Decentralized Resource Management for Edge Computing

SSF Modane

CERCES

success securing critical energy infrastructures

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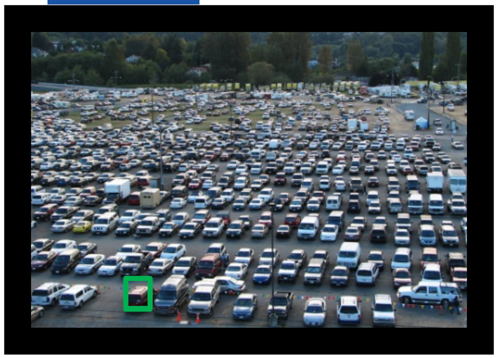
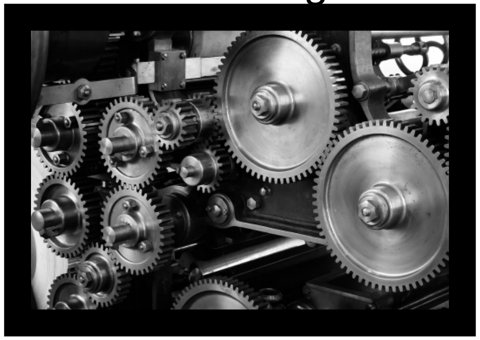
Edge Computing and IoT

