UAV-Assisted MEC Architecture for Collaborative Task Offloading in Urban IoT Environment

Maximizing User Satisfaction and Service Provider Profit

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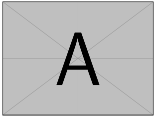

Outline

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Key Innovation

First work to address three-way collaboration between IoTs, UAVs, and Edge Servers while considering both user and SP perspectives

Motivation: Why UAV-Assisted MEC?

Challenges in Urban IoT

- IoT devices: limited processing resources and battery life

UAV Advantages

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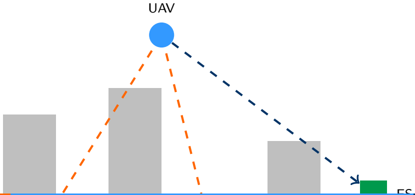

Literature Survey: State-of-the-Art

Research Area	Key Contributions	Limitations

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MEC Task Offloading	• Deep RL approaches • Service caching • Delay minimization	Assumes consistent connectivity; not suitable for urban obstacles

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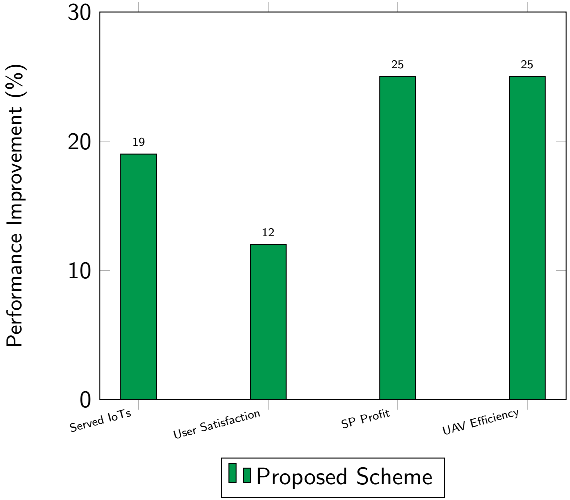
Proposed Approach vs. State-of-the-Art

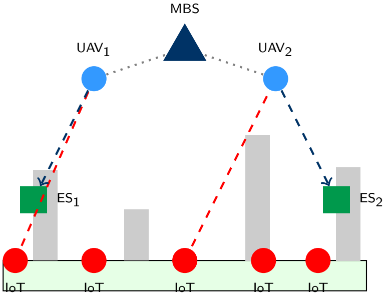


Key Achievements

System Model: Architecture Overview

System Components:

- *M* IoT devices with tasks $T_m = (D_m, C_m, \tau_m)$



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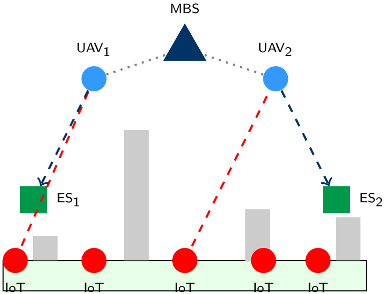

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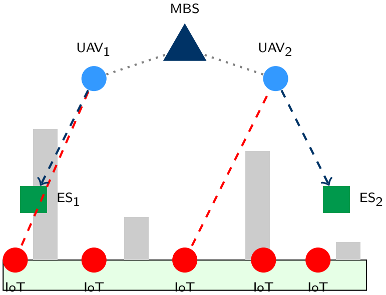

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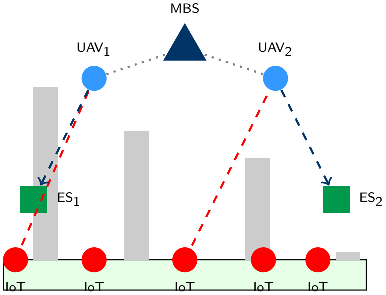

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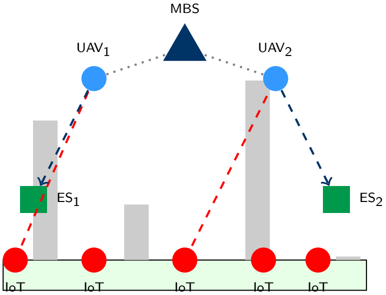

