Potential Game based Channel Allocation for Vehicular Edge Computing

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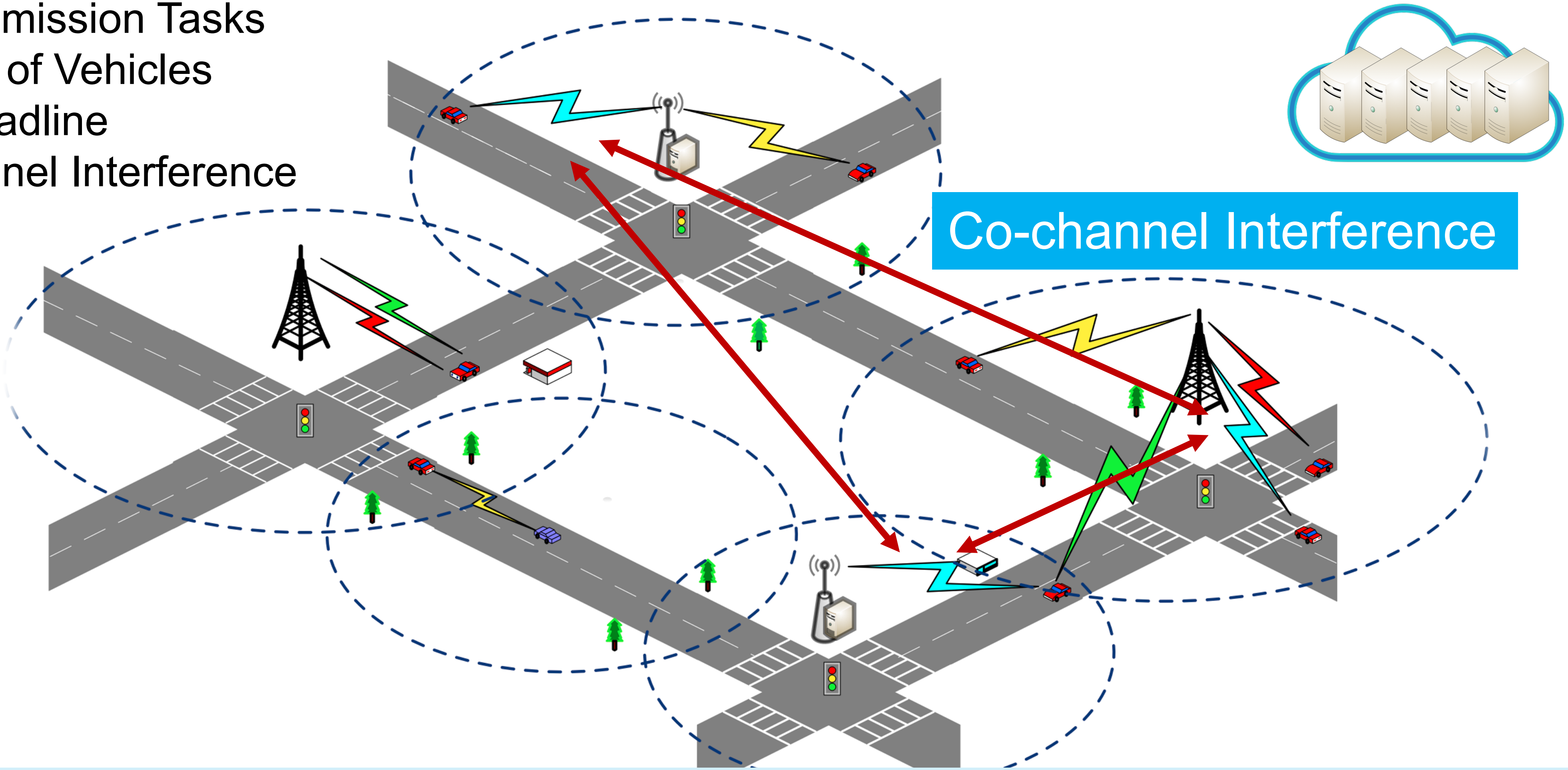
Introduction Vehicular Edge Computing Architecture

Data Transmission Tasks
- Mobility of Vehicles
- Task Deadline
- Co-channel Interference



