Hierarchical Edge-Cloud Computing for Mobile Blockchain Mining Game

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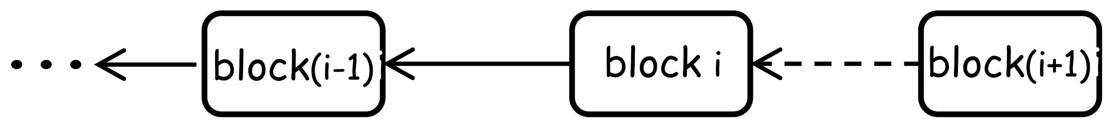
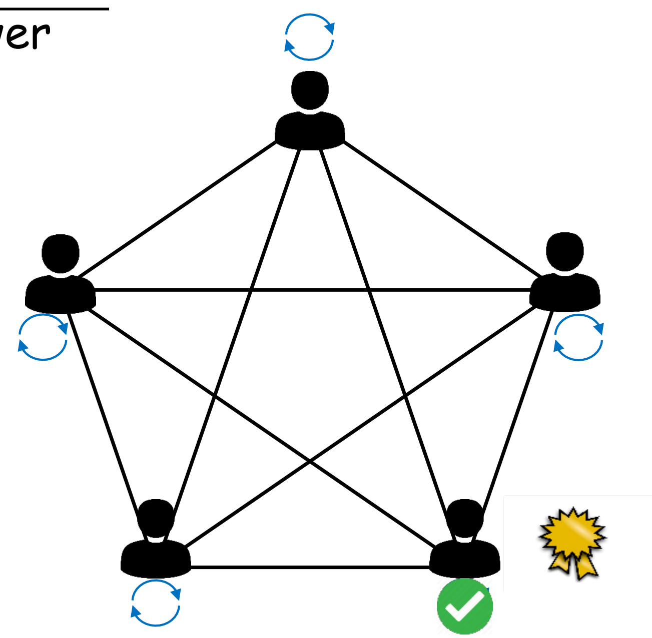
1. Blockchain

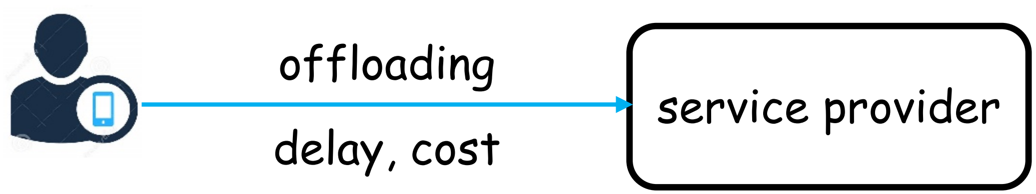
- PoW-based blockchain mining
  - Mining a block is a puzzle solving race on miners' computing power
- Mining incentive
  - Each block will be rewarded with R
  - Prob . of winning a puzzle solving race
    - W_i = computing rate = $\dfrac{\text{individual computing power}}{\text{total computing power}}$





Motivation: Apply in Mobile Devices

- Few blockchain applications in mobile environments
  - Mobile devices cannot satisfy mining requirements
    - Limited computing power and energy
  - Solution: computation offloading