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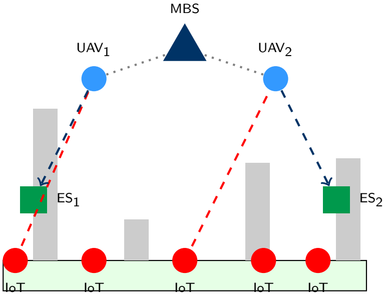

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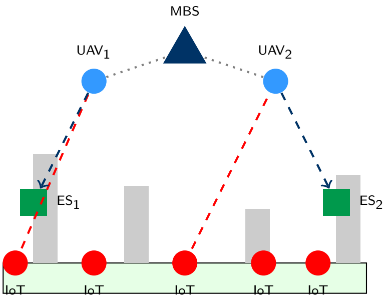

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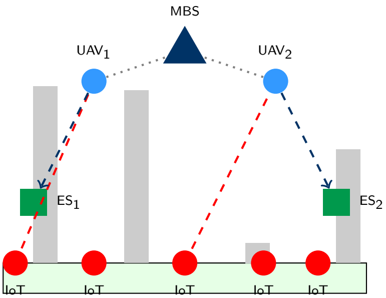

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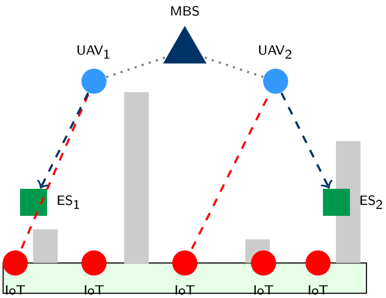

Communication Model:

- Probabilistic LoS path loss
- PRB allocation: N_U per UAV
- SINR threshold: $\Gamma \geq \Gamma_{th}$

Problem Formulation: Objective Function

Service Provider Profit Model

$$\text{Maximize } P_{SP} = \sum_{m=1}^{M} \sum_{k=1}^{K} \sum_{l=1}^{L} \delta_{m,k,l} \cdot P_{m,k,l} - K \cdot C_{UAV}$$

where:

- $\delta_{m,k,l} \in \{0, 1\}$: Offloading decision (IoT $m \to$ UAV $k \to$ ES l)
- $P_{m,k,l} = R_{m,k,l} - C_{m,k,l}$: Profit per successful offload
- $R_{m,k,l} = v \cdot \frac{D_m}{\tau_m}$: Revenue (proportional to data rate)
- $C_{m,k,l} = w \cdot \frac{D_m}{t_l^{proc}}$: ES leasing cost
- $K \cdot C_{UAV}$: UAV operational cost

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Total Delay Constraint

$$t_{m,k,l} = \underbrace{t_{m,k,l}^{trans}}_{\text{Transmission delay}} + \underbrace{t_l^{proc}}_{\text{Processing delay}} \leq \tau_m$$

Problem Formulation: Optimization Problem

Joint Optimization Problem (P1)

$$\max_{\Delta, K, X_U, Y_U} \quad P_{SP}$$

$$\text{subject to:} \quad \sum_{k=1}^{K}\sum_{l=1}^{L}\delta_{m,k,l} \leq 1, \quad \forall m \in \{1,\ldots,M\} \quad \text{(Each IoT paired once)}$$

$$\sum_{m=1}^{M}\sum_{l=1}^{L}\delta_{m,k,l} \leq N_U, \quad \forall k \in \{1,\ldots,K\} \quad \text{(UAV capacity)}$$

$$\sum_{m=1}^{M}\sum_{k=1}^{K}\delta_{m,k,l} \leq N_S, \quad \forall l \in \{1,\ldots,L\} \quad \text{(ES capacity)}$$

$$\sum_{m=1}^{M}\sum_{k=1}^{K}\sum_{l=1}^{L}\delta_{m,k,l} \geq \zeta M \quad \text{(Min service demand)}$$

$$\Gamma_{m,k}, \Gamma_{k,l} \geq \Gamma_{th} \quad \text{(SINR threshold)}$$

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Problem Decomposition Strategy

Joint Optimization Problem (P1)
NP-Hard: Offloading + Topology

Subproblem 1 (P2)
Offload Strategy Optimization

Subproblem 2 (P4)
UAV Topology Optimization

Solution: R-TMSC Algorithm

(Three-sided Matching)

Solution: K-means Iterative Algorithm

(Clustering-based positioning)

