Joint Allocation of Computing and Wireless Resources to Autonomous Devices in Mobile Edge Computing

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Mobile Edge Computing (MEC)

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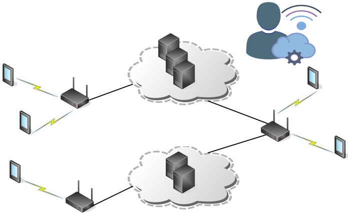
Enabler of 5G

- High bandwidth and computing resources close to the end users
- Interaction between end users decisions and MEC infrastructure decisions



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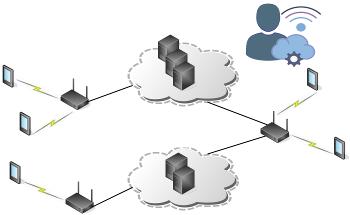

Important Question

- How users and the infrastructure interact with each other?

MEC System

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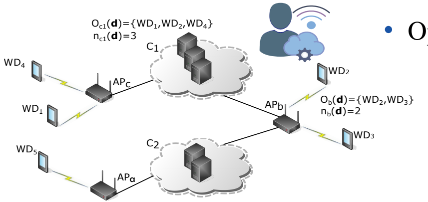

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  - multiple edge clouds $\mathcal{C} = \{1, 2, ..., C\}$
  - multiple APs $\mathcal{A} = \{1, 2, ..., A\}$

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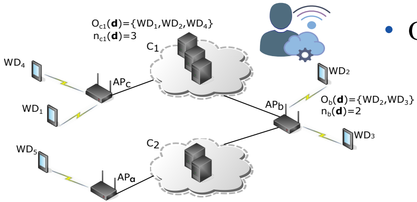

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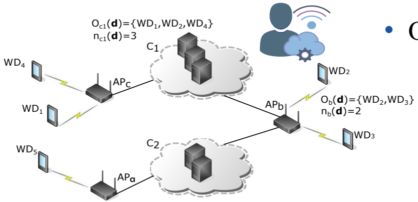

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Computation Offloading

- Task of WD i, $< D_i, L_i >$
  - size of the input data D_i
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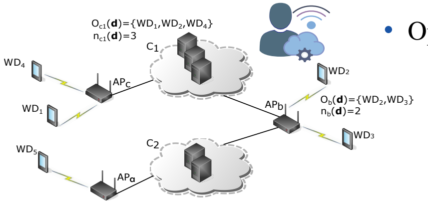

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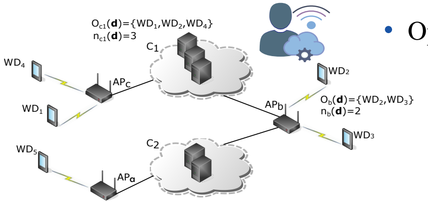

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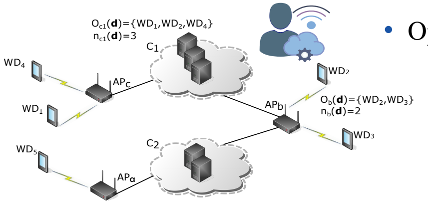

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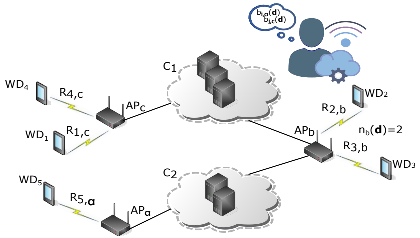
Wireless Resource Management



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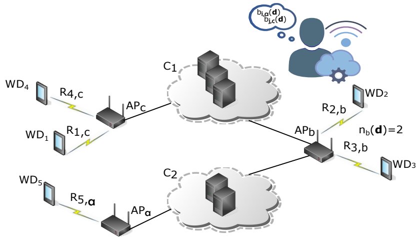

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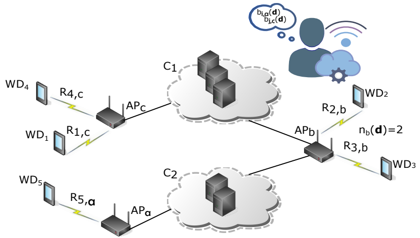