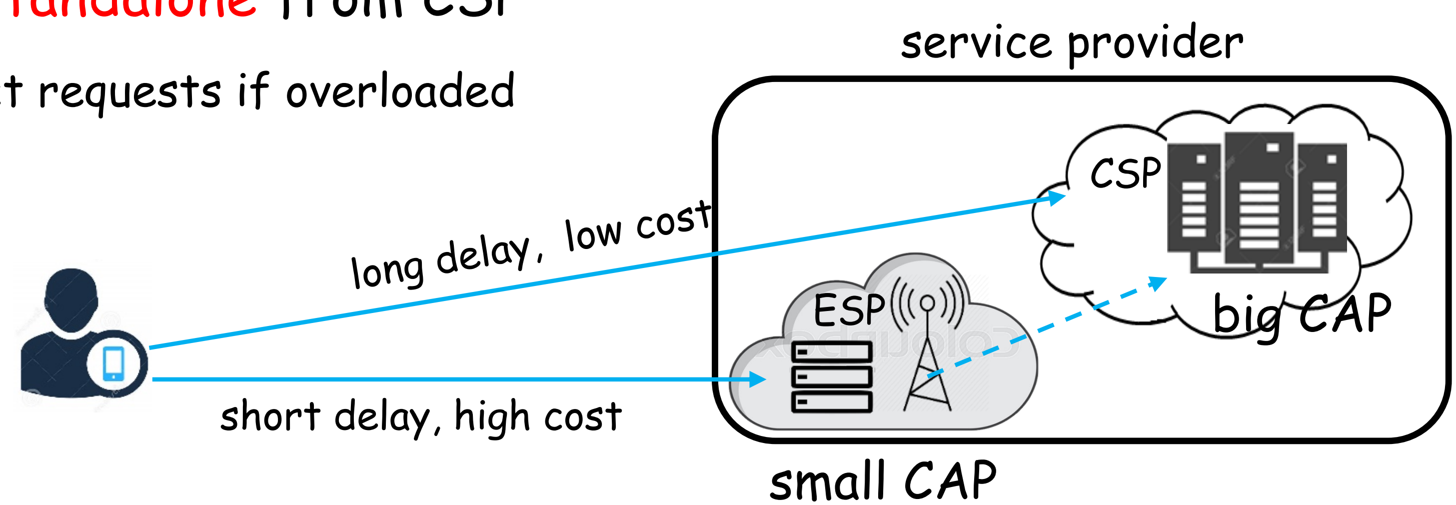
- Offloading incurs delay (d) and cost (C) from service provider
- A miner's utility $\boxed{U_i = R \cdot W_i - C}$
- W_i = (1 - $\beta(d)$) X computing rate

specific function of delay

proportional to computing power

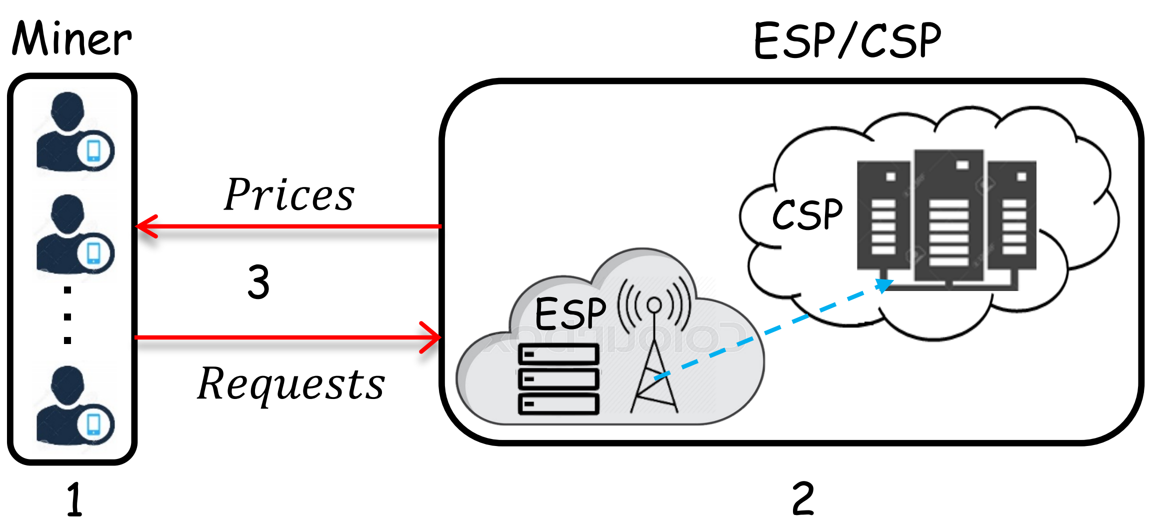
A Two-layer Offloading Paradigm

- Two service providers
  - A remote cloud computing service provider (CSP)
    - Rich resource capacity, low price, long delay
  - A nearby edge computing service provider (ESP)
    - Limited resource capacity ($E_{\max}$), high price, short delay
- Different operation modes
  - ESP is connected to CSP
    - Auto-transfer requests to CSP if overloaded
  - ESP is standalone from CSP
    - Reject requests if overloaded



2. Problem Formulation

1. Nash subgame of N miners to maximize utility U_i
   - Decide on resource share from ESP (e_i) and CSP (c_i)
2. Nash subgame of ESP/CSP to maximize revenue $V_e(V_c)$
   - Decide on the resource unit price $P_e(P_c)$
3. Stackelberg game between miners and ESP/CSP
   - Interplay between leaders (ESP/CSP) and followers (miners).



