UAV-Enabled Wireless-Powered Mobile Edge Computing System

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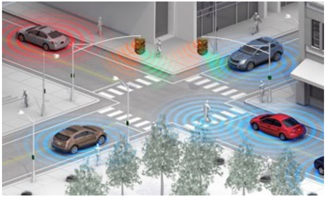
- 5G MEC background
- UAV based MEC architectures ad applications
- System model
- Problem formulation and solving
- Performance results
- Conclusions

5G Applications

(a) VR/AR Gaming

(b) IoT and Smart City

(c) Critical Control



(d) Autonomous Driving

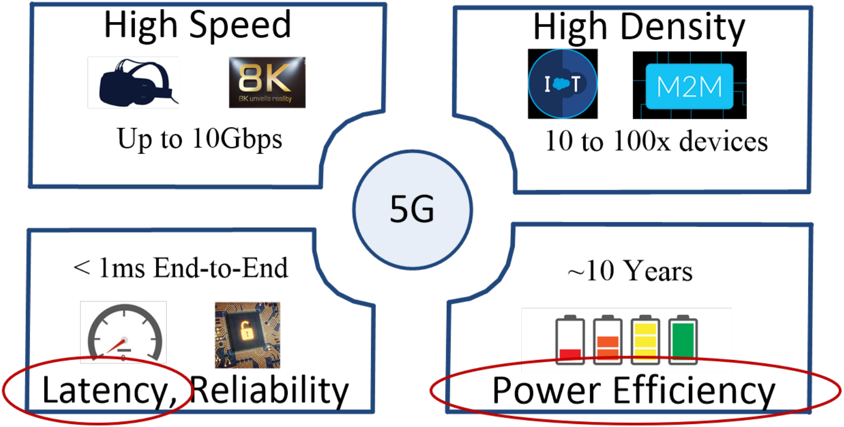
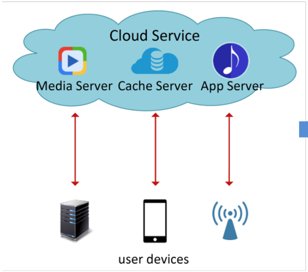


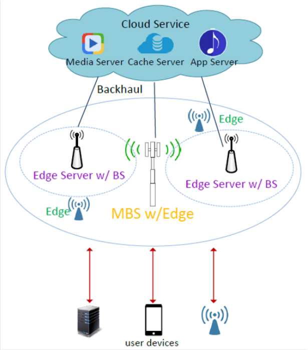
Figure 2: One possible solution: MEC

Mobile Edge Computing

- Cloud computing gives feasible solution for low-power devices, by providing centralized computation resources.
- However, cloud servers may locate far from users, induces longer processing delay.
- By placing powerful mobile devices in close proximity, acting as a intermediate layer, edge computing is more flexible and can reduce delay.



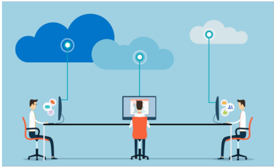
cloud computing



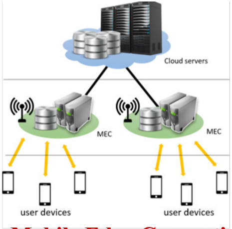
edge computing

Mobile Edge Computing

- Transformation from cloud to edge can be an interplay between communication and computation.
- In the cloud era, the relative bottleneck is computation speed. Thus, processing is done via sending tasks remotely.
- Lately powerful devices have been emerging, communication may become a relative bottleneck.