Objective: Allocating sub-channels for different data transmission tasks and maximizing the number of completed tasks

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Problem Formulation **Mobility-aware Communication Model**

- Signal to Interference and Nosie Ratio, SINR

$$\mu_{nm}^{k}(t_i) = \frac{\underbrace{\boxed{|h_{nm}|^2 \cdot \Psi \cdot d_{nm}(t_i)^{-\lambda} \cdot p_n}}_{\text{Signal}}}{\underbrace{\boxed{\sum_{x=1,x\neq n}^{|E(t_i)|} \sum_{y=1}^{|B(t_i)|} |h_{xm}|^2 \Psi d_{xm}(t_i)^{-\lambda} p_x \mathbb{I}_{xy}^{k}(t_i)}}_{\text{Co-channel Interference}} + N_0}$$

- Transmission Rate

$$\boxed{\delta_{nm}^{k}(t_i)} = \omega_n \log_2\left(1 + \mu_{nm}^{k}(t_i)\right)$$

- Transmission Data Size

$$\boxed{z_{nm}^{k}} = \int_{t_i}^{min\left(t_{mi}^{e}, t_i + t_{mi}^{c}\right)} \delta_{nm}^{k}(t)\, dt$$

Problem Formulation **Channel Allocation Problem**

- Allocation Strategy

$A(t_i) \in \{0,1\}^{|E(t_i)|\times|B(t_i)|\times|Q|}$ $\quad a_{nm}^{k}(t_i) = 1$ $\quad \mathbb{A}(t_i) = \prod_{j=i}^{|T|} A(t_j) = A(t_i)\times A(t_{i+1})\times\cdots\times A(t_{|T|})$

- Objective Function

$$\sum_{i=1}^{|T|} \max_{\mathbb{A}(t_i)} \sum_{m=1}^{|B(t_i)|} \boxed{\mathbb{I}_{z_{mi}\le\sum_{n=1}^{|E(t_i)|}\sum_{k=1}^{|Q_n(t_i)|}\int_{t_i}^{t_i+\beta\sum_{j=i}^{|T|}a_{nm}^{k}(t_j)}\delta_{nm}^{k}(t)\,\mathrm{d}t}}$$

Task Completion Indicator

$$s.t.\begin{cases} C1: a_{nm}^{k}(t_i) \in \{0,1\}, \forall e_n \in E(t_i), \forall b_m \in B(t_i), \forall q_k \in Q_n(t_i), \forall t_i \in T \\ C2: a_{nm}^{k}(t_i) = 0, \text{if } d_{nm}(t_i) > c_n \\ C3: a_{nm}^{k}(t_i) = 0, \text{if } q_k \notin Q_n(t_i) \\ C4: \sum_{m=1}^{|B_i|} a_{nm}^{k}(t_i) \le 1, \forall q_k \in Q_n(t_i) \\ C5: \sum_{j=i}^{|T|} a_{nm}^{k}(t_j) \le \left\lfloor \frac{min(t_m(t_i)-t_i, t_m^c)}{\beta} \right\rfloor \end{cases}$$

$C2$ Vehicles can only be allocated channels within the coverage of edge nodes

$C3$ The channel allocated by the edge node must be the currently available channel

$C4$ Each channel of the edge node is assigned to at most one task

$C5$ The total length of the channel occupation time slice needs to be less than the task deadline and the channel maintenance time

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Potential Game Model **Distributed Game Transformation**

Edge Nodes

Allocation Strategy

Players

Strategies

$A(t_i) \in \{0,1\}^{|E(t_i)|\times|B(t_i)|\times|Q|}$

$a_n(t_i) \in \{0,1\}^{|B(t_i)|\times|Q_n(t_i)|\times||T|-i+1|}$

$$\sum_{i=1}^{|T|} \max_{\mathbb{A}(t_i)} \boxed{\sum_{m=1}^{|B(t_i)|} \mathbb{1}_{z_{mi} \le \sum_{n=1}^{|E(t_i)|} \sum_{k=1}^{|Q_n(t_i)|} \int_{t_i}^{t_i+\beta\sum_{j=i}^{|T|} a_{nm}^k(t_j)} \delta_{nm}^k(t)\, \mathrm{dt}}}$$

$$u_n(a_n(t_i), \boldsymbol{a}_{-n}(t_i)) = \sum_{m=1}^{|B(t_i)|} \mathbb{1}_{z_{mi} \le \sum_{n=1}^{|E(t_i)|} \sum_{k=1}^{|Q_n(t_i)|} \int_{t_i}^{t_i+\beta\sum_{j=i}^{|T|} a_{nm}^k(t_j)} \delta_{nm}^k(t)\, \mathrm{dt}}$$