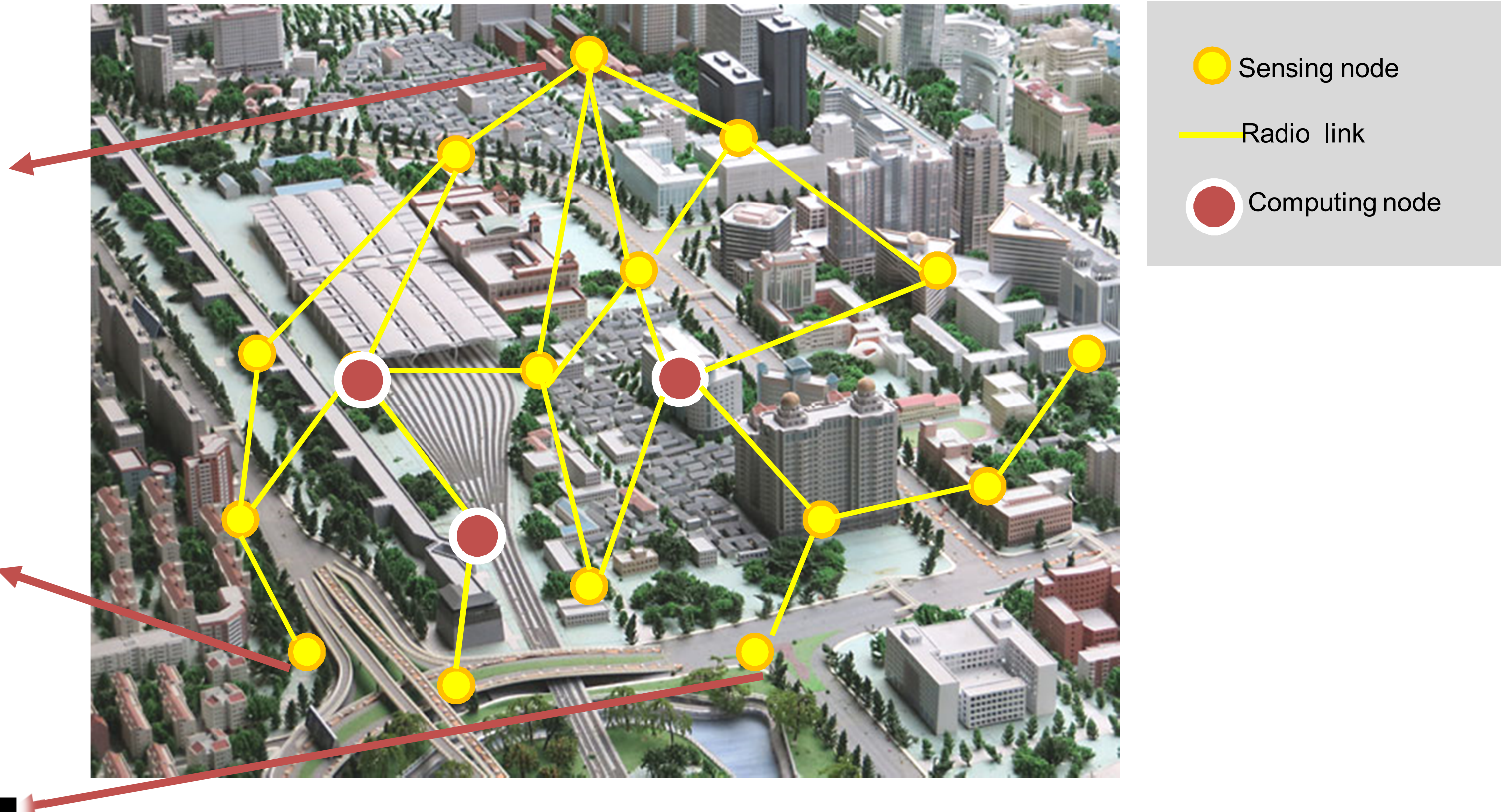


Monitoring



Maintenance

Control

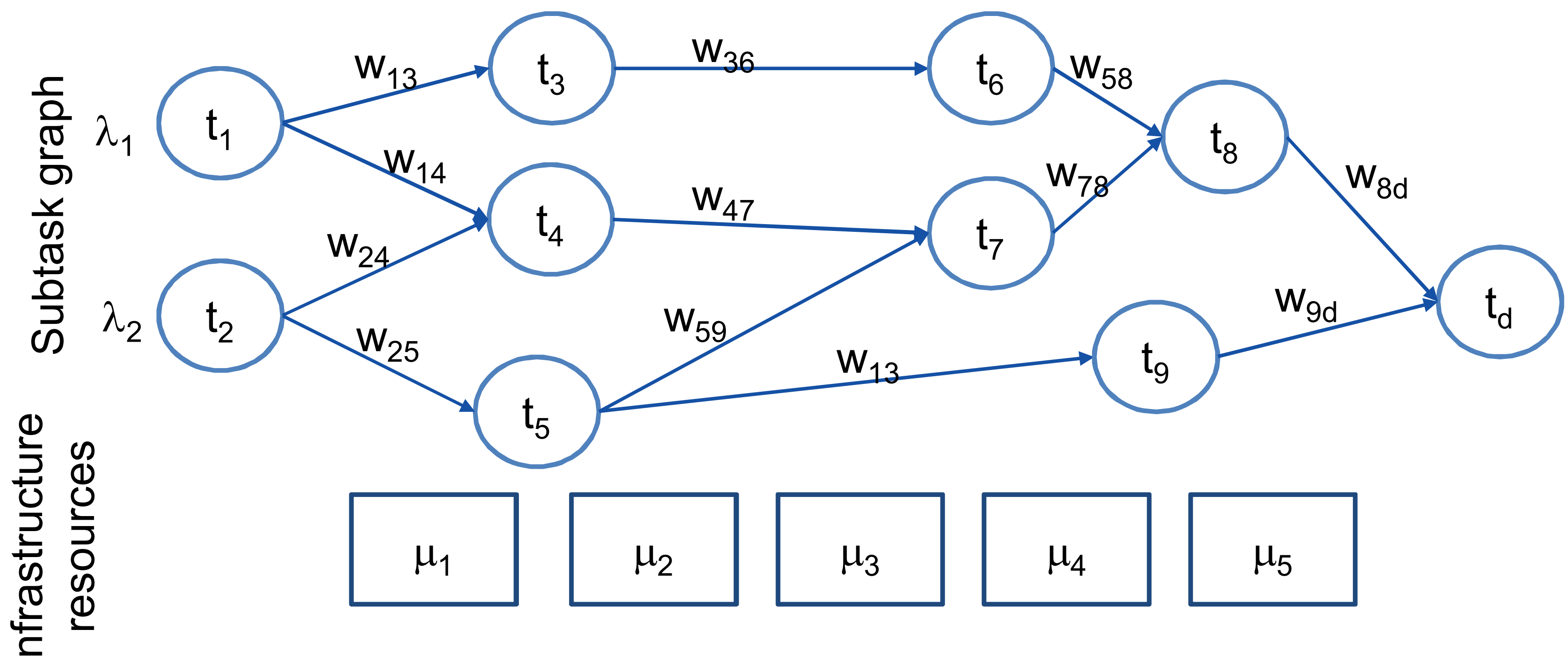


- “Decentralized cloud computing” in small data centers at the network edge
  - Enabler of IoT, cognitive assistants, tactile internet

- Requires adaptive distributed allocation of computing and communication resources

Edge Computing Resource Management

- Task partitioning and assignment
- Local vs. edge vs. cloud execution
- Joint management of wireless and computing resources



Edge Computing Resource Management

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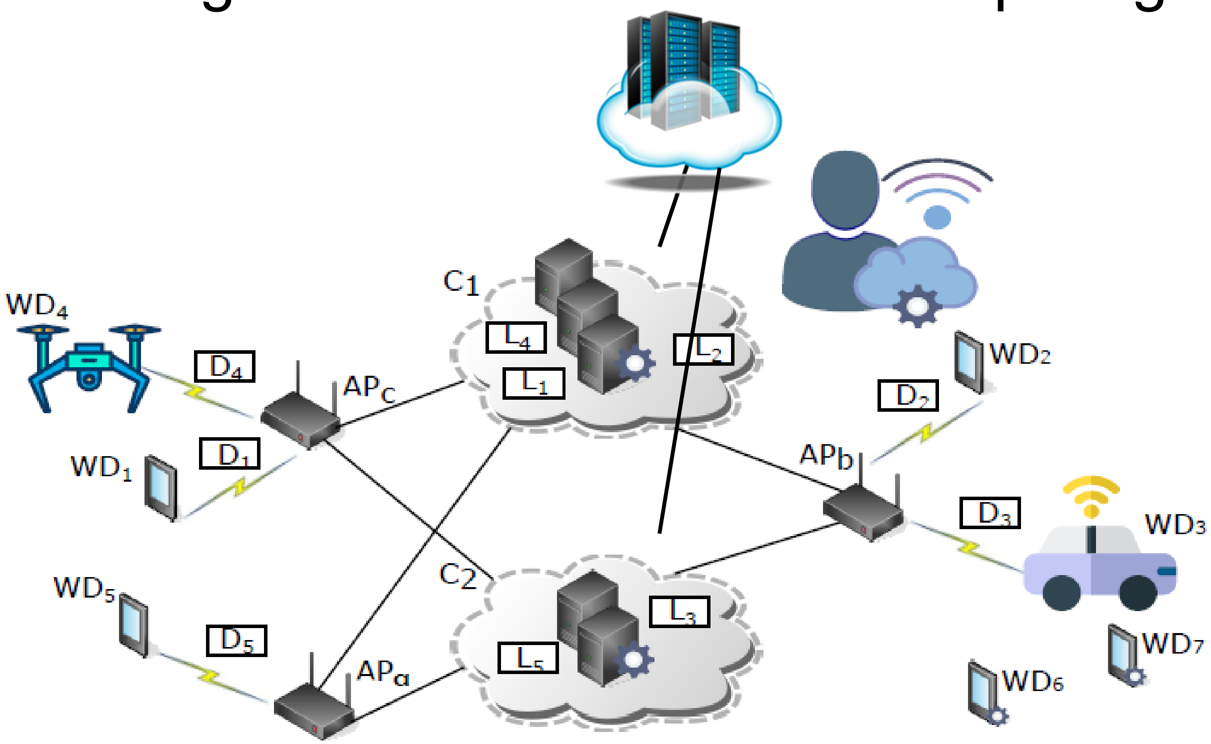
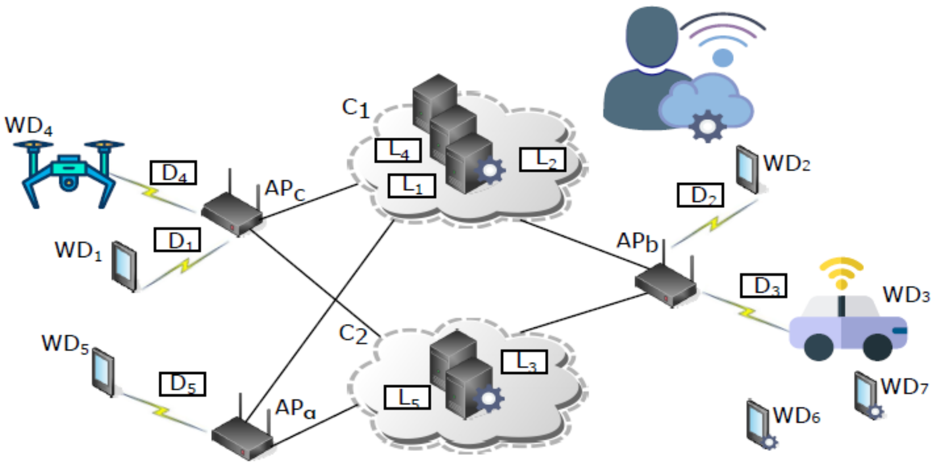