Latency ⇒



Cloud Computing | **Mobile Edge Computing**

Communication ⟺ Computation

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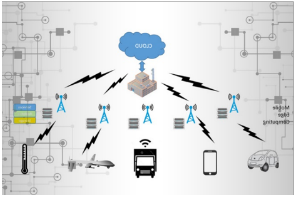
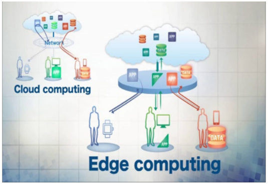
Mobile Edge Computing



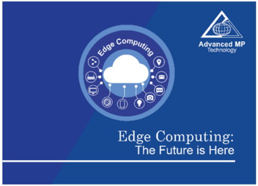
Close to users, high uploading efficiency and low latency



Medium scale: flexible deployment

Mobile edge Computing

Massive existing base stations: low cost



Cooperation: improve computation capability

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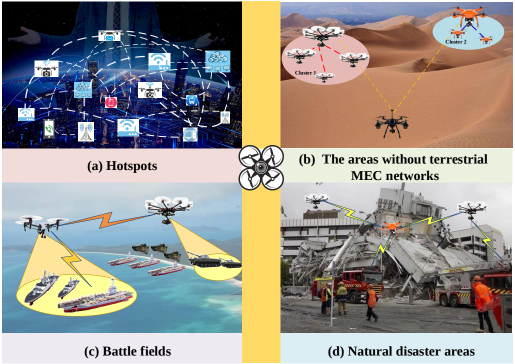
UAV-based MEC

- Flexible deployment: UAV can be deployed in most scenarios, even in wilderness, desert, and complex terrains, where the terrestrial MEC networks may not be conveniently and reliably established.
- Better communications performance: there is a high possibility that short-distance line-of-sight (LoS) links exist for computation tasks offloading and computation results downloading.
- Flexible trajectory: improve the user computation performance. They can be particularly helpful in the situations in which conventional terrestrial MEC systems are destroyed by natural disasters.

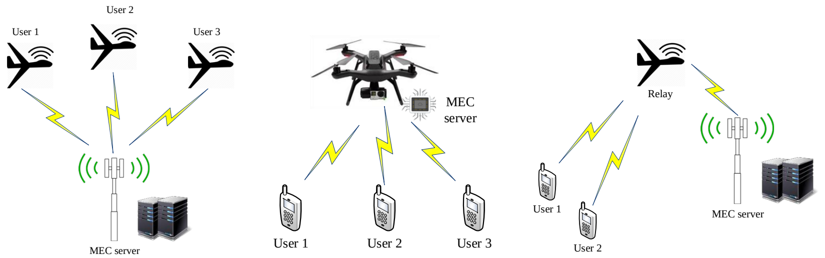
UAV based MEC Applications

- Hotspots: Exploited to assist the terrestrial MEC systems for executing the high volume computation tasks.
- Outside the Coverage of Terrestrial MEC Networks: Monitor the environment so that the corresponding strategies can be taken to protect the environment.
- Battlefields: UAV-enabled MEC networks can process massive real-time computational tasks for special missions.
- Natural Disaster: UAV can help to process the rescue or reconstruction related tasks.



UAV Based MEC Architectures

- UAV functions as a user that needs to execute its own computation tasks. A UAV may not be able to perform extensive computational tasks. It will need to offload its tasks to the ground MEC server for computing.
- UAV functions as the MEC server that helps the ground users to perform task computing after the ground users offload their computation tasks to the UAV.
- UAV works as a relay for assisting the users to efficiently offload their computation tasks to the MEC server.



(a) User. (b) MEC server. (c) Relay.

In UAV-enabled MEC networks, there can be two operation modes, namely, partial offloading mode and binary computation mode.

- For the partial offloading mode, the computation task is partitioned into two parts. One part is offloaded to the MEC server for computing while the other part is locally computed.
- For the binary computation mode, each computation task has to be executed as a whole. It can be either executed locally or completely offloaded.

- Resource allocation is important due to UAV battery concern and trajectory constraint.
- Resource allocation in UAV-enabled MEC networks should consider resources involved in three processes, namely, task offloading, local computing, and UAV's flying process.
- Resource allocation in the UAV-enabled MEC networks can be designed to achieve different objectives, such as computation bits maximization, energy minimization, computation efficiency maximization, cost minimization, completion time minimization, and fairness consideration.