Miners' Subgame

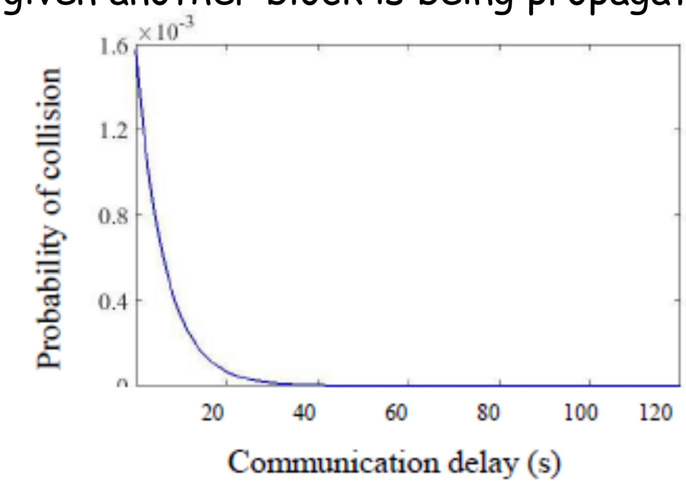
- Formulation of strategy and objective
  - Determine e_i and c_i under budget limitation B_i to

$$maximize \quad U_i = R \cdot W_i - (P_e \cdot e_i + P_c \cdot c_i)$$

- Winning probability W_i and delay d
  - d discounts W_i by $1 - \beta(d)$
    - $\boxed{\beta(d) = 1 - e^{-\lambda d}}$

      represent mining difficulty
  - Tradeoff on delay and price
    - CSP lowers cost while decreasing W_i
    - ESP increases W_i while adding cost

PDF of a conflicting block being found given another block is being propagated



Validation of Winning Probability

- W_i combines winning either in edge or cloud
  - $W_i = W_i^e + W_i^c$
    - $W_i^e = \frac{e_i}{E+C} \cdot \left(1 + \frac{\beta C}{E}\right)$ and $W_i^c = \frac{c_i}{E+C} \cdot (1-\beta)$
    - where $E = \sum_{i=1}^{N} e_i$ and $C = \sum_{i=1}^{N} c_i$
  - **Theorem 1**. W_i is valid to express winning probability of individual miners in a mobile blockchain mining network
    - Proof: We present the full verification process by checking that $\sum_{i=1}^{N} W_i = 1$ always holds.

Service Providers' Subgame

- Formulation of strategy and objective
  - ESP determines a unit price P_e to

$$maximize \quad V_e = (P_e - C_e) \cdot E \quad where\ E = \sum_{i=1}^{N} e_i$$

ESP unit cost ESP sold-out units

  - CSP determines a unit price P_c to

$$maximize \quad V_c = (P_c - C_c) \cdot C \quad where\ C = \sum_{i=1}^{N} c_i$$

CSP unit cost CSP sold-out units

Stackelberg Game

- A two-stage game
  - Stage 1: ESP/CSP subgame
    - ESP(CSP) optimizes its unit price $P_e(P_c)$ by predicting the miners' reactions as well as considering the rival's price strategy.
  - Stage 2: miner subgame
    - each miner responds to the current prices, by sending requests to ESP/CSP, considering its budget and other miners' requests.
- Stackelberg equilibrium (SE)
  - formed by subgame perfect Nash equilibria (NE) in both the leader stage and the follower stage

Game Analysis in Connected Mode

- **Theorem 2**. A unique NE exists in miner subgame
- **Theorem 3**. Stackelberg game has a unique SE
- A best response algorithm to find the unique SE point in Stackelberg game.
- **Theorem 4**. If all miners have identical budgets B, each miner's request in NE can be expressed as