MEC System Model



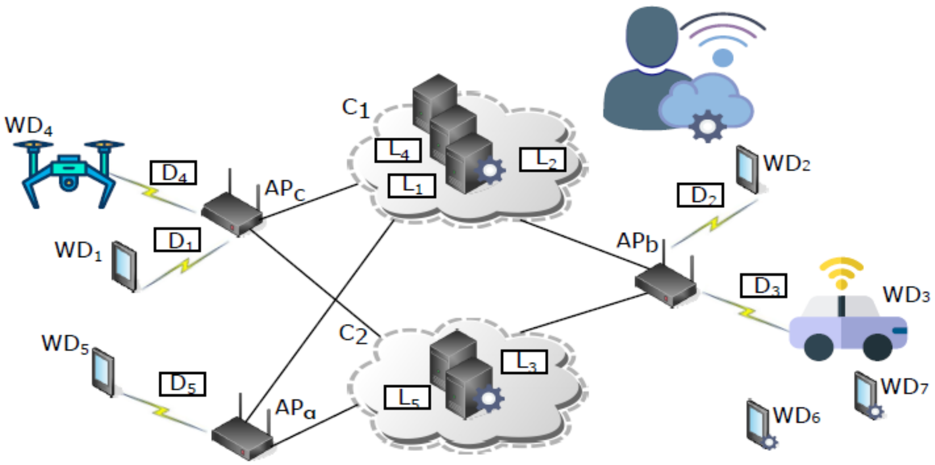
- Wireless devices (WDs) $\mathcal{N}$
- Operator manages
  - Edge clouds (ECs) $\mathcal{C}$
  - APs $\mathcal{A}$
  - WD i can connect to APs $\mathcal{A}_i \subseteq \mathcal{A}$

Computation offloading

- Task of WD i, $< D_i, L_i >$
  - size of the input data D_i
  - computational complexity L_i
- Decision d_i of WD $i \in \mathcal{N}$
- Set of decisions for all WDs is a *strategy profile* $\mathbf{d}$

S. Josilo, G. Dán, ``Joint Management of Wireless and Computing Resources for Computation Offloading in Mobile Edge Clouds," IEEE Trans. on Cloud Computing, accepted for publication

Communication Model



- $R_{i,a}$: PHY rate of WD i on AP a
- $u_{i,a}$: uplink access provisioning coefficient

Transmission time

$O_a(\mathbf{d})$: offloaders via AP a in strategy profile $\mathbf{d}$

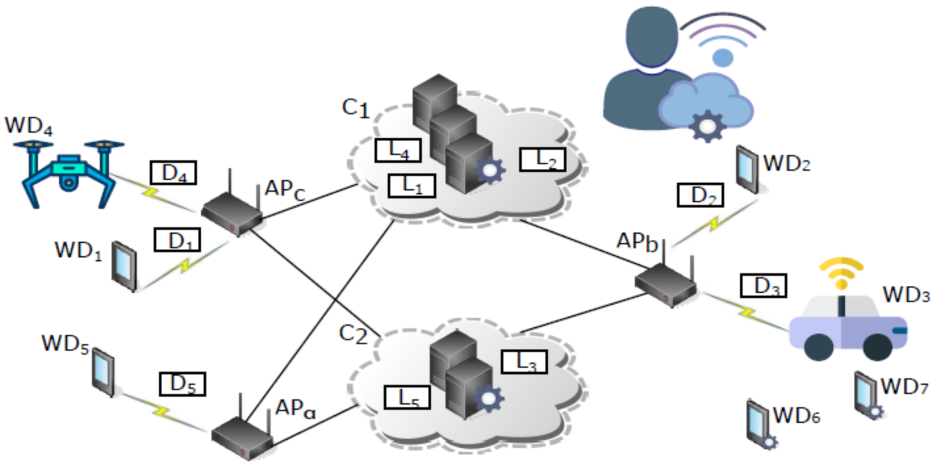
- Uplink rate of WD i via AP a

$$\omega_{i,a}(\mathbf{d}, \mathbf{u}_a) = R_{i,a} \frac{u_{i,a}}{\sum_{j \in O_a(\mathbf{d})} u_{j,a}}$$

- Transmission time of WD i for offloading via AP a

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

Communication Model



- $R_{i,a}$: PHY rate of WD i on AP a
- $u_{i,a}$: uplink access provisioning coefficient

Transmission time

Example: $u_{i,a} = 1$ corresponds to equal sharing

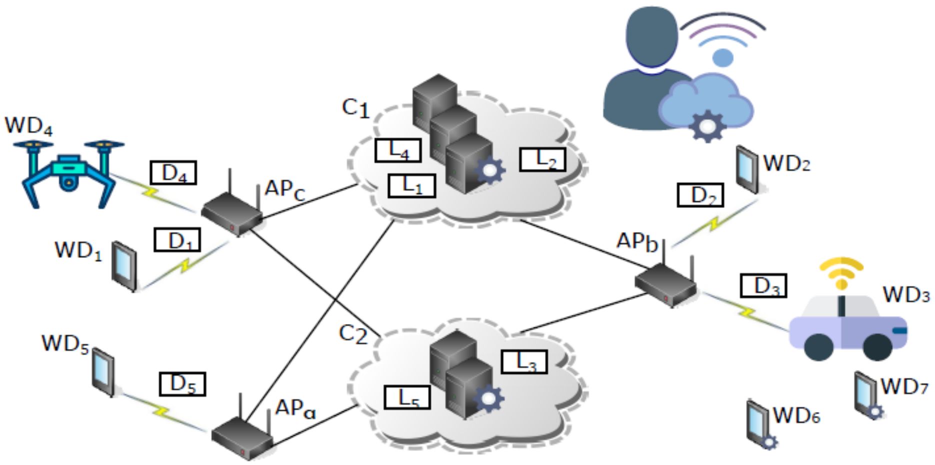
- Uplink rate of WD i via AP a

$$\omega_{i,a}(\mathbf{d}, \mathbf{u}_a) = R_{i,a} \frac{u_{i,a}}{\sum_{j \in O_a(\mathbf{d})} u_{j,a}}$$