Iterative Joint Optimization

Proposed Solution: R-TMSC Algorithm

Three-Sided Matching with Cyclic Preferences

Key Insight: Agents have cyclic preference structure

1. IoT devices prefer UAVs with **better SINR**

Proposed Solution: R-TMSC Algorithm

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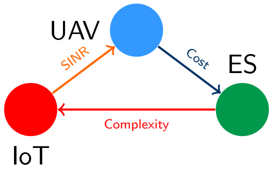
Preference Lists:

- PL_{I_m}: UAVs sorted by $\Gamma_{m,k}$ (descending)
- PL_{U_k}: ESs sorted by q_l (ascending)
- PL_{S_l}: IoTs sorted by $D_m C_m$ (ascending)



R-TMSC Matching Algorithm

Algorithm 1 R-TMSC Offloading

Initialize $M_t = \emptyset$
while not converged **do**
  for each IoT I_m **do**
    Find $U^* = Z_{I_m} \cap Z^*_{I_m}$
    if $U^* \neq \emptyset$ **then**
      $U_k = \text{Head}(U^*)$
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      $S_l = \text{Head}(S^*)$
      Update M_t with (I_m, U_k, S_l)
    end if
  end for
end while
return M_t (stable matching set)

Key Concepts:

- M_t: Set of matching triplets (I_m, U_k, S_l)

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- Z_{I_m}: UAVs preferred over current match