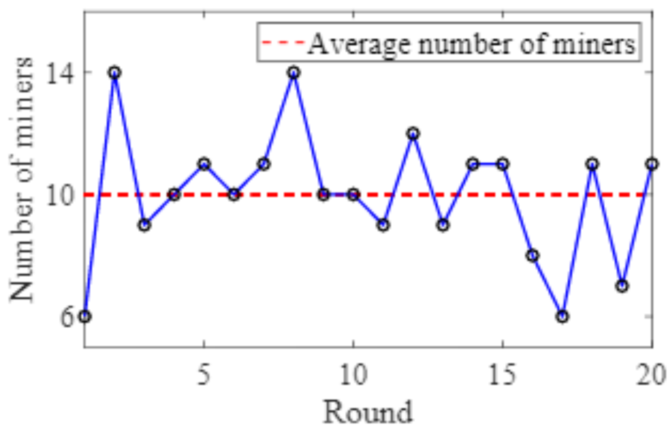
$$\begin{cases} e_i^* = \dfrac{B\beta h}{(1-\beta+h\beta)(P_e-P_c)}, \\ c_i^* = \dfrac{B\left[(1-\beta)(P_e-P_c)-P_c\beta h\right]}{P_c(1-\beta+h\beta)(P_e-P_c)} \end{cases}$$

Game Analysis in Standalone Mode

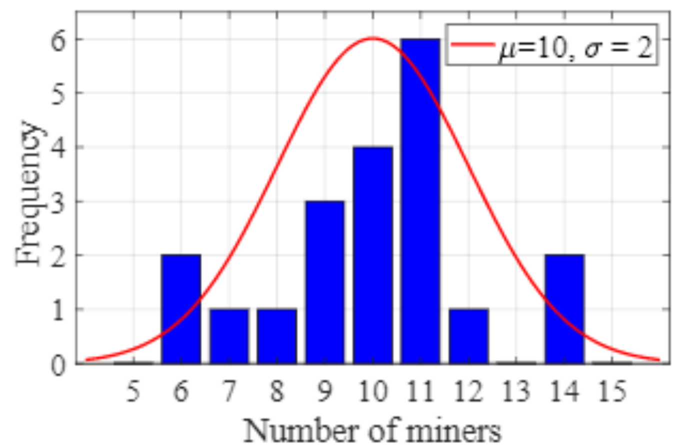
- **Theorem 5.** Given a price set (P_e, P_c), there exists at least one NE in miner subgame.
- **Theorem 6**. SE exists in the Stackelberg game.
  - Note: there may exist more than one SE point.
- A distributed price bargaining algorithm with guaranteed convergence to find one SE point.

System Dynamics: Population Uncertainty

- The number of miners changes in each round
  - Modeled as a random variable $N \sim \mathcal{N}(\mu, \sigma^2)$
    - where $N = k$ with probability $P(k) = \Phi(k) - \Phi(k-1)$



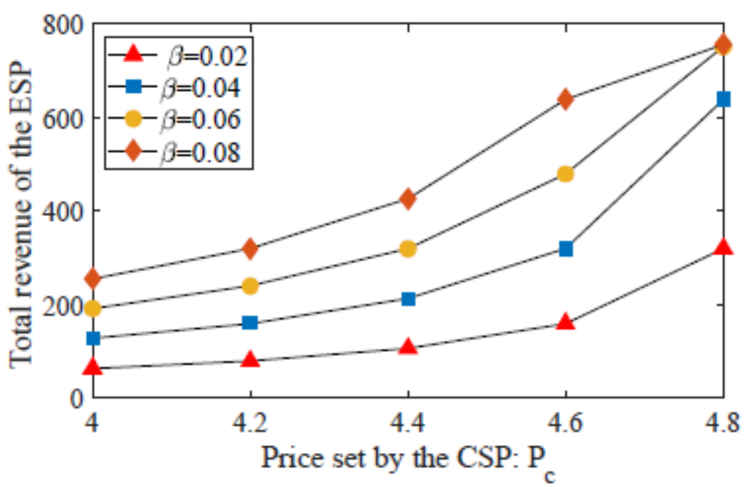
(a) Statistics on the miner number among 20 mining rounds.