- Transmission time of WD i for offloading via AP a

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

Computing Model



Local computing

- F_i^l computing capability of WD i
- Local execution time of WD i's task

$$T_{i,l}^{exe} = \frac{L_i}{F_i^l}$$

Computation offloading

- F^c : computing capability of EC c
- $p_{i,c}$: computing power provisioning coefficient

$O_c(\mathbf{d})$: offloaders to EC c in strategy profile $\mathbf{d}$

- Computing capability allocated to WD i by EC c

$$F_i^c(\mathbf{d}, \mathbf{p}_c) = F^c \frac{p_{i,c}}{\sum_{j \in O_c(\mathbf{d})} p_{j,c}}$$

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

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

Cost – Task Completion Time

Local Computing Cost

$$C_i^l = T_{i,l}^{exe}$$

Cloud Offloading Cost

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

System Cost

$$C(\mathbf{d}, \mathbf{u}, \mathbf{p}) = \underbrace{\sum_{i \in \mathcal{N}} \sum_{(a,c) \in \mathcal{A}_i \times \mathcal{C}} I_{d_i,(a,c)} C_{i,a}^c(\mathbf{d}, \mathbf{u}_a, \mathbf{p}_c)}_{\text{offloading}} + \underbrace{\sum_{i \in \mathcal{N}} I_{d_i,i} C_i^l}_{\text{local execution}},$$

$$I_{d_i,r} = \begin{cases} 1, & \text{if } d_i = r \\ 0, & \text{otherwise} \end{cases}$$

Mobile Edge Computation Offloading Game (MCOG)

Objective of the operator

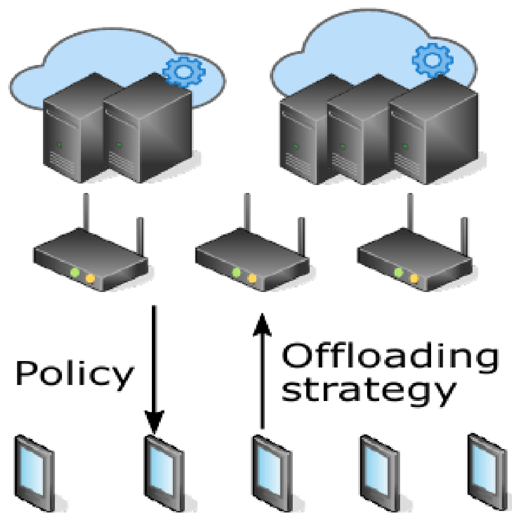
- Minimization of total cost

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

Objective of WDs

- Minimization of own cost

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



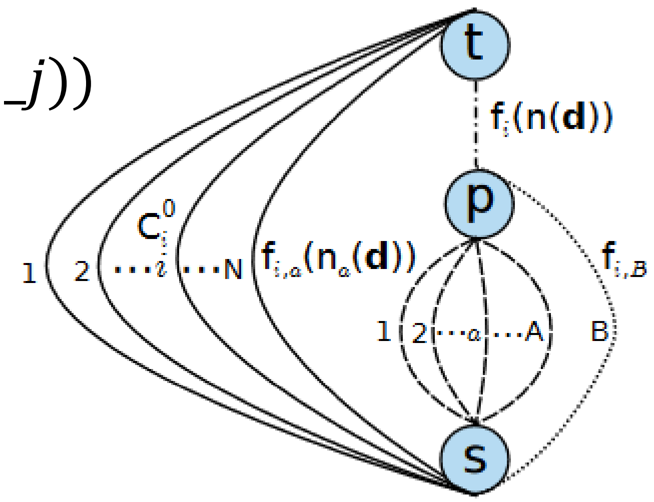
- Multi-leader common-follower Stackelberg game

Game theory crash course

- Best response
  - Optimal strategy given the other players' strategies
    - $B(d_{-i}) = argmin_{d_i} C_i(d_i, d_{-i})$
- Nash equilibrium
  - Strategy profile d^* such that no player wants to deviate
    - $d_i^* \in B(d_{-i}^*)$
- Stackelberg equilibrium (SPE)
  - $d_i^* = argmin_{d_i} C\_i(d_i, B(d_i))$

Game theory crash course

- Potential function
  - $\Psi(d_i, d_{-i}) - \Psi(d_i', d_{-i}) = u_i(d_i, d_{-i}) - \mathrm{u_i}(d_i', d_{-i})$
- Generalized ordinal potential function
  - $u_i(d_i, d_{-i}) - \Psi(d_i', d_{-i}) > 0 \rightarrow \Psi(d_i, d_{-i}) - \Psi(d_i', d_{-i}) > 0$
- (Player specific weighted) Congestion game
  - Set of primary resources: T
  - Set of strategies: $d_i \subseteq T$
  - Cost function: $C_i(\boldsymbol{d}) = \sum_{t \in \mathrm{d_i}} c\_i(f(j: t \in d\_j))$



Questions addressed

- Does MCOG admit a SPE?
  - Cost minimizing (CM) operator
  - Time fair (TF) operator

$$\mathfrak{A}_t = \{(\mathbf{u}, \mathbf{p}) | u_{i,a} = 1, p_{i,c} = 1, \forall i \in \mathcal{N}, a \in \mathcal{A}, c \in \mathcal{C}\}$$

- Can SPE be computed using a decentralized algorithm?
  - What is the complexity of the algorithm?
  - How good is the resulting system performance?