- Potential Function

$$\phi_n(a_n(t_i), \boldsymbol{a}_{-n}(t_i)) = \sum_{m=1}^{|B(t_i)|} \mathbb{1}_{z_{mi}-\theta_{m,E(t_i)/\{n\}} \le \sum_{k=1}^{|Q_n(t_i)|} \int_{t_i}^{t_i+\beta\sum_{j=i}^{|T|} a_{nm}^k(t_j)} \delta_{nm}^k(t)\, dt}$$

- Exact Potential Game

$$u_n(a_n(t_i)^*, \boldsymbol{a}_{-n}(t_i)) - u_n(a_n(t_i), \boldsymbol{a}_{-n}(t_i)) = \phi_n(a_n(t_i)^*, \boldsymbol{a}_{-n}(t_i)) - \phi_i(a_n(t_i), \boldsymbol{a}_{-n}(t_i))$$

Theorem: Given the potential function of the game, the channel allocation game is an exact potential game, which possesses at least one Nash Equilibrium

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Algorithm Design **Incentive-based Probability Update and Strategy Selection (IPUS²)**

Initialization

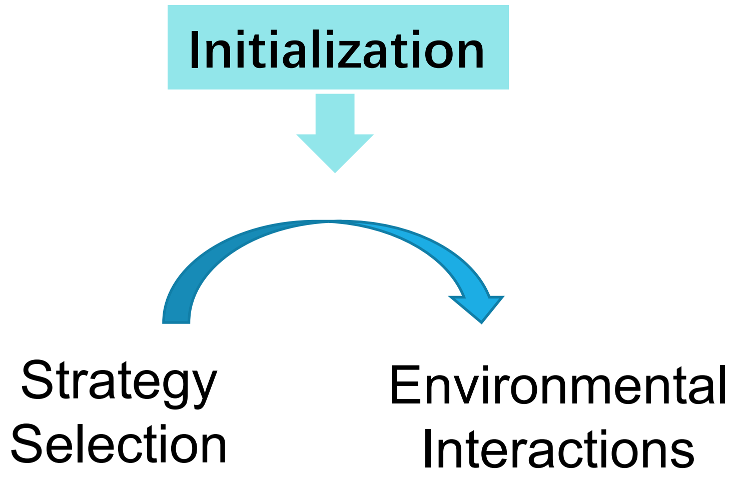
- Strategy Selection Probability

$$x_{n,0}\left(a_n(t_i)\right) = 1/|\mathcal{A}_n(t_i)|$$

	a_1	a_2
b_1	0.5, 0.5	1, 1
b_2	1, 1	2, 2

Iteration	0	1	2	3	4
Strategy	/	$a_1 b_1$	$a_2 b_1$	$a_1 b_1$	$a_2 b_2$
$s(a_1)$	0	0	0	-0.5	0
$s(a_2)$	0	0	1	0	2
$s(b_1)$	0	0	1	-0.5	0
$s(b_2)$	0	0	0	0	2
$x_A(a_1)$	0.5	0.5	0.5	0.375	0.375
$x_A(a_2)$	0.5	0.5	0.75	0.75	1
$x_B(b_1)$	0.5	0.5	0.75	0.6625	0.6625
$x_B(b_2)$	0.5	0.5	0.5	0.5	1

Algorithm Design **Incentive-based Probability Update and Strategy Selection (IPUS^2)**