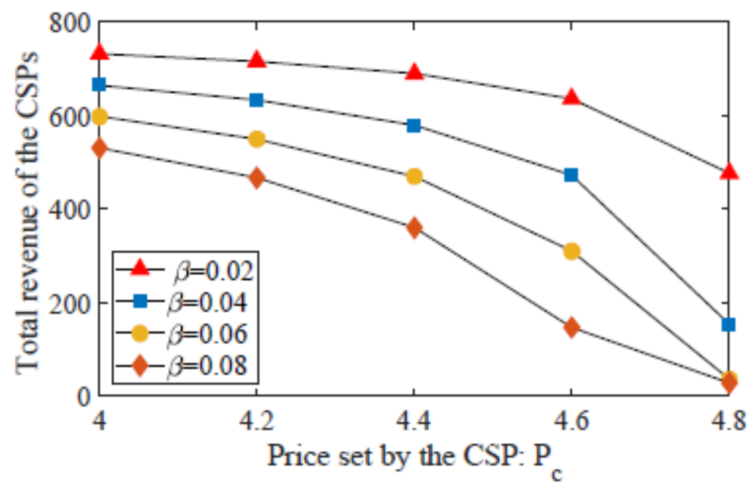
(b) Corresponding histogram and underlying distribution $N(\mu, \sigma^2)$.

4. Experiment

- Setting
  - A small network of 5 miners with identical budgets B=200
  - Each experiment is averaged over 50 rounds
- Miner subgame equilibrium
  - influences of communication delay
    - Delay decreases the number of resources sold by CSP and his revenue.



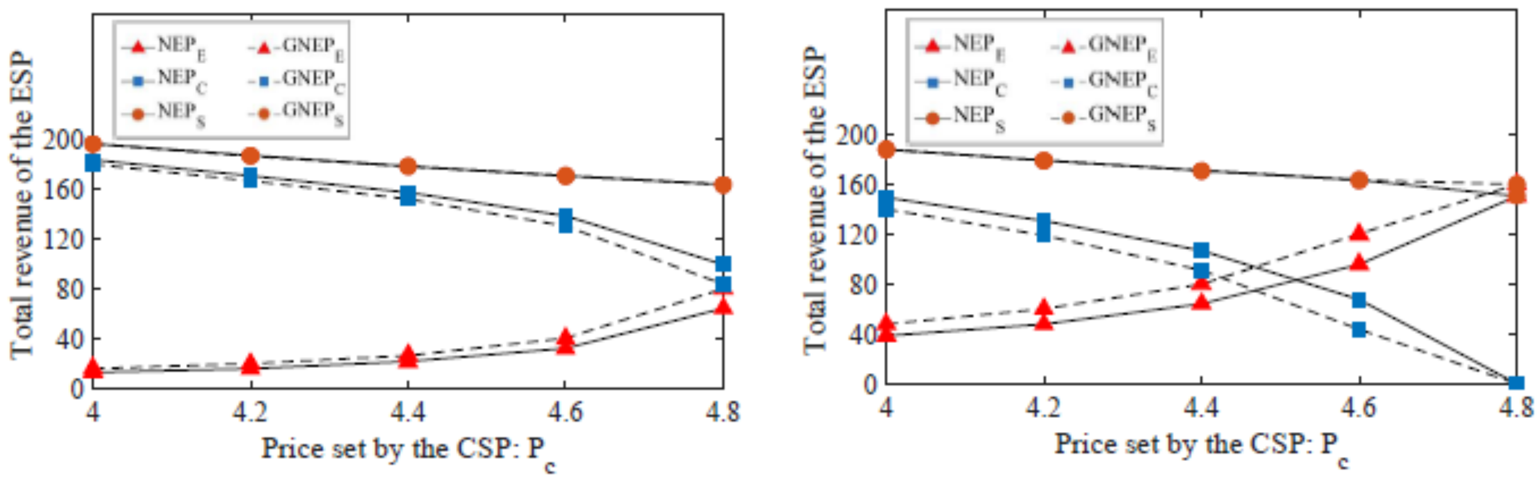
(a) The ESP's revenue.



(b) The CSP's revenue.

Miner Subgame Equilibrium

- Influences of operation modes
  - Miners are discouraged from buying units from an ESP working in the connected mode.
  - Crosses in (b) the CSP's optimal prices under different communication delays.