Main result: Polynomial time decentralized algorithm with approximation ratio bound for optimizing MU assignment

S. Josilo, G. Dán, ``Joint Management of Wireless and Computing Resources for Computation Offloading in Mobile Edge Clouds," IEEE Trans. on Cloud Computing, accepted for publication

Optimal policy of the CM operator

Cost minimization problem

$$\min_{(\mathbf{u},\mathbf{p})\in\mathfrak{A}_c} C(\mathbf{d},\mathbf{u},\mathbf{p})$$

$$\text{s.t.} \quad \sum_{j\in O_a(\mathbf{d})} u_{j,a} = 1, \quad \forall a \in \mathcal{A}$$

$$\sum_{j\in O_c(\mathbf{d})} p_{j,c} = 1. \quad \forall c \in \mathcal{C}$$

Optimal resource allocation policy of the CM operator

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

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

$$p^*_{i,c}(\mathbf{d}) = \frac{\sqrt{L_i/F^c}}{\sum_{j\in O_c(\mathbf{d})}\sqrt{L_j/F^c}}, \forall i \in O_c(\mathbf{d}), \forall c \in \mathcal{C}$$

Equivalent Game under the CM operator

Strategic game played by WDs

- For any allocation policy of the operator, game $\Gamma =< \mathcal{N}, (\mathfrak{D}_i)_i, (C_i)_i >$ played by WDs is a player-specific weighted congestion game

Game Γ under the optimal policy of the CM operator

- We transform Γ into a congestion game Γ^c with resource dependent weights

Offloading cost: $\bar{C}^c{}_{i,a}(\mathbf{d}) = \omega_{i,a} \sum_{j \in O_a(\mathbf{d})} \omega_{j,a} + \omega_{i,c} \sum_{j \in O_c(\mathbf{d})} \omega_{j,c}$

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

- Does strategic game Γ^c have a Nash equilibrium (NE)?

Main Results (CM operator)

NE existence

- Game Γ^c has a NE $\bar{\mathbf{d}}^*$
  - Proof based on exact potential function

Improve Local Computing (ILC) algorithm

- Starts from a strategy profile in which all WDs perform computation locally
- Allows WDs to start to offload in non-increasing order of their task complexities

$AU(\mathbf{d})$

while $\exists\ WD\ j\ s.t.\ d_j \neq \arg\min_{d'_j \in \mathfrak{D}_j} \bar{C}_j(d'_j, d_{-j})$

$\quad d_j^* = \arg\min_{d'_j \in \mathfrak{D}_j} \bar{C}_j(d'_j, d_{-j})$

$\quad \mathbf{d} = (d_j^*, d_{-j})$

end

- Initialization results in minimal number of iterations

Main Results (CM operator)

SPE existence

- The MEC-OG has a SPE $(\bar{\mathbf{d}}^*, \mathbf{u}^*, \mathbf{p}^*)$
  - Optimal provisioning coefficients $\mathbf{u}^*$ and $\mathbf{p}^*$ have closed form expressions
  - ILC algorithm computes an equilibrium $\bar{\mathbf{d}}^*$ of offloading decisions

Price of anarchy (PoA)

- Ratio of worst case NE cost and minimal social cost

$$PoA \leq \frac{3+\sqrt{5}}{2}$$

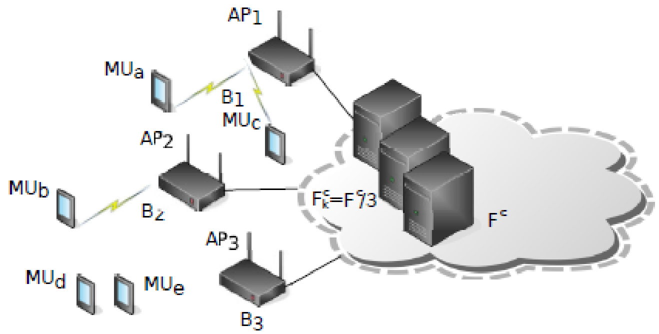
- Provides bound on approximation ratio

The Case of a TF operator

- Game $\Gamma^t = <\mathcal{N}, (\mathfrak{D}_i)_i, (C_i)_i>$ played by WDs under TF operator is a player-specific congestion game

$$\text{Offloading cost: } \widetilde{C^c}_{i,a}(\mathbf{d}) = \frac{D_i}{R_{i,a}} n_a(\mathbf{d}) + \frac{L_i}{F^c} n_c(\mathbf{d})$$

- Γ^t is not a potential game
  - Proof by constructing I-cycle



$$(1,2,1,0,0) \xrightarrow[c]{} (1,2,\color{red}{2}\color{black},0,0) \xrightarrow[b]{} (1,\color{red}{0}\color{black},2,0,0) \xrightarrow[d]{} (1,0,2,\color{red}{2}\color{black},0) \xrightarrow[e]{} (1,0,2,2,\color{red}{2}\color{black})$$
$$\xrightarrow[c]{} (1,0,\color{red}{1}\color{black},2,2) \xrightarrow[b]{} (1,\color{red}{3}\color{black},1,2,2) \xrightarrow[e]{} (1,3,1,2,\color{red}{0}\color{black}) \xrightarrow[d]{} (1,3,1,\color{red}{0}\color{black},0) \xrightarrow[b]{}$$
$$(1,\color{red}{2}\color{black},1,0,0)$$

S. Josilo, G. Dán, ``A Game Theoretic Analysis of Selfish Mobile Computation Offloading," in Proc. of IEEE Infocom, May 2017

S. Josilo, G. Dán, ``Selfish Decentralized Computation Offloading for Mobile Cloud Computing in Dense Wireless Networks," IEEE Trans. on Mobile Computing, vol. 18., no. 1., Jan. 2019, pp. 207-220

Main Results for the TF operator

Γ^t admits a pure NE

Constructive proof

- Join and Plan Asynchronous Updates (JPAU)
  - Starts from empty system
  - Adds WDs one at a time
    - Lets them play their best replies – in a certain order