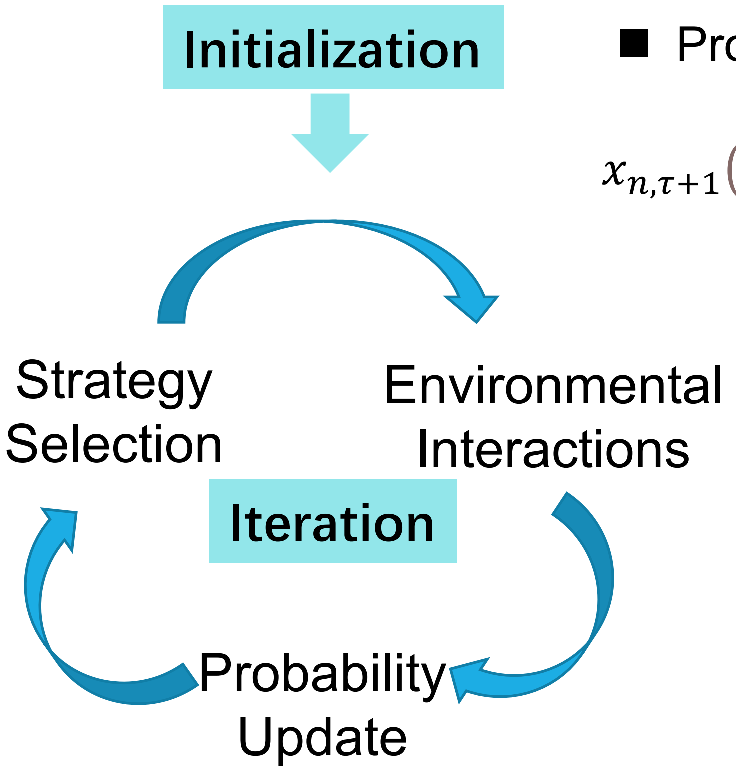
- Probability Update Value

$$s_n(a_n(t_i)) = \frac{\xi_n(a_n(t_i)) - max(\Xi_n(\mathcal{A}_n(t_i)))}{max(\Xi_n(\mathcal{A}_n(t_i)))}$$

	a_1	a_2
b_1	0.5, 0.5	1, 1
b_2	1, 1	2, 2

Iteration	0	1	2	3	4
Strategy	/	$a_1 b_1$	$a_2 b_1$	$a_1 b_1$	$a_2 b_2$
$s(a_1)$	0	(0.5-0.5)/0.5	0	-0.5	0
$s(a_2)$	0	0	1	0	2
$s(b_1)$	0	(0.5-0.5)/0.5	1	-0.5	0
$s(b_2)$	0	0	0	0	2
$x_A(a_1)$	0.5	0.5	0.5	0.375	0.375
$x_A(a_2)$	0.5	0.5	0.75	0.75	1
$x_B(b_1)$	0.5	0.5	0.75	0.6625	0.6625
$x_B(b_2)$	0.5	0.5	0.5	0.5	1

Algorithm Design **Incentive-based Probability Update and Strategy Selection (IPUS²)**



- Probability Update Function

$$x_{n,\tau+1}(a_n(t_i)) = \begin{cases} x_{n,\tau}(a_n(t_i)) + \eta s_n(a_n(t_i))\left(1 - x_{n,\tau}(a_n(t_i))\right) & s_n(a_n(t_i)) \geq 0 \\ x_{n,\tau}(a_n(t_i)) + \eta s_n(a_n(t_i)) x_{n,\tau}(a_n(t_i)) & s_n(a_n(t_i)) < 0 \end{cases}$$