R-TMSC Matching Algorithm

Algorithm 3 R-TMSC Offloading

```
Initialize M_t = ∅
while not converged do
    for each IoT I_m do
        Find U* = Z_{I_m} ∩ Z*_{I_m}
        if U* ≠ ∅ then
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Properties:

- Finds stable matching
- Satisfies all constraints
- Maximizes number of served IoTs

UAV Topology Optimization: K-means Approach

Objectives:

- Determine minimum number of UAVs K

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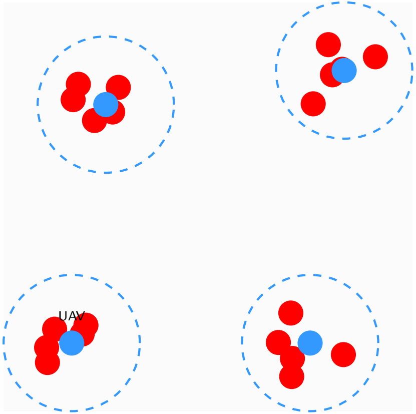

K-means Clustering Result

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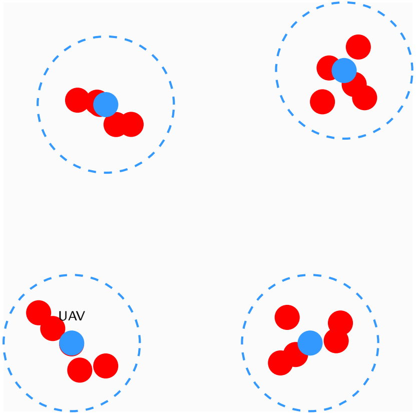
Iterative Process:

1. Start with $K_{initial} = \lceil M/N_U \rceil$
2. Cluster IoT locations using K-means



K-means Clustering Result

UAV Topology Optimization: K-means Approach

Objectives:

- Determine minimum number of UAVs K
- Find optimal positions (x_{U_k}, y_{U_k})
- Ensure $\geq \zeta\%$ IoTs are served

Iterative Process:

1. Start with $K_{initial} = \lceil M/N_U \rceil$
2. Cluster IoT locations using K-means
3. Position UAV at cluster centroid:

$$x_{U_k} = \frac{1}{N_{CL_k}} \sum_{I_m \in CL_k} x_{I_m}$$

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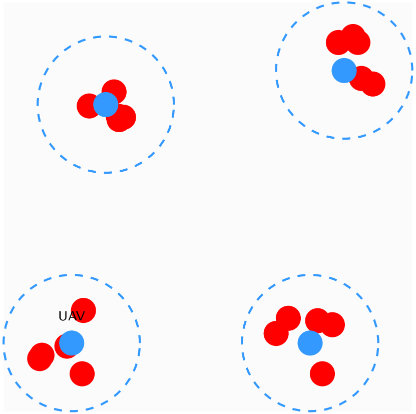

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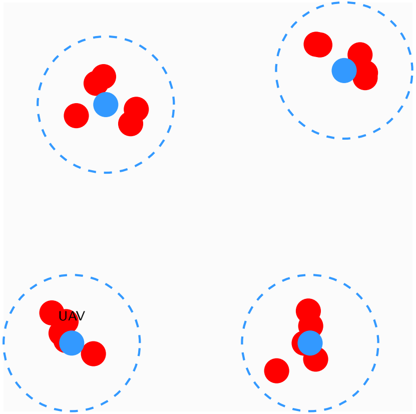
4. Update K based on service coverage



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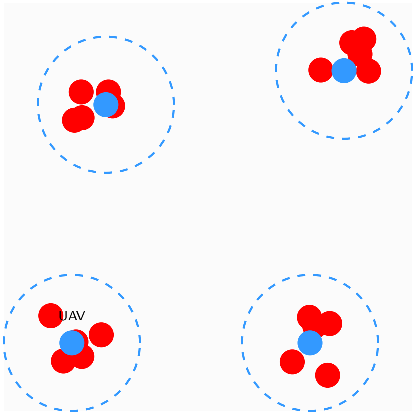

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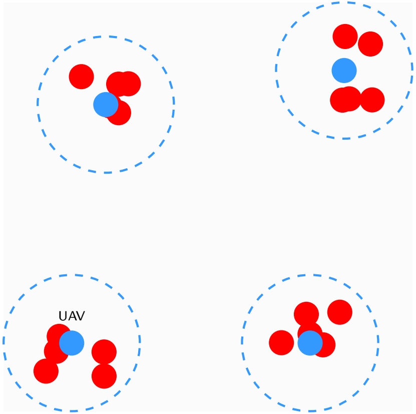
5. Iterate until convergence



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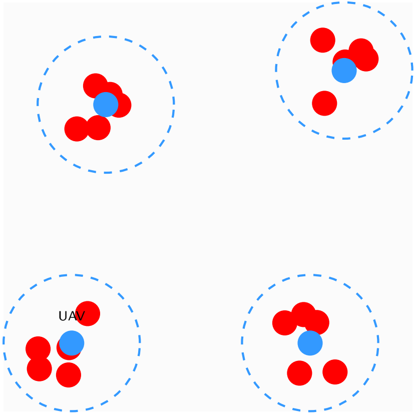
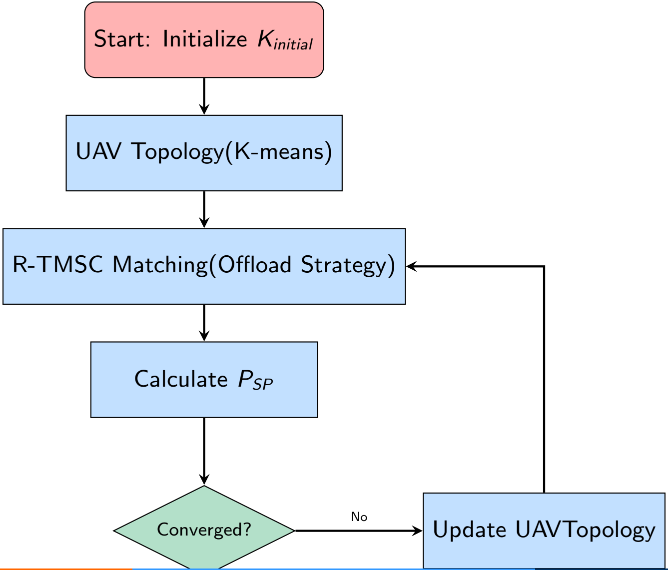


K-means Clustering Result

Advantages:

Joint Optimization: Putting It All Together



Implementation Plan: System Architecture

Hardware Components:

- **IoT Devices**

Software Modules:

Implementation Plan: System Architecture

Hardware Components:

- **IoT Devices**
  - Sensors, cameras, etc.

Software Modules:

Implementation Plan: System Architecture

Hardware Components:

- **IoT Devices**
  - Sensors, cameras, etc.
  - Generate computation tasks

Software Modules:

Implementation Plan: System Architecture

Hardware Components:

- **IoT Devices**
  - Sensors, cameras, etc.
  - Generate computation tasks
  - Limited processing power

Software Modules:

Implementation Plan: System Architecture

Hardware Components:

- **IoT Devices**
  - Sensors, cameras, etc.
  - Generate computation tasks
  - Limited processing power
- **UAV Fleet**

Software Modules:

Implementation Plan: System Architecture

Hardware Components:

- **IoT Devices**
  - Sensors, cameras, etc.
  - Generate computation tasks
  - Limited processing power
- **UAV Fleet**
  - Communication relay nodes

Software Modules:

Implementation Plan: System Architecture

Hardware Components:

- **IoT Devices**
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- **UAV Fleet**
  - Communication relay nodes
  - Fixed altitude deployment

Software Modules:

Implementation Plan: System Architecture

Hardware Components:

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Software Modules:

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Software Modules:

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Software Modules:

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Software Modules:

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Software Modules:

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Software Modules:

1. **Communication Module**

Implementation Plan: System Architecture

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Software Modules:

1. **Communication Module**
   - LoS path loss calculation

Implementation Plan: System Architecture

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  - Algorithm execution

Software Modules:

1. **Communication Module**
   - LoS path loss calculation
   - SINR measurement

Implementation Plan: System Architecture

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Software Modules:

1. **Communication Module**
   - LoS path loss calculation
   - SINR measurement
   - PRB allocation

Implementation Plan: System Architecture

Hardware Components:

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Software Modules:

1. **Communication Module**
   - LoS path loss calculation
   - SINR measurement
   - PRB allocation
2. **Task Management**

Implementation Plan: System Architecture

Hardware Components:

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Software Modules:

1. **Communication Module**
   - LoS path loss calculation
   - SINR measurement
   - PRB allocation
2. **Task Management**
   - Task queue at UAVs

Implementation Plan: System Architecture

Hardware Components:

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Software Modules:

1. **Communication Module**
   - LoS path loss calculation
   - SINR measurement
   - PRB allocation
2. **Task Management**
   - Task queue at UAVs
   - Buffer management

Implementation Plan: System Architecture

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Software Modules:

1. **Communication Module**
   - LoS path loss calculation
   - SINR measurement
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2. **Task Management**
   - Task queue at UAVs
   - Buffer management
   - Delay monitoring

Implementation Plan: System Architecture

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Software Modules:

1. **Communication Module**
   - LoS path loss calculation
   - SINR measurement
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   - Buffer management
   - Delay monitoring
3. **Optimization Engine**

Implementation Plan: System Architecture

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   - R-TMSC algorithm

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4. **Monitoring & Analytics**

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4. **Monitoring & Analytics**
   - Performance metrics

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   - Preference list generation
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   - Performance metrics
   - User satisfaction tracking

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   - Performance metrics
   - User satisfaction tracking
   - Profit calculation

Implementation Plan: Deployment Steps