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Computation Offloading through AP a

- Uplink rate of WD i via AP a

$$\omega_{i,a}(\mathbf{d}, \mathbf{b}_a) = \frac{R_{i,a}}{n_a(\mathbf{d}) b_{i,a}(\mathbf{d})}$$

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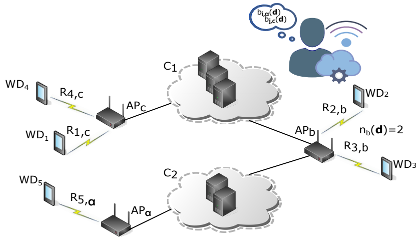

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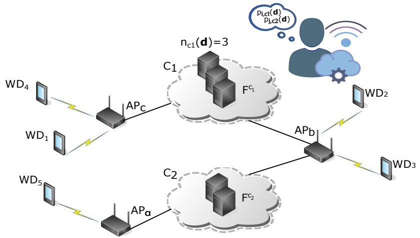
$$\omega_{i,a}(\mathbf{d}, \mathbf{b}_a) = \frac{R_{i,a}}{n_a(\mathbf{d}) b_{i,a}(\mathbf{d})}$$

- Transmission time of WD i for offloading via AP a

$$T_{i,a}^{off}(\mathbf{d}, \mathbf{b}_a) = \frac{D_i}{\omega_{i,a}(\mathbf{d}, \mathbf{b}_a)}$$

Computing Resource Management



- F^c : computing capability of cloud c

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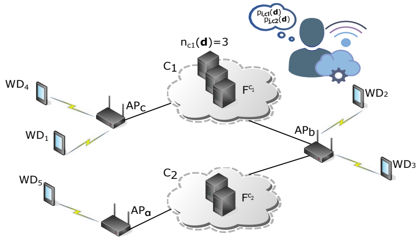

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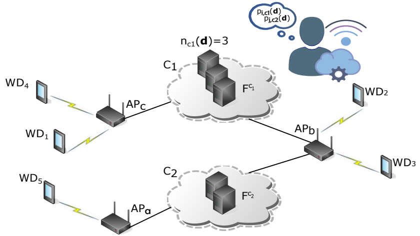

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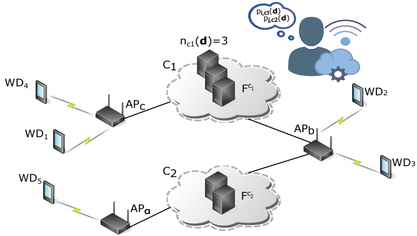
Computation Offloading to Cloud c

- Computing capability allocated to WD i by cloud c

$$F_i^c(\mathbf{d}, \mathbf{p}_c) = \frac{F^c}{n_c(\mathbf{d}) p_{i,c}(\mathbf{d})}$$

Computing Resource Management



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- Computing capability allocated to WD i by cloud c

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- Execution time of WD i's task in cloud c

$$T_{i,c}^{exe}(\mathbf{d}, \mathbf{p}_c) = \frac{L_i}{F_i^c(\mathbf{d},\mathbf{p}_c)}$$

Cost Model

- Task completion time minimization

Cost of WD i

$$C_{i,a}^{c}(\mathbf{d},\mathbf{b}_a,\mathbf{p}_c) = T_{i,a}^{off}(\mathbf{d},\mathbf{b}_a) + T_{i,c}^{exe}(\mathbf{d},\mathbf{p}_c)$$

System Cost

$$C(\mathbf{d},\mathbf{b},\mathbf{p}) = \sum_{(c,a)\in\mathcal{C}\times\mathcal{A}_c}\ \sum_{i\in O_c(\mathbf{d})\cap O_a(\mathbf{d})} C_{i,a}^{c}(\mathbf{d},\mathbf{b}_a,\mathbf{p}_c)$$

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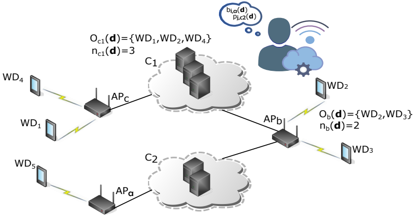
2. Is there an allocation of tasks in which all selfish devices are satisfied?
3. Can it be computed using a decentralized algorithm?
4. How good is the system performance?
5. What is the complexity of the algorithm?

