Self-Adaptive Energy Efficient Operation in UAV-assisted Public Safety Networks

Internet of Things Lab – IoT Lab UNM

Performance and Resource OpTimizatiOn in Networks Lab – PROTON Lab UNM

ELECTRICAL & COMPUTER ENGINEERING

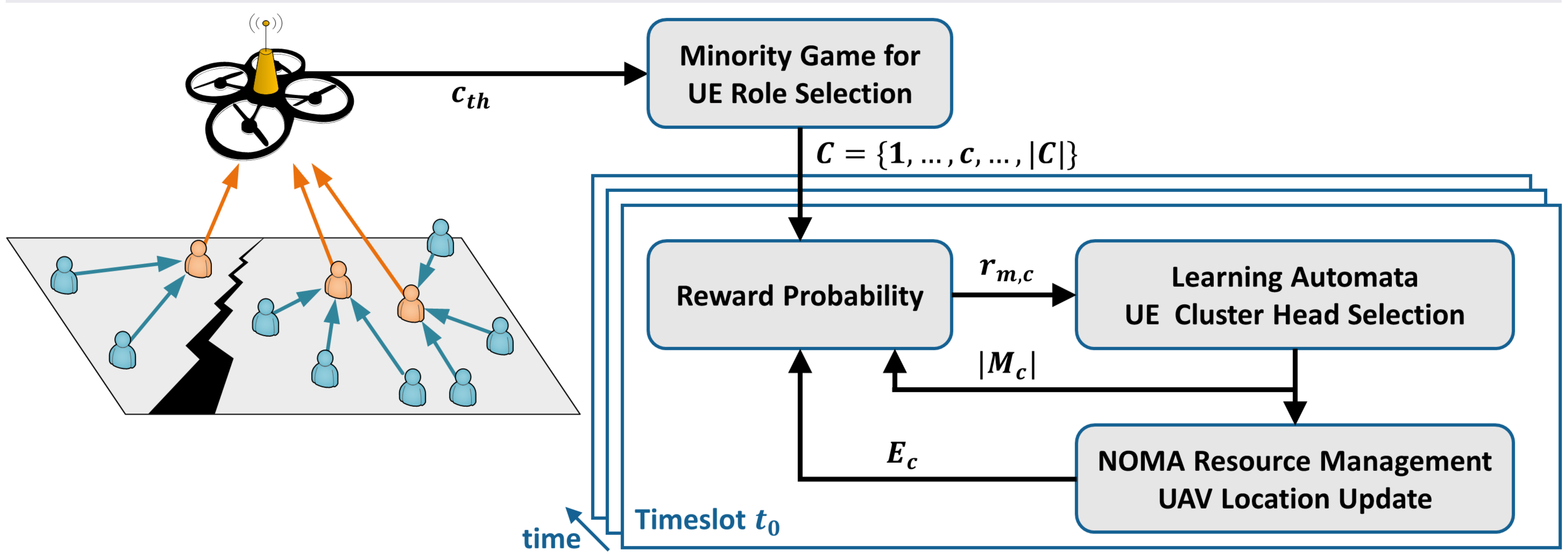
School of Electrical and Computer Engineering
National Technical University of Athens

Dimitrios Sikeridis, Eirini Eleni Tsiropoulou, Michael Devetsikiotis | The University of New Mexico

Symeon Papavassiliou | National Technical University of Athens

Contributions

- ✓ Introduce an UAV-assisted Public Safety Network architecture of UE devices operating in a NOMA limited-interference environment
- ✓ Define distinct UE roles with a set of critical UEs acting as clusterheads and the rest acting as PSN cluster members
- ✓ Utilize a Minority Game theoretic mechanism for distributed UEs' role selection
- ✓ Introduce a clustering scheme based on reinforcement learning considering UEs' physical proximity and battery life
- ✓ Calculate the UAV/eNB trajectory towards maximizing the energy availability of the clusterhead-acting critical UEs
- ✓ Holistic utility function representing QoS prerequisites of UE devices
- ✓ Distributed optimization problem of each device's utility function to determine the optimal transmission power - Energy-efficient resource allocation framework