	a_1	a_2
b_1	0.5, 0.5	1, 1
b_2	1, 1	2, 2

Iteration	0	1	2	3	4
Strategy	/	$a_1 b_1$	$a_2 b_1$	$a_1 b_1$	$a_2 b_2$
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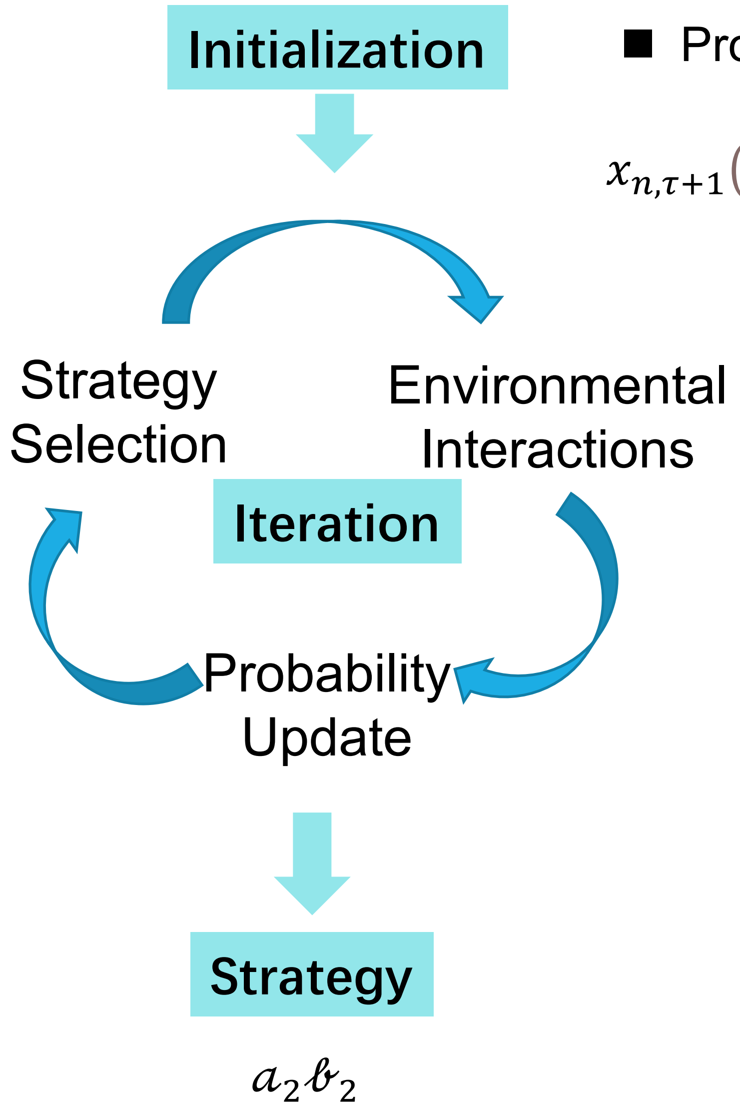
$s(b_1)$	0	0	1	-0.5	0
$s(b_2)$	0	0	0	0	2
$x_A(a_1)$	0.5	0.5	0.5	0.375	0.375
$x_A(a_2)$	0.5	0.5	0.75	0.75	1
$x_B(b_1)$	0.5	0.5	0.75	0.6625	0.6625
$x_B(b_2)$	0.5	0.5	0.5	0.5	1

Algorithm Design **Incentive-based Probability Update and Strategy Selection (IPUS²)**



- Probability Update Function

$$x_{n,\tau+1}(a_n(t_i)) = \begin{cases} x_{n,\tau}(a_n(t_i)) + \eta s_n(a_n(t_i))\left(1 - x_{n,\tau}(a_n(t_i))\right) & s_n(a_n(t_i)) \geq 0 \\ x_{n,\tau}(a_n(t_i)) + \eta s_n(a_n(t_i)) x_{n,\tau}(a_n(t_i)) & s_n(a_n(t_i)) < 0 \end{cases}$$

	a_1	a_2
b_1	0.5 / 0.5	1 / 1
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$x_A(a_2)$	0.5	0.5	0.75	0.75	$\boxed{1}$
$x_B(b_1)$	0.5	0.5	0.75	0.6625	0.6625
$x_B(b_2)$	0.5	0.5	0.5	0.5	$\boxed{1}$