Phase 1: System Initialization

1. Deploy ESs at strategic urban locations with 5G infrastructure
2. Configure ES computing capacities $\{q_1, q_2, \ldots, q_L\}$
3. Set system parameters: N_U, N_S, Γ_{th}, ζ, altitude H
4. Initialize MBS coordination framework

Implementation Plan: Deployment Steps

Phase 1: System Initialization

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Phase 2: UAV Deployment

1. Collect IoT device position data $Q_I = \{Q_{I_m}, m = 1, \ldots, M\}$
2. Calculate initial UAV count: $K_{initial} = \lceil M/N_U \rceil$
3. Apply K-means clustering to determine UAV positions (x_{U_k}, y_{U_k}, H)
4. Deploy UAVs at calculated positions

Implementation Plan: Deployment Steps

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Phase 3: Preference List Generation

1. Measure SINR for all IoT-UAV pairs: $\Gamma_{m,k}$
2. Measure SINR for all UAV-ES pairs: $\Gamma_{k,l}$

Implementation Plan: Operational Workflow

Phase 4: Task Offloading Execution

1. IoT devices submit task requests $T_m = (D_m, C_m, \tau_m)$ to MBS
2. MBS executes R-TMSC algorithm to find stable matching set M_t
3. Generate offloading strategy $\Delta = \{\delta_{m,k,l}\}$ from M_t
4. Communicate assignments to IoTs, UAVs, and ESs
5. Execute task offloading: IoT $\rightarrow$ UAV $\rightarrow$ ES
6. Monitor delay constraints and SINR thresholds

Implementation Plan: Operational Workflow

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6. Monitor delay constraints and SINR thresholds

Phase 5: Dynamic Optimization

1. Calculate current SP profit: P_{SP}
2. Evaluate service coverage: percentage of served IoTs
3. If service coverage $< \zeta$: Increase UAV count and reposition
4. If service coverage $> \zeta$: Try to reduce UAV count (cost optimization)
5. Update UAV topology using K-means iterative algorithm

Implementation Plan: Performance Monitoring

Real-time Metrics:

- Number of active IoT devices
- Served IoT percentage
- Average task completion delay
- SINR distribution
- UAV buffer utilization
- ES computational load

Implementation Plan: Performance Monitoring

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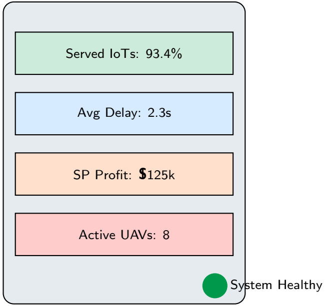
Business Metrics:

- Revenue from task offloading
- ES leasing costs
- UAV operational costs
- Overall SP profit
- User satisfaction scores

Monitoring Dashboard



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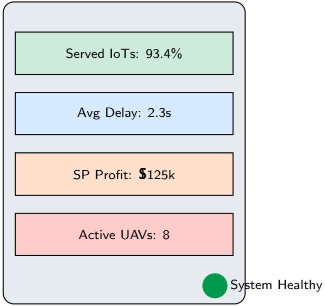
Monitoring Dashboard



Adaptive Actions:

- Trigger re-optimization on significant changes
- Alert on constraint violations
- Automatic UAV repositioning

Simulation Setup and Parameters

Environment Setup:

- Area: 1 km $\times$ 1 km urban region
- IoT distribution: Uniform random
- ES positions: Fixed strategic locations
- UAV altitude: 100-150m
- Communication: 5G NR at 2.4 GHz

System Parameters:

- IoT devices: $M \in [50, 300]$
- Edge Servers: $L \in [4, 12]$
- UAV capacity: $N_U = 20$ IoTs
- ES capacity: $N_S = 40$ tasks
- Service threshold: $\zeta = 90\%$

Task Characteristics:

- Data size: $D_m \in [0.5, 5]$ MB
- CPU cycles: $C_m \in [500, 1500]$ cycles/bit
- Max delay: $\tau_m \in [1, 10]$ seconds

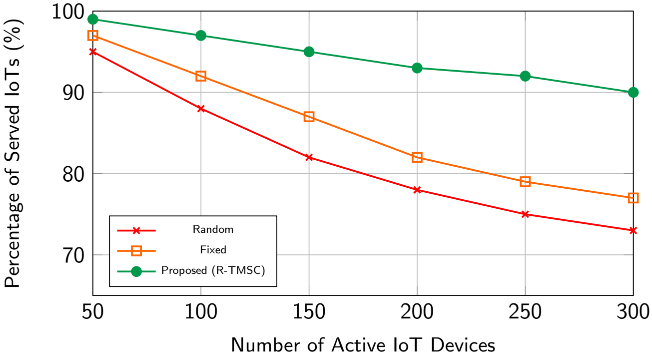
