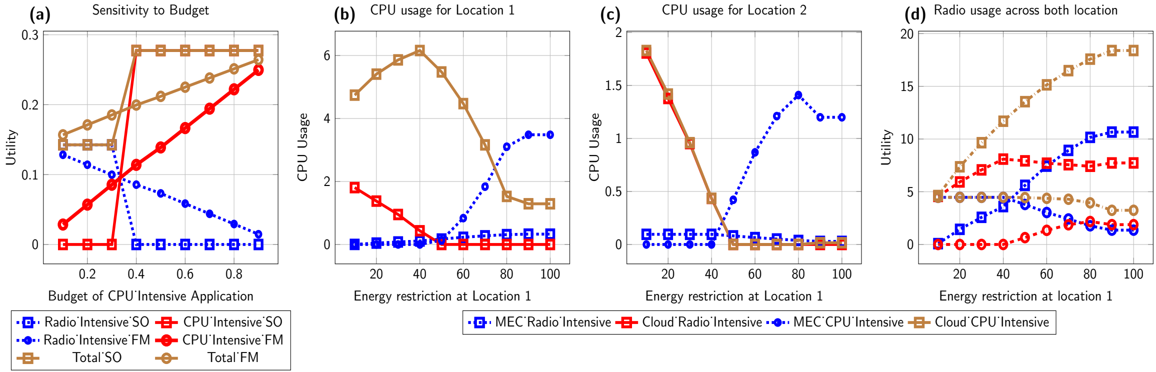


Figure: Variation in the usage of: (a) radio, (b) CPU, and the utility derived from both MEC and cloud facilities vs. local energy consumption constraints.

Conclusion and Future work

- Fisher market based cost-aware multi-resource allocation scheme
- Proposed resource allocation mechanism achieves Nash welfare and proportional fairness
- Design decentralized competitive equilibrium seeking algorithm
- Edge AI as application

Thank You