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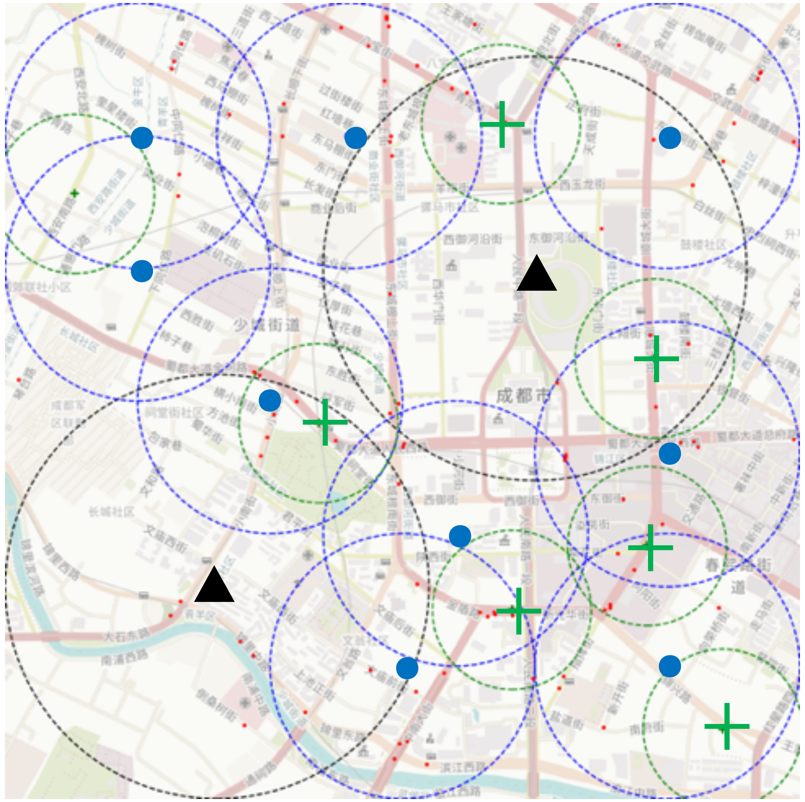
Performance Evaluation **Experiment Settings**

■ Experiment Dataset

- Taxi Trajectories in 3x3 km Area of Chengdu City
- 2 Base Stations, 9 RSUs, 5 Vehicular Edge Nodes



▲ Base Station ● RSU + Vehicular Edge Node

■ Price of Anarchy, PoA

$$\mathrm{PoA} = \frac{\max_{a\in\mathbb{A}} w(a)}{\min_{a^*\in\mathbb{A}^{\mathrm{NE}}} w(a^*)}$$

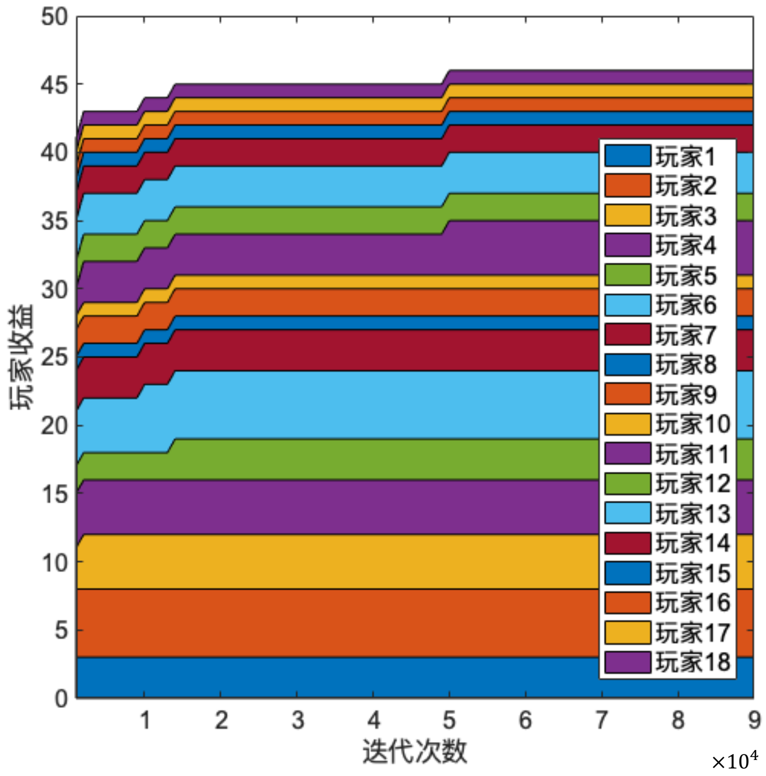
■ Task Completion Ratio

$$\mathcal{U}(t_i) = \frac{\sum_{m=1}^{|B(t_i)|} \mathbb{1}_{z_{mi} \le \sum_{n=1}^{|E(t_i)|} \sum_{k=1}^{|Q_n(t_i)|} \int_{t_i}^{t_i+\beta\sum_{j=i}^{|T|} a_{nm}^k(t_j)} \delta_{nm}^k(t)\,\mathrm{d}t}}{|B(t_i)|}$$