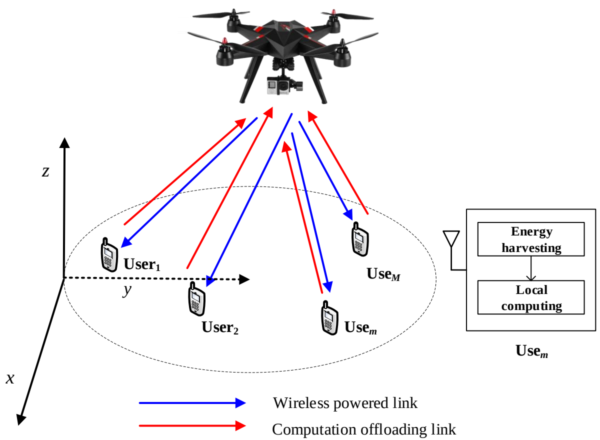
Case Study: Computation Rate Maximization in UAV-Enabled Wireless Powered Mobile-Edge Computing [1]

MEC and wireless power transfer (WPT) are two promising techniques to enhance the computation capability and to prolong the operational time of low-power wireless devices that are ubiquitous in Internet of Things.

- The computation rate maximization problems are investigated under both partial and binary computation offloading modes, subject to the energy harvesting causal constraint and the UAV's speed constraint.
- The closed-form expressions for the optimal central processing unit frequencies, user offloading time, and user transmit power are derived.
- The optimal selection scheme on whether users choose to locally compute or offload computation tasks is proposed for the binary computation offloading mode.

[1] F. Zhou, Y. Wu, R. Q. Hu and Y. Qian, "Computation Rate Maximization in UAV-Enabled Wireless-Powered Mobile-Edge Computing Systems," in IEEE Journal on Selected Areas in Communications, vol. 36, no. 9, pp. 1927-1941, Sept. 2018.

System model



UAV: has an RF energy transmitter and an MEC server; transmits energy to M users and provides MEC services for these users.
User: has an energy harvesting circuit and can store energy; simultaneously performs energy harvesting, local computing, and computation offloading.

System model

- A 3D Euclidean coordinate is adopted. User m's location is fixed on the ground q_m, where $\mathrm{q}_m = [x_m, y_m]$. x_m and y_m are the horizontal plane coordinates.
- A finite time horizon with duration T is considered. During T, the UAV flies at the same altitude level denoted by H $(H > 0)$.
- The finite time T is discretized into N equal time slots, denoted by $n = 1, 2, \cdots, N$.
- At n, the horizontal plane coordinate of UAV is $\mathrm{q}_u[n] = [x_u[n], y_u[n]]$.
- The channel power gain $h_m[n]$ between the UAV and the mth user, can be given as

$$h_m[n] = \frac{\beta_0}{H^2 + \left\|\mathrm{q}_u[n] - \mathrm{q}_m\right\|^2}, m \in \mathcal{M}, n \in \mathcal{N}. \quad (1)$$

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$$h_m[n] = \frac{\beta_0}{H^2 + \left\|\mathrm{q}_u[n] - \mathrm{q}_m\right\|^2}, m \in \mathcal{M}, n \in \mathcal{N}, \quad (2)$$

Partial Computation Offloading

- Under the partial computation offloading mode, the computation task of each user can be partitioned into two parts, one for local computing and one for offloading to the UAV.
- The energy consumed for local computing and task offloading comes from the harvested energy.
- The linear energy harvesting model is applied, the harvested energy $E_m[n]$ at the mth user during n time slots is given as

$$E_m[n] = \sum_{i=1}^{n} \frac{T\eta_0 h_m[i] P_0}{N}, m \in \mathcal{M}, n \in \mathcal{N}, \tag{3}$$

where η_0 denotes the energy conservation efficiency, $0 < \eta_0 \leq 1$ and P_0 is the transmit power of the UAV. The UAV employs a constant power transmission.