System Model

- ❑ Uplink of a Non-Orthogonal Multiple Access (NOMA) wireless network in an $l \times l$ area
- ❑ Multiple UE devices $M = \{1, \dots, m, \dots, |M|\}$ and a set of critical UEs $C = \{1, \dots, c, \dots, |C|\}$
- ❑ One eNB-acting mobile UAV with velocity per axis: $\{u^x_{UAV}, u^y_{UAV}, u^z_{UAV}\}$
- ❑ Two types of communication: D2D & D2eNB
- ❑ Devices determine optimal uplink transmission power P^*_m

NOMA Wireless Setting

- ❑ Sorted channel gain $G_{m,m}$ among devices $G_{M,m} \leq \dots \leq G_{1,m}$
- ❑ Sensed Interference by device m following Successive Interference Cancellation (SIC)

$$I_m(\mathbf{P_{-m}}) = \sum_{m' \geq m+1}^{|M|} G_{m',m} P_{m'} + I_0$$

- ❑ Signal-to-Interference-plus-Noise-Ratio (SINR) of m to receiver k $\quad \gamma_m(P_m, \mathbf{P_{-m}}) = \frac{G_{m,k} P_m}{I_k}$

Minority Game for UEs' Role Selection

- ❑ Game Model: An odd number of agents compete for a shared resource, select between two options and the group that forms the minority wins $G_{MG} = [M, \{A_m\}, \{R_{a_m}(m)\}]$
  - M the set of UEs, A_m the set of actions – acting roles
  - $R_{a_m}(m)$ the payoff the UE m receives after selecting role a_m
- ❑ Cutoff value c_{th} denoting desired number of clusterheads – the minority group
- ❑ During each game round i UEs chose between two possible actions a_m
- ❑ Attendance $c^{[i]}$: the collective sum of UEs' actions – population of minority group
- ❑ Shared resource: Location of the UAV
  - If $c^{[i]} \leq c_{th}$ the $c^{[i]}$ clusterheads are considered winners
  - If $c^{[i]} > c_{th}$ the members are considered Minority Game winners as the increased number of chs leads to poor UAV positioning and thus poor energy efficiency
- ❑ After action selection the UAV (central MG entity) broadcasts the winning choice
- ❑ Received Payoff:

$$R^{[i]}_{a_m=1}(m) = \begin{cases} 1, & if\ c^{[i]} \leq c_{th} \\ 0, & otherwise \end{cases} \quad R^{[i]}_{a_m=0}(m) = \begin{cases} 1, & if\ c^{[i]} > c_{th} \\ 0, & otherwise \end{cases}$$

- ❑ Minority Game solved utilizing a Q-learning mechanism

Reinforcement Learning-based Clustering

- ❑ Reward probability $r^{[t]}_{m,c}$ to reflect the competitiveness of each ch c as perceived from the member UE m and is given by:

$$r'^{[t]}_{m,c} = \frac{E^{[t-1]}_c}{|M_c|^{[t-1]} \cdot (d_{m,c})^2}, \quad r^{[t]}_{m,c} = \frac{r'^{[t]}_{m,c}}{\sum_{c=1}^{|C|} r'^{[t]}_{m,c}}$$

- ❑ Learning automata action probability $Pr^{[t]}_{m,c}$ of device m, selecting ch c
- ❑ For a device m associated with ch c, the probability of choosing the same ch:

$$Pr^{[t]}_{m,c} = Pr^{[t-1]}_{m,c} + b \cdot r^{[t-1]}_{m,c} \cdot (1 - Pr^{[t-1]}_{m,c})$$

- ❑ The probability to change to a new clusterhead c′:

$$Pr^{[t]}_{m,c'} = Pr^{[t-1]}_{m,c'} - b \cdot r^{[t-1]}_{m,c} \cdot Pr^{[t-1]}_{m,c'}$$