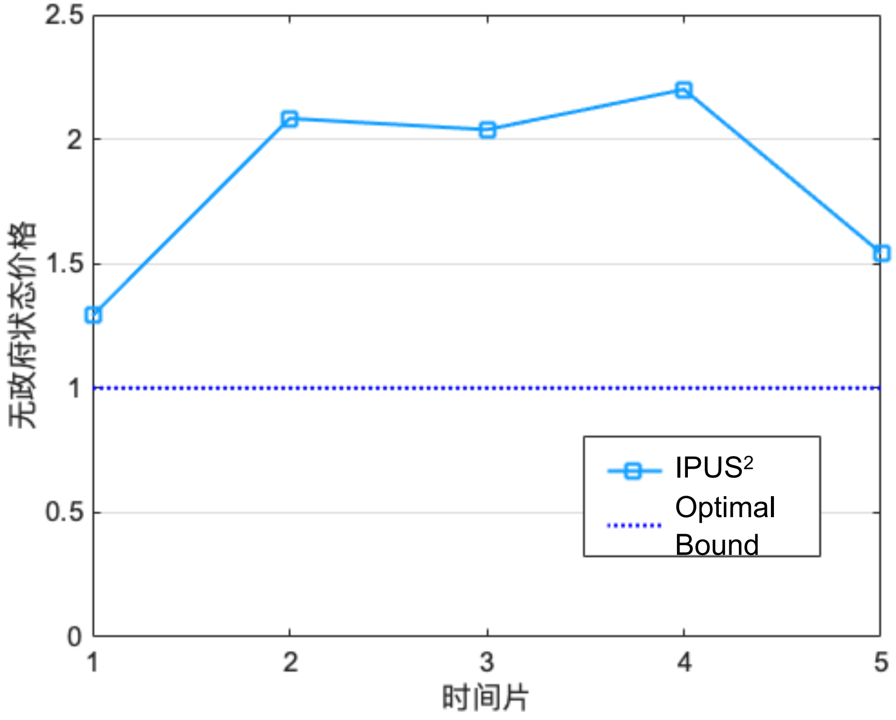
■ Channel Utilization Efficiency

$$\mathcal{E}(t_i) = \sum_{m=1}^{|B(t_i)|} \frac{\sum_{n=1}^{|E(t_i)|} \sum_{k=1}^{|Q_n(t_i)|} \int_{t_i}^{t_i+\beta\sum_{j=i}^{|T|} a_{nm}^k(t_j)} \delta_{nm}^k(t)\,\mathrm{d}t}{\sum_{k=1}^{|Q_n(t_i)|} \sum_{j=i}^{|T|} a_{nm}^k(t_j)} \Big/ |B(t_i)|$$