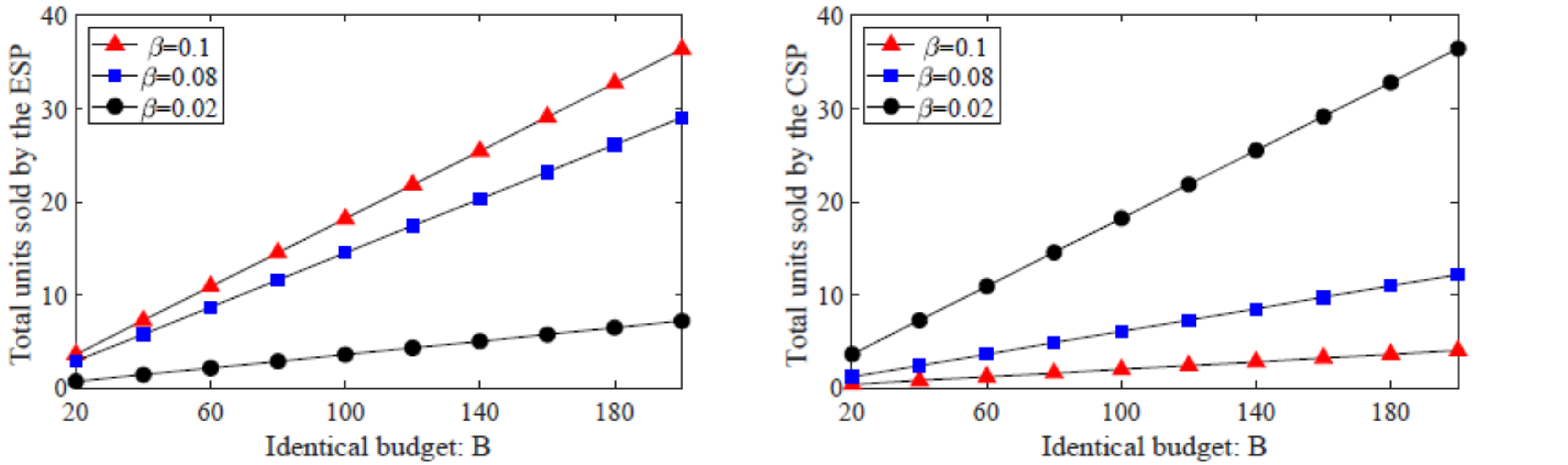


(a) $\beta = 0.02$.

(b) $\beta = 0.06$.

Miner Subgame Equilibrium

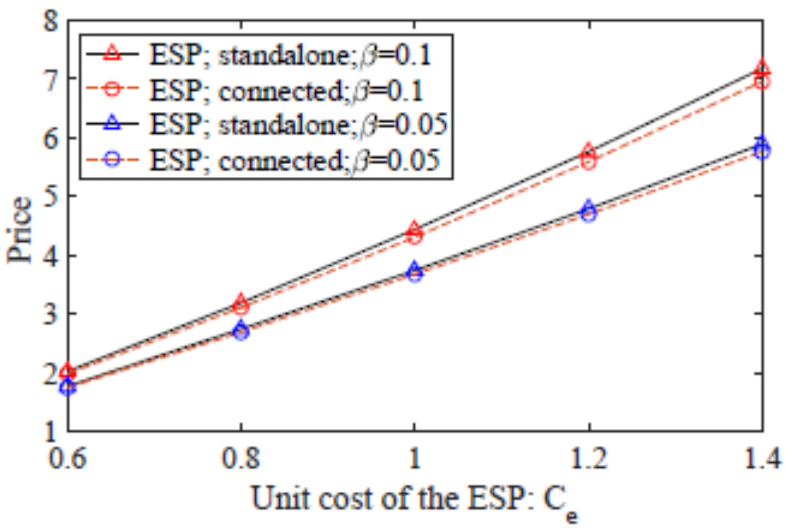
- Influences of miners' budgets
  - Higher budgets, more requests as well as more revenues



(a) A miner's request to the ESP. (b) A miner's request to the CSP.

ESP/CSP Subgame Equilibrium

- Influences of service providers' costs
  - prices increase linearly as unit costs increases
  - ESP charges a higher price