Mobile Edge Computation Offloading Game (MEC-OG)



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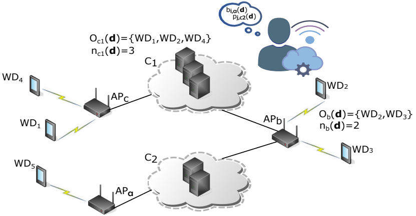

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Objective of the Operator

- Joint optimization of wireless and computing resources

$$\min_{\mathbf{b},\mathbf{p}\succeq 0} C(\mathbf{d},\mathbf{b},\mathbf{p})$$

$$\text{s.t.} \sum_{i\in O_a(\mathbf{d})} \frac{1}{b_{i,a}(\mathbf{d})} = n_a(\mathbf{d}), \forall a \in \mathcal{A}$$

$$\sum_{i\in O_c(\mathbf{d})} \frac{1}{p_{i,c}(\mathbf{d})} = n_c(\mathbf{d}), \forall c \in \mathcal{C}$$

Objective of WDs

- Minimization of their own cost

$$\min_{d_i\in\mathfrak{D}_i} C_i(d_i, d_{-i}, \mathbf{b}_a^*, \mathbf{p}_c^*)$$

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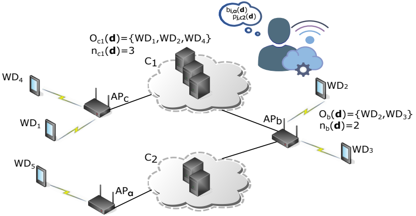

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Important Question

- Does the MEC-OG have a subgame perfect equilibrium (SPE)?

Optimal Resource Allocation Policy of the Operator

- Best response of the operator to strategy profile **d** chosen by WDs

$$b^*_{i,a}(\mathbf{d}) = \frac{\sum_{j \in O_a(\mathbf{d})} \sqrt{D_j/R_{j,a}}}{n_a(\mathbf{d})\sqrt{D_i/R_{i,a}}}, \forall i \in O_a(\mathbf{d}), \forall a \in \mathcal{A}$$

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Interaction Between WDs under Optimal Policy of the Operator

- Original player-specific weighted congestion game can be transformed into a congestion game $\Gamma = <\mathcal{N}, (\mathfrak{D}_i)_i, (C_i)_i>$ with resource dependent weights

weights: $$\omega_{i,a} = \sqrt{\frac{D_i}{R_{i,a}}}, \omega_{i,c} = \sqrt{\frac{L_i}{F^c}}$$

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Important Question

- Does the resulting strategic game have a Nash equilibrium (NE)?

Main Results

NE Existence

- Weighted congestion game Γ played between WDs has a NE $\mathbf{d}^*$
  - proof based on showing that the game has an exact potential function

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SPE Existence

- Stackelberg game played between WDs and the operator has a SPE $(\mathbf{d}^*, \mathbf{b}^*, \mathbf{p}^*)$
  - optimal provisioning coefficients $\mathbf{b}^*$ and $\mathbf{p}^*$ have closed form expressions
  - WDs can compute an equilibrium allocation $\mathbf{d}^*$ of offloading decisions in a decentralized manner using the IO algorithm

User Focused Performance Analysis

Evaluation Scenario

- $A = 5$ APs, homogeneous clouds with $F^c = 64$ *Gcycles*
- Tasks: $D_i \sim \mathcal{U}(0.2, 4)$ *Mb* , $L_i = D_i X$ *Gcycles* , $X \sim \Gamma(0.5, 1.6)$ *Gcycles/b*

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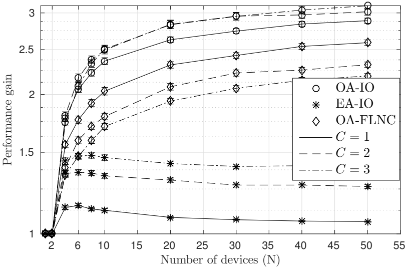
Defined w.r.t. *equal alocation* (EA) policy and the *fastest-link nearest-cloud* (FLNC) algorithm