Performance Evaluation **Simulation Results**



The Convergence of The IPUS²

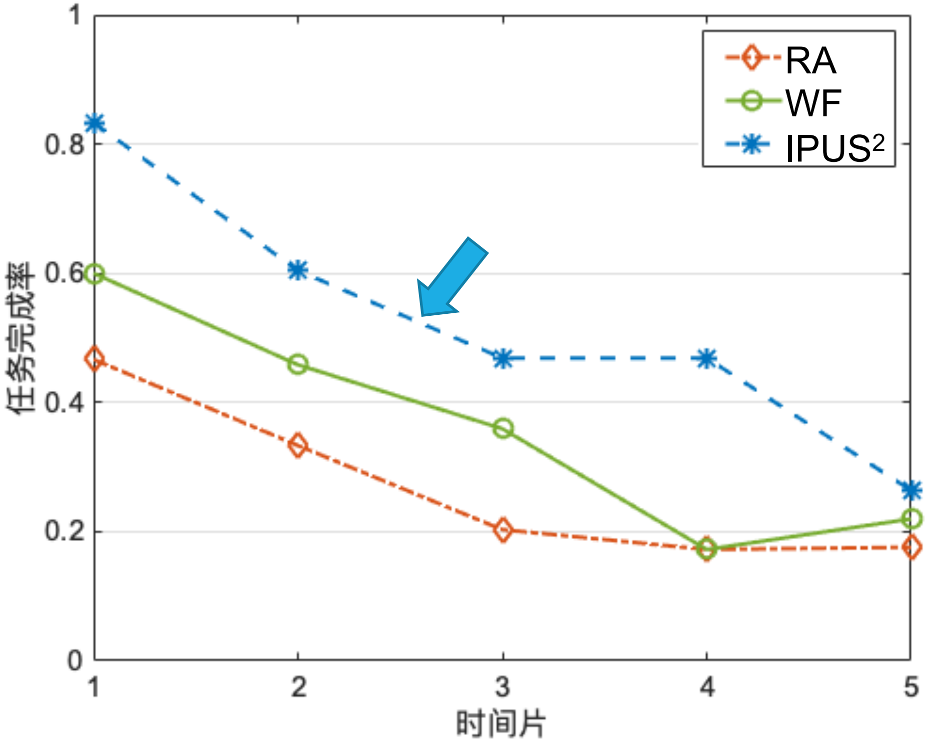


The Effectiveness of The Nash Equilibrium

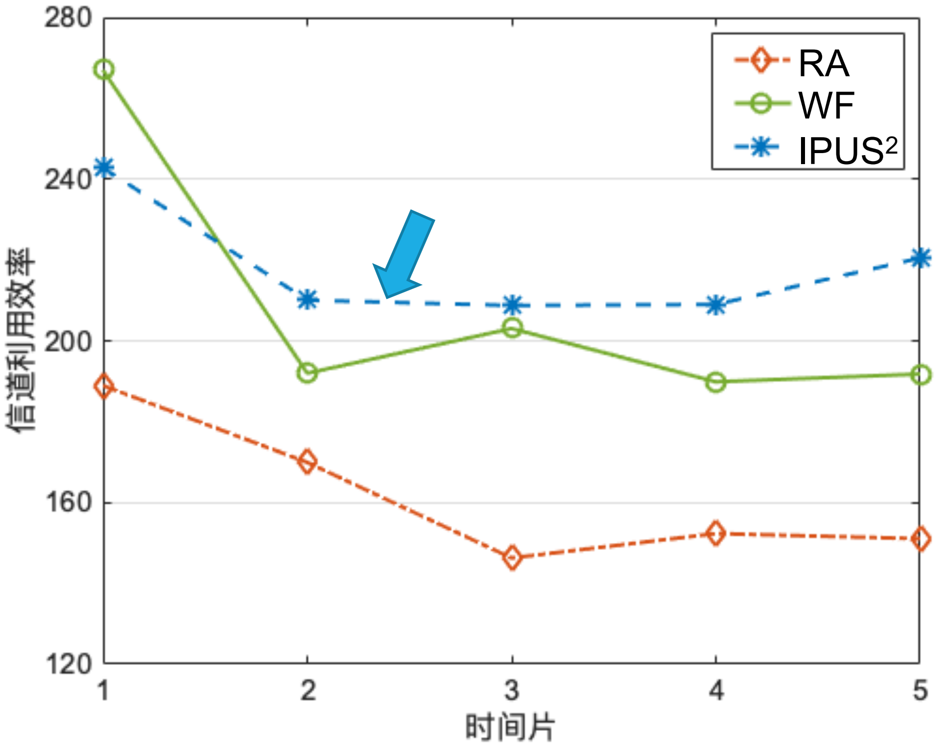
Performance Evaluation **Simulation Results**

The Comparative Algorithms

- Random Allocation, RA
- Water Filling, WF



Task Completion Ratio



Channel Utilization Efficiency

Conclusion

- We **formulated the problem** of channel allocation in vehicular edge computing, and transformed the global optimization problem into a **distributed channel allocation potential game**

- We proposed an Incentive-based Probability Update and Strategy Selection (**IPUS^2**) algorithm, and verified the **convergence** of the IPUS^2 and the **effectiveness** of the Nash Equilibrium

- We give an experiment with **real vehicle trajectories**, and the results showed **IPUS^2 outperforms** existing representative algorithms

Thank You