Computational complexity $O(AN^3)$

$\mathbf{d}^* = JPAU(\mathcal{N}, \mathcal{A}, \mathcal{C})$

```
/*First WD enters the game*/
Let d ← ∅, i ← 1
d*_i(1) = arg min_{d_i ∈ 𝔇_i} C_i(d_i, d_{-i})
d*(1) = d*_i(1)
for n = 2 : N do
    /*Corresponds to induction phase*/
    Let i ← n
    d*_i(n) = arg min_{d_i ∈ 𝔇_i} C_i(d_i, d*_{-i}(n − 1))
    d(n) = (d*_i(n), d*(n − 1))
    if d*_i(n) = (a, c)
        /*Corresponds to update phase*/
        if ∃j∈O_{(a,c)}(d(n)) for which a BR is local computing
            /*Corresponds to case (i)*/
            d'(n) = (j, d_{-j}(n))
        end
    else if ∃j∈O_{(a,c')}(d(n)), c'≠c for which a BR is local computing
        /*Corresponds to case (ii)*/
        d'(n) = (j, d_{-j}(n))
        k ← O_c(d'(n))
        d'(n) = ((·, c'), d'_{-k}(n))
    else if ∃j∈O_a(d(n)), a'≠a for which a BR is changing to AP a'
        /*Corresponds to case (iii)*/
        d'(n) = ((a', ·), d_{-j}(n))
        while ∃j∈O(d'(n)) that can decrease its offloading cost
            d*_j(n) = arg min_{d'_j ∈ 𝔇_j} C_j(d'_j, d'_{-j}(n))
            d'(n) = (d*_j(n), d'_{-j}(n))
        end
    else
        d'(n) = d(n)
    end
    a'' ← a for which n_a(d'(n)) = n_a(d*(n − 1)) + 1
    c ← c' for which n_{c'}(d'(n)) = n_{c'}(d*(n − 1)) + 1
    if ∃j∈O_{(a',c)}(d'(n)), a'≠a'' for which a BR is local computing
        /*Corresponds to case (iv)*/
        d'(n) = (j, d'_{-j}(n))
        if ∃j ∈ O_{a''}(d'(n)) for which a BR is changing to AP a'
            k ← O_{a''}(d'(n))
            d'(n) = ((a', ·), d'_{-k}(n))
        else
            while ∃j∈O(d'(n)) that can decrease its offloading cost
                d*_j(n) = arg min_{d'_j ∈ 𝔇_j} C_j(d'_j, d'_{-j}(n))
                d'(n) = (d*_j(n), d'_{-j}(n))
            end
            if ∃k ∈ 𝒩_n \ O(d'(n)) for which a BR is (a', c)
                d'(n) = ((a', c), d'_{-k}(n))
            end
            if ∃j∈O_{(a',c)}(d'(n)), a'≠a for which a BR is local computing
                go to 35
            end
        end
    end
    d*(n) = d'(n)
end
return d*(N)
```

More Results for the TF operator

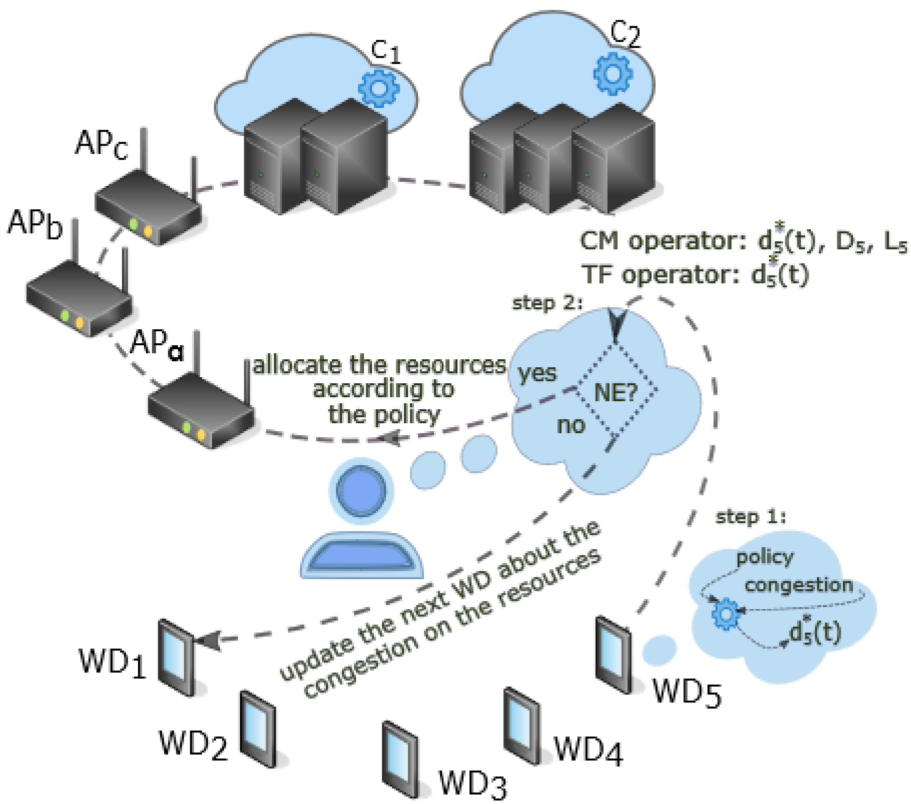
SPE existence

- The MEC-OG has a SPE $(\widetilde{\mathbf{d}}^*, \mathbf{u}^t, \mathbf{p}^t)$
  - Time-fair provisioning coefficients $\mathbf{u}^t$ and $\mathbf{p}^t$
  - JPAU algorithm computes an equilibrium $\widetilde{\mathbf{d}}^*$ of offloading decisions

Price of Anarchy

$$PoA \leq N + 1$$

Decentralized Implementation



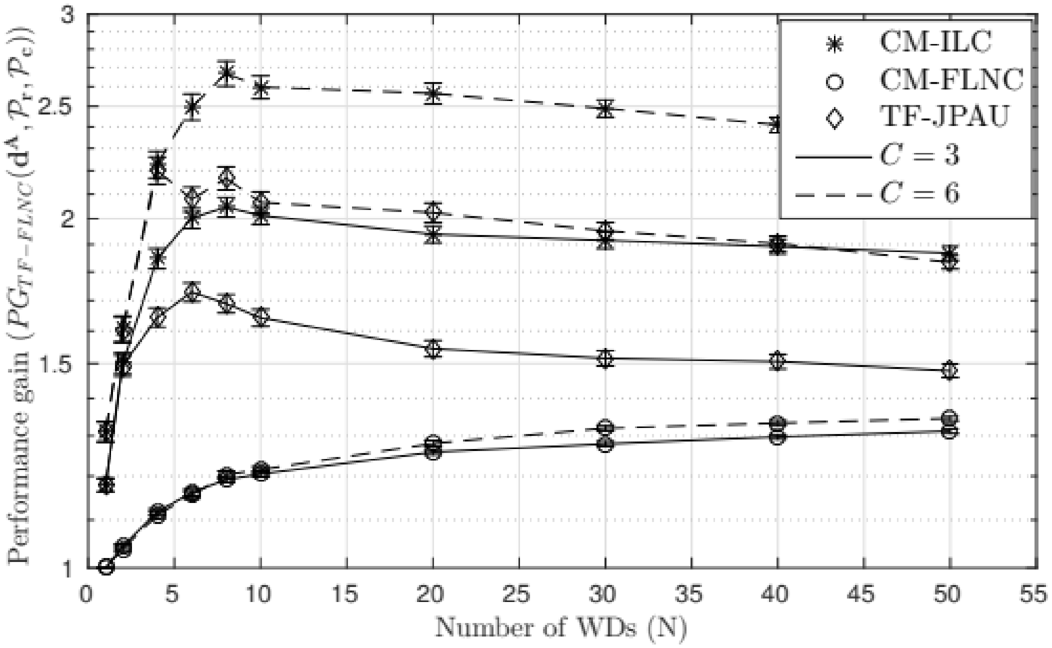
User Focused Performance Analysis

Evaluation scenario

- $A = 5$ APs, heterogeneous ECs $F^{c,tot} = 192$ *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*