UAV Positioning & Resource Management

- ❑ The UAV performs a uniform motion towards each 3D space axis within a bounded range. The specific position for each timeslot aims to extend the energy availability of the clusterheads:

$$\begin{Bmatrix} x^*_{UAV} \\ y^*_{UAV} \\ z^*_{UAV} \end{Bmatrix} = \underset{\substack{x_{UAV} \\ y_{UAV} \\ z_{UAV}}}{argmax} \left[\sum_{\forall c \in C} E^{[t-1]}_c - \sum_{\forall c \in C} t \cdot P^*_c(d_{c,UAV}) \right]$$

$$s.t.\ 0 \leq x^{[t-1]}_{UAV} - u^x_{UAV} \cdot t \leq x_{UAV} \leq x^{[t-1]}_{UAV} + u^x_{UAV} \cdot t \leq l$$

$$0 \leq y^{[t-1]}_{UAV} - u^y_{UAV} \cdot t \leq y_{UAV} \leq y^{[t-1]}_{UAV} + u^y_{UAV} \cdot t \leq l$$

$$h_{min} \leq z^{[t-1]}_{UAV} - u^z_{UAV} \cdot t \leq z_{UAV} \leq z^{[t-1]}_{UAV} + u^z_{UAV} \cdot t$$

UE's Utility Function

$$U_m(P_m) = \frac{W \cdot f_m(\gamma_m)}{P_m}$$

Optimization Problem

$$\max_{P_m \in A_m} U_m(P_m, \mathbf{P_{-m}})$$
$$s.t.\ 0 < P_m \leq P^{Max}_m$$

Strategy Space & Non-cooperative game

$$G = [M, \{A_m\}, \{U_m\}]$$
$$A_m = (0, P^{Max}_m]$$
$$\mathbf{P}^* = [P^*_1, \dots, P^*_m, \dots, P^*_{|M|}]^T$$
$$U_m(P^*_m, \mathbf{P_{-m}}) \geq U_m(P_m, \mathbf{P_{-m}})$$

Unique Optimal Uplink Transmission Power

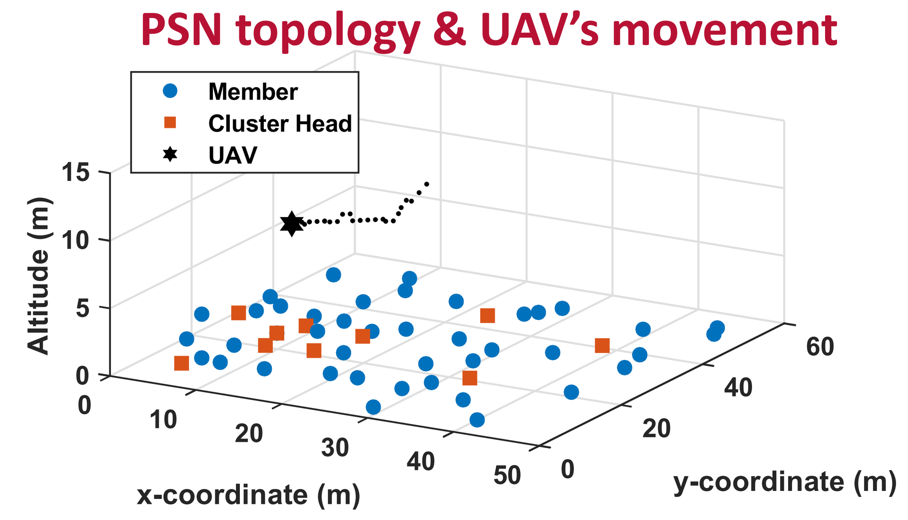
Theorem 1 *The non-cooperative power control game G has a unique Nash equilibrium point* $\mathbf{P}^* = [P^*_1, \dots, P^*_m, \dots, P^*_{|M|}]^T$,

$$P^*_m(d_{m,m'}) = min\left\{\frac{\gamma^*_m I_m}{W\, G_{m,m'}}, P^{Max}_m\right\}$$