Pricing Model:

- Revenue param: $v = 0.1$ \$/Mbps
- Cost param: $w = 0.01$ \$/Mbps
- UAV cost: $C_{UAV} = 100$ \$/UAV

Benchmark Schemes:

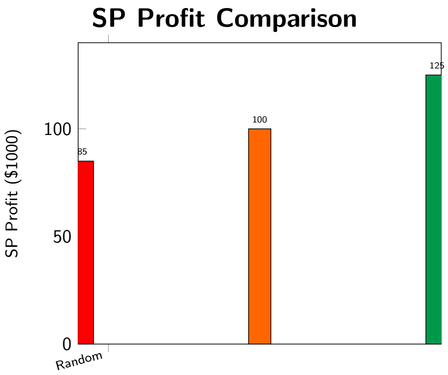
1. Fixed Offloading: Predefined associations
2. Random Offloading: Random pairing
3. Proposed R-TMSC: Our scheme

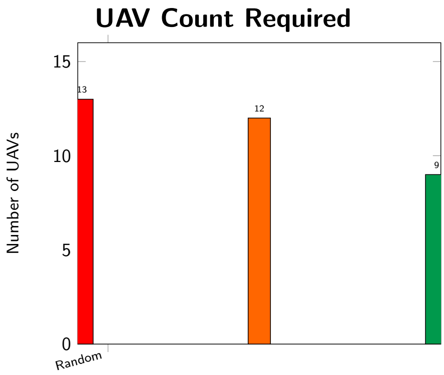
Results: Performance Comparison



- **Proposed scheme achieves 93.4% average served IoT percentage**
- **19% improvement** over Fixed and **28% improvement** over Random
- Maintains high performance even with increasing IoT density

Results: SP Profit and UAV Efficiency





Key Findings

- **25% higher SP profit** with proposed scheme
- **25% fewer UAVs required compared to benchmarks**

Conclusion and Future Work

Key Contributions

- Novel **UAV-assisted MEC architecture** for urban IoT environments
- First work addressing **three-sided collaboration** (IoT-UAV-ES) with **SP profit maximization**
- **R-TMSC algorithm** for stable matching based on cyclic preferences
- **K-means iterative algorithm** for optimal UAV topology
- Comprehensive evaluation showing **significant performance improvements**

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Performance Highlights

- ✓ 19% more IoTs served
- ✓ 25% higher SP profit
- ✓ 12% better user satisfaction
- ✓ 25% fewer UAVs required

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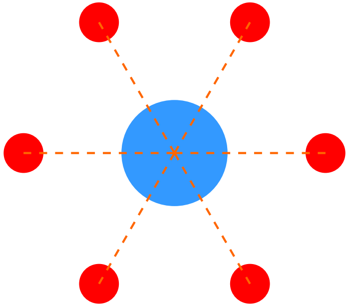
Future Research Directions

- Extension to **dynamic IoT mobility scenarios**

Thank You!

Questions & Discussion



Backup Slides

Additional Technical Details

Mathematical Formulation: Detailed Communication Model

Path Loss Model

$$PL_{i,j} = \beta_0 d_{i,j}^2 \left(P_{i,j}^{LoS} \mu^{LoS} + P_{i,j}^{NLoS} \mu^{NLoS} \right)$$

where:

- $\beta_0 = (4\pi f/c)^2$: Free space path loss at reference distance
- $d_{i,j} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2 + H^2}$: Euclidean distance
- $P_{i,j}^{LoS} = \frac{1}{1+a\exp(-b(\theta_{i,j}-a))}$: LoS probability
- $\theta_{i,j} = \sin^{-1}(H/d_{i,j})$: Elevation angle

SINR and Data Rate

$$\Gamma_{i,j} = \frac{P_i/PL_{i,j}}{\sum_{i' \neq i} P_{i'}/PL_{i',j} + N_0}, \quad r_{i,j} = B_{i,j} \log(1 + \Gamma_{i,j})$$

Algorithm Complexity Analysis

Algorithm Component	Complexity	Explanation
R-TMSC Matching	$O(n_1 \cdot MKL)$	n_1 iterations, matching triplets
K-means Topology	$O(n_2 \cdot K)$	n_2 iterations, update positions
Joint Optimization	$O(n \cdot [n_1 MKL + n_2 K])$	n outer iterations

Practical Performance

- Typical values: $n = 4$, $n_1 = 3$, $n_2 = 2$
- For $M = 200$, $K = 10$, $L = 8$: Total complexity $\approx O(19.2 \times 10^4)$
- Execution time: 60ms per outer iteration, 240ms total
- **Suitable for quasi-static scenarios** (minutes to hours)

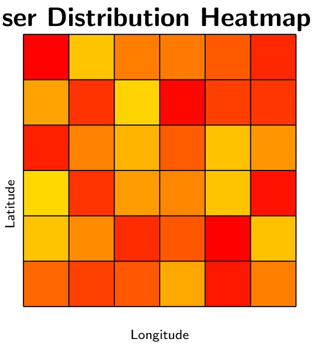
Real-World Dataset Validation

China Mobile User Dataset:

- Real user geolocation data
- Region: 22.5-23.3°N, 112.5-114.8°E
- Time window: 10 AM - 12 PM
- 15-minute time slots

Results:

- 10% higher served percentage vs. Fixed
- 28% higher served percentage vs. Random
- $1.2\times$ SP profit compared to Fixed
- $1.5\times$ SP profit compared to Random



Validates robustness in non-uniform distributions