Performance gain

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



- *Performance gain* increases with decreasing marginal gain in N
- *Performance gain* increases with the number of edge ECs
- Largest *performance gain*
  - Operator implements OA policy
  - WDs compute offloading decisions using the ILC algorithm

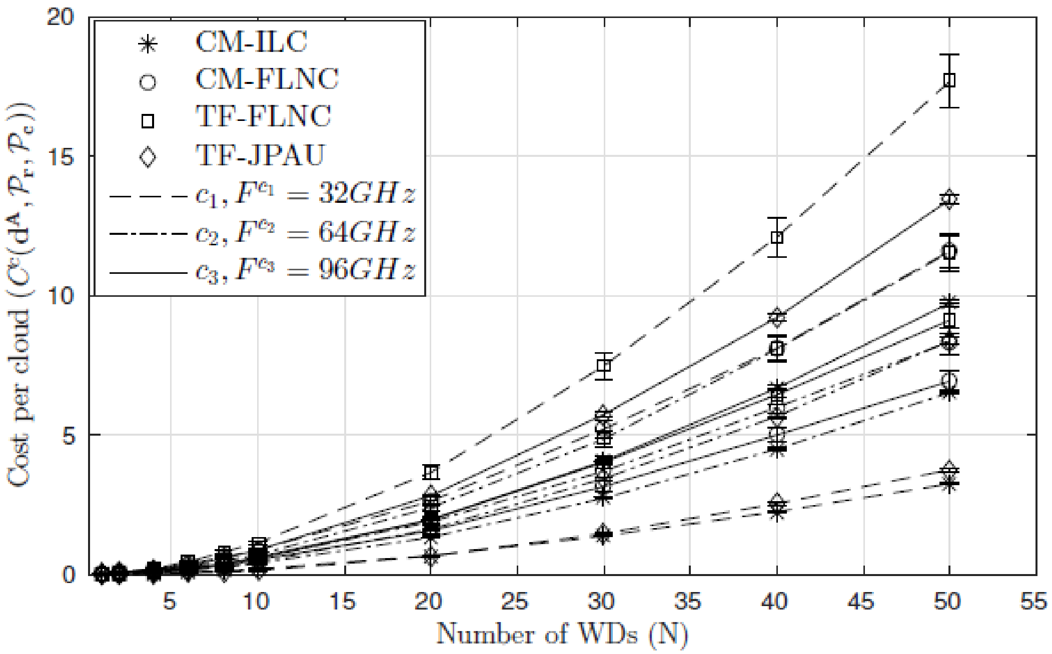
Cloud Focused Performance Analysis

Evaluation scenario

- $A = 5$ APs, $C = 3$ heterogeneous ECs $F^{c,tot} = 192\ Gcycles$
- Tasks: $D_i \sim \mathcal{U}(0.2, 4)\ Mb$, $L_i = D_i X\ Gcycles$, $X \sim \Gamma(0.5, 1.6)\ Gcycles/b$

Cost per cloud

Defined as $C^c(\mathbf{d}) = \sum_{i \in O_c(\mathbf{d})} C_i(\mathbf{d})$



- *Cost per cloud* increases with the number N of WDs
- *Cost per cloud* is proportional to the EC's computing capability in case of equilibria under OA and EA policies

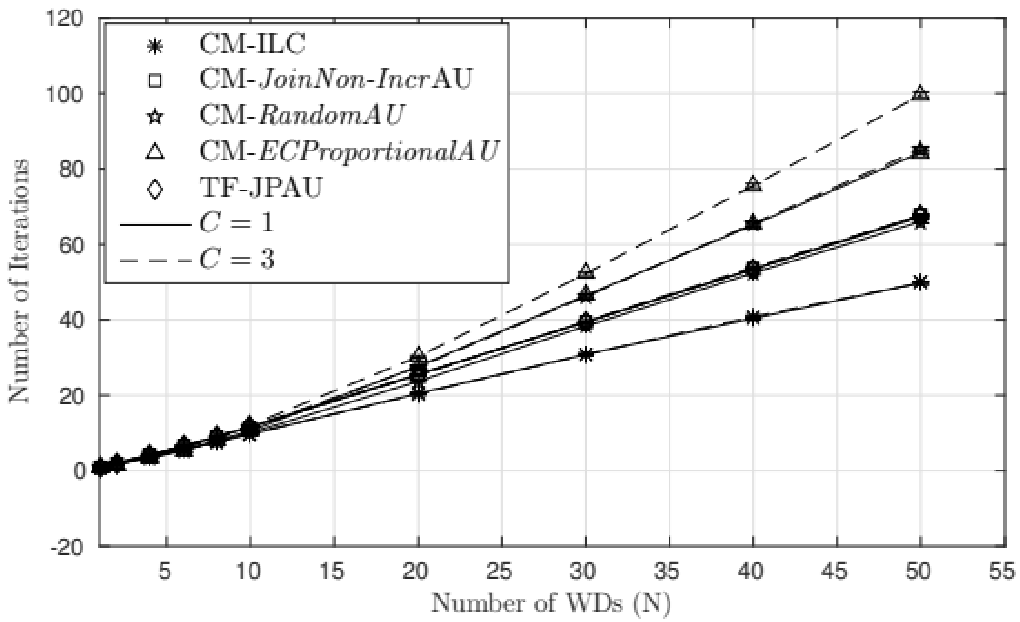
Computational Complexity

Evaluation scenario

- $A = 5$ APs, homogeneous ECs $F^{c,tot} = 192\ Gcycles$
- Tasks: $D_i \sim \mathcal{U}(0.2, 4)\ Mb$, $L_i = D_i X\ Gcycles$, $X \sim \Gamma(0.5, 1.6)\ Gcycles/b$