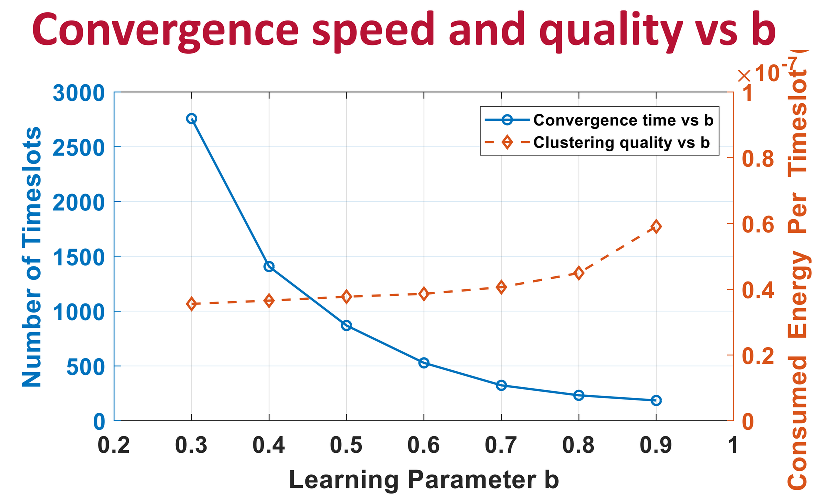
for all m, $m \in M$, *with* γ^*_m *being the unique positive solution of the equation* $\frac{\partial f_m(\gamma_m)}{\partial \gamma_m}\gamma_m - f_m(\gamma_m) = 0$.

Performance Evaluation

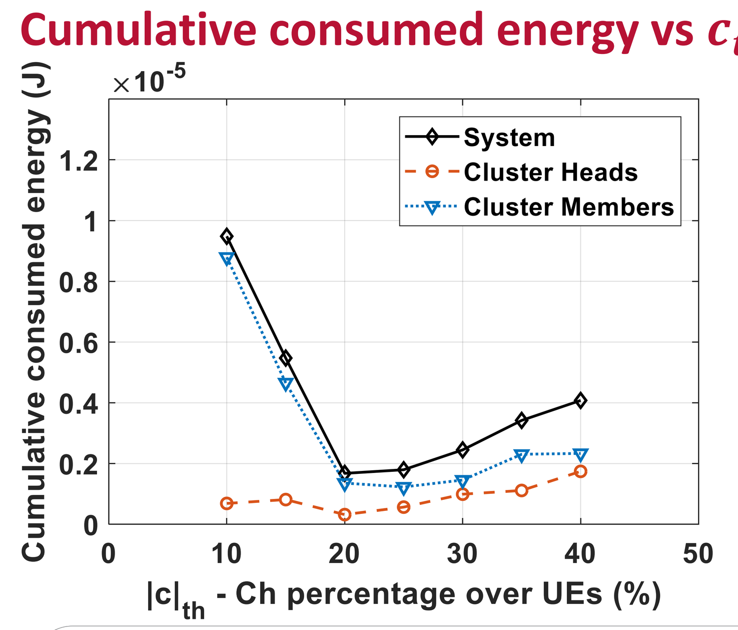
PSN topology & UAV's movement



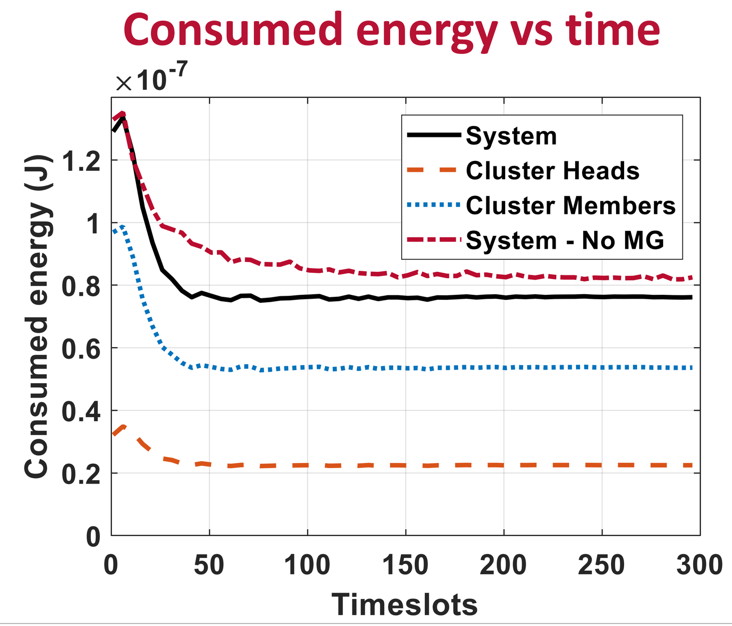
Convergence speed and quality vs b



Cumulative consumed energy vs c_{th}



Consumed energy vs time



Energy efficiency study