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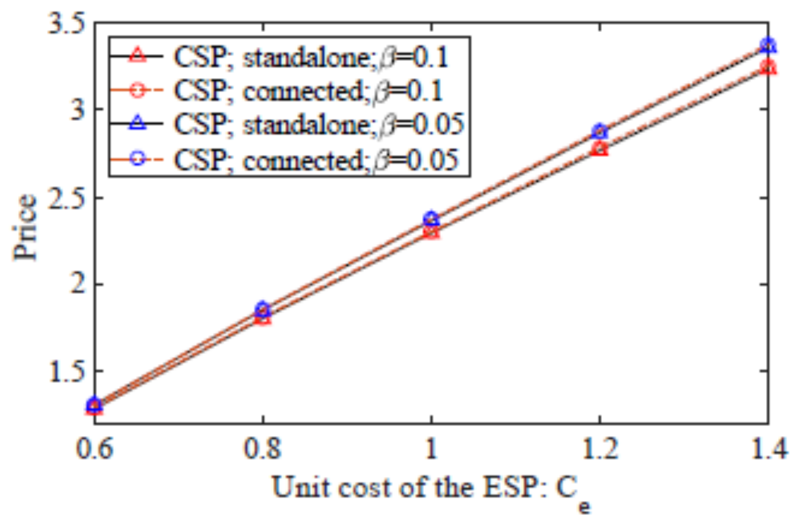
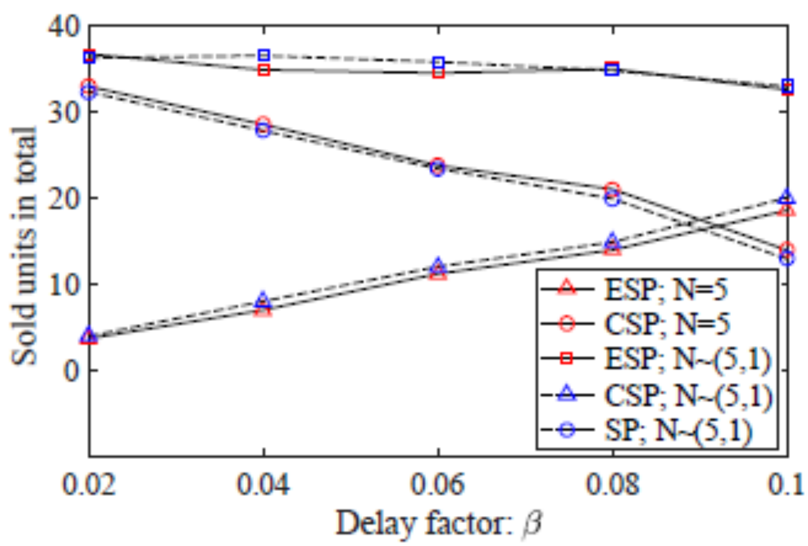


(b) $\beta = 0.06$.

Population Uncertainty

- Render miners more aggressive to buy computing resources from the ESP



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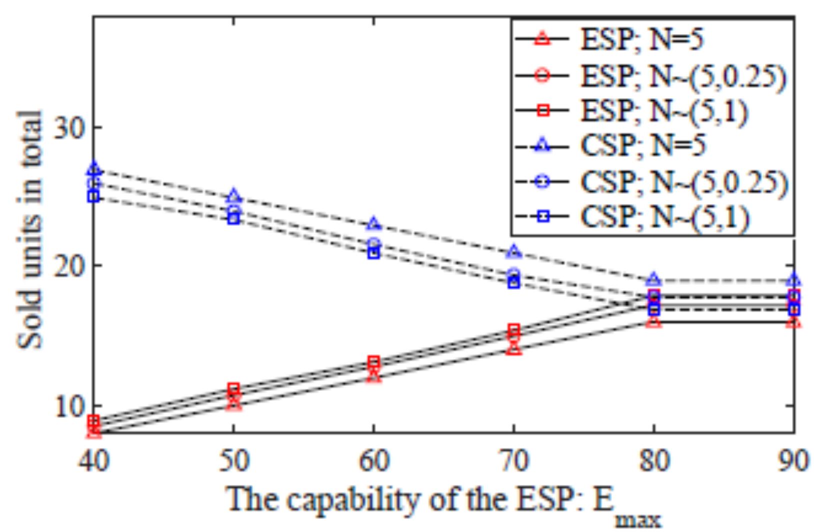

(b) $\beta = 0.06$.

5. Conclusion

- A Stackelberg game with two subgames
  - Consider delay and cost tradeoff in mobile mining environment
  - Model the relation between winning probability and delay
  - Solve a price-based resource management problem
- Two ESP operation modes:
  - Connected vs standalone
- Impacts of population uncertainty
- Experiments to confirm theoretical analysis

Thank you

Q & A