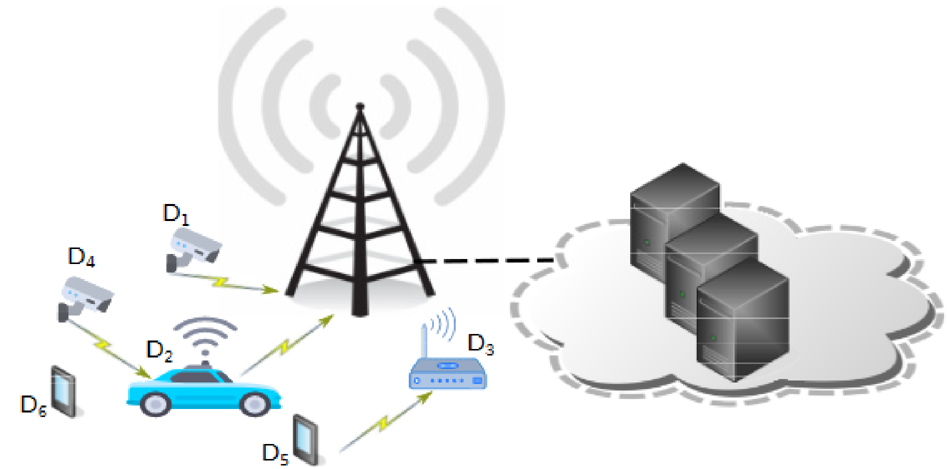
Number of iterations

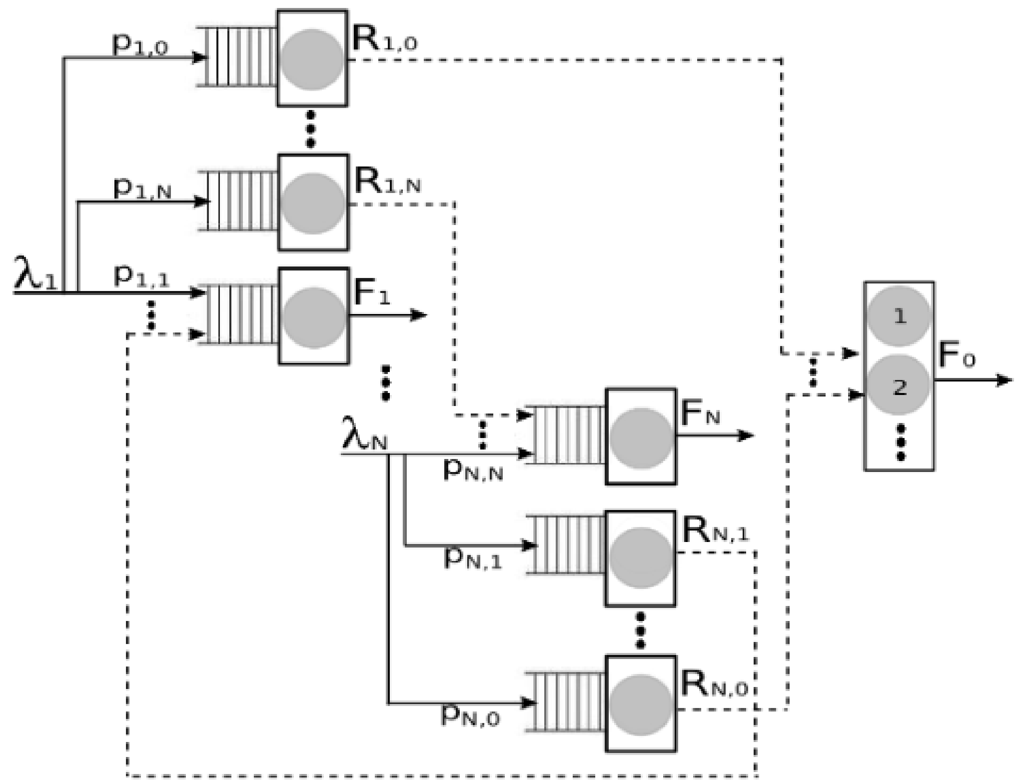
- Randomly chosen strategy profile
- All WDs offload-congestion per EC proportional to its computing capability
- Empty system-WDs added in non-increasing order of their task complexities



- Number of iterations scales approximately linearly with the number N of WDs
- Number of iterations is sensitive to the starting strategy profile
  - Smallest in the case of the ILC algorithm

Alternative Model of Computation Offloading



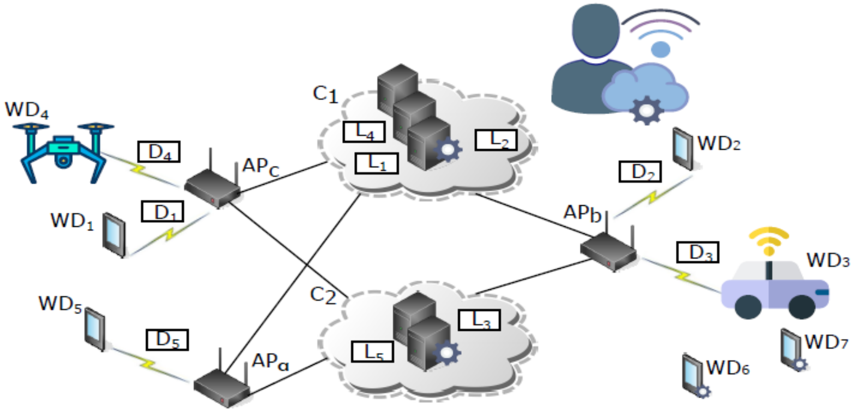


- Offloading to
  - Devices, edge cloud, remote cloud
- Model
  - Stochastic arrival process
  - Transmission and computing times
- Greedy vs. probabilistic offloading
- Results
  - Equilibrium offloading strategy

S. Josilo, G. Dán, ``Decentralized Algorithm for Randomized Task Allocation in Fog Computing Systems," IEEE/ACM Trans. on Networking, vol. 27., no. 1., Feb. 2019, pp. 85-97

Conclusion

- Multi-user computation offloading
  - Joint management of communication and computing resources
  - Multi-user interaction
- Game theoretical approach to resource management
  - Polynomial time decentralized algorithm(s)
  - Approximation ratio bound
- Significant performance gains
  - Compared to uncoordinated behavior
- Many interesting open questions
  - Node-edge-cloud continuum
  - More detailed models of computing



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success securing critical energy infrastructures

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