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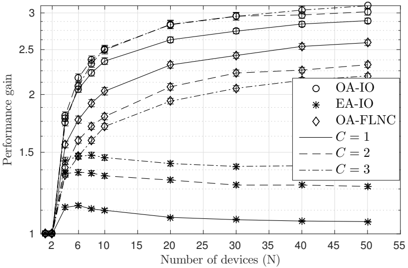

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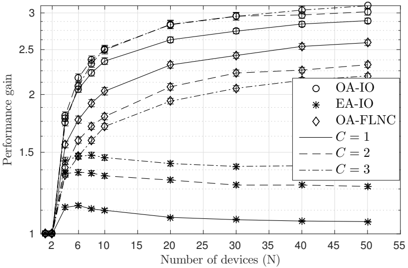

- *Performance gain* increases with decreasing marginal gain in N
- *Performance gain* increases with the number of clouds
- Largest *performance gain*
  - operator implements OA policy
  - WDs compute offloading decisions using the IO algorithm

Cloud Focused Performance Analysis

Evaluation Scenario

- $A = 5$ APs, $C = 3$ heterogeneous clouds
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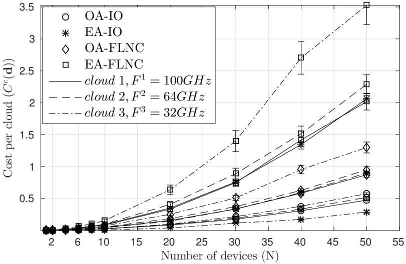
Defined as $C^c(\mathbf{d}) = \sum_{i \in O_c(\mathbf{d})} C_i(\mathbf{d})$



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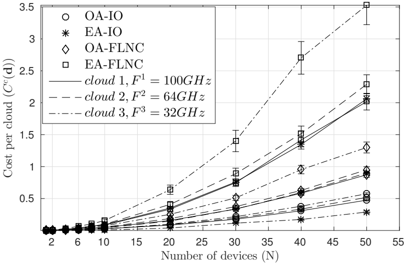

- *Cost per cloud* increases with the number N of WDs
- *Cost per cloud* is approximately the same for all clouds in the case of the OA policy and the IO algorithm

Computational Complexity

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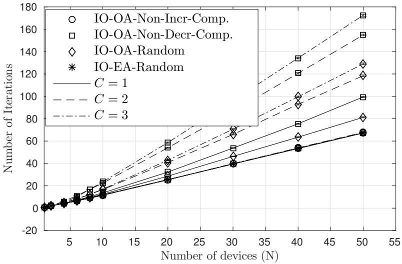
- Tasks: $D_i \sim \mathcal{U}(0.2, 4)$ *Mb* , $L_i = D_i X$ *Gcycles* , $X \sim \Gamma(0.5, 1.6)$ *Gcycles/b*

IO Algorithm - Three Orders of Adding WDs

- Non-increasing order of tasks' complexities
- Non-decreasing order of tasks' complexities
- Random order



- Number of iterations scales approximately linearly with the number N of WDs

Computational Complexity

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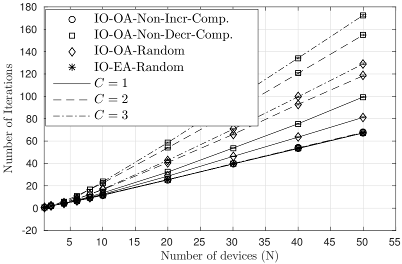

- Number of iterations scales approximately linearly with the number N of WDs
- Number of iterations is sensitive to the order of adding WDs
  - it is smallest when WDs are added in non-increasing order of their task complexities

Summary and Future Work

- Provided game theoretical analysis of the interaction between
  - operator that manages wireless and computing resources in a MEC system and
  - autonomous WDs that aim at minimizing their own task completion time

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  - operator that manages wireless and computing resources in a MEC system and
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- Interesting extensions
  - model in which WDs can perform computation locally
  - energy consumption minimization problem
  - stochastic model of task arrivals

Joint Allocation of Computing and Wireless Resources to Autonomous Devices in Mobile Edge Computing

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