Partial Computation Offloading: Local Computation

- C: the number of CPU cycles required for computing one bit of raw data at each user.
- $f_m[n]$: the CPU frequency of the mth user during the nth slot with a unit of cycles per second.
- The total computation bits executed at the mth user during n slots given as

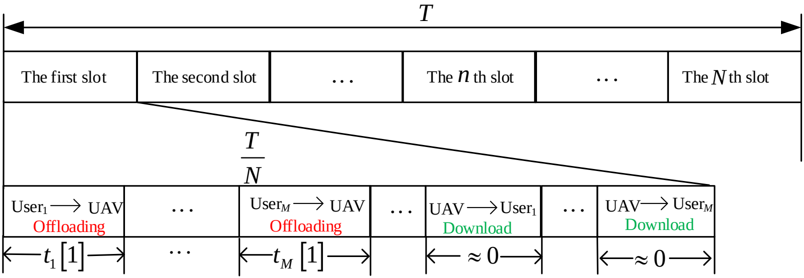
$$\sum_{k=1}^{n} \frac{T f_m[k]}{NC},$$

and the total consumed energy for local commputing at the mth user is

$$\frac{T}{N} \sum_{k=1}^{n} \gamma_c f_m^3[k],$$

where γ_c is the effective capacitance coefficient of the processor's chip at the mth user.

- A TDMA protocol shown in is applied.
- Each time slot consists of three stages, the offloading stage, the computation stage, and the downloading stage.
- In the offloading stage, M users offload their respective computation task one by one during each slot.Let $t_m[n] \times T/N$ $(0 \leq t_m[n] \leq 1)$ denote the duration in which the mth user offloads its computation task to the UAV at the nth slot.



$R_m[n]$ denotes the total number of bits that the mth user offloads to the UAV during the nth slot.

$$R_m[n] \leq \frac{BTt_m[n]}{\nu_m N}\log_2\left(1+\frac{h_m[n]P_m[n]}{\sigma_0^2}\right), n \in \mathcal{N}, m \in \mathcal{M}, \quad (4)$$

where B is the communication bandwidth; $P_m[n]$ is the transmit power of the mth user at the nth slot and σ_0^2 denotes the noise power at the mth user.

- The total offloading time of all the users does not exceed the duration of one time slot,

$$\sum_{m=1}^{M} t_m[n] \leq 1, n \in \mathcal{N}. \quad (5)$$

- The energy consumed for local computing and task offloading comes from the harvested energy,

$$\frac{T}{N}\sum_{k=1}^{n}\left[\gamma_c f_m^3[k] + t_m[k] P_m[k]\right] \leq \frac{\eta_0 T}{N}\sum_{k=1}^{n} h_m[k] P_0, n \in \mathcal{N}, m \in \mathcal{M}. \quad (6)$$

- Under the partial computation offloading mode, the total number of computed bits is

$$R_m = \sum_{n=1}^{N} \frac{T f_m[n]}{NC} + \frac{BT t_m[n]}{\nu_m N}\log_2\left(1 + \frac{h_m[n] P_m[n]}{\sigma_0^2}\right), m \in \mathcal{M}. \quad (7)$$

- Under the binary computation offloading, the computation task cannot be partitioned.
- $\mathcal{M}_0$: task offloading users. $\mathcal{M} = \mathcal{M}_0 \cup \mathcal{M}_1$ and $\mathcal{M}_0 \cap \mathcal{M}_1 = \Theta$.
- A user in $\mathcal{M}_0$ exploits all the harvested energy to perform local computing.
- We have the total computation rate of the ith user R_i^L as

$$R_i^L = \sum_{n=1}^{N} \frac{T f_i [n]}{NC}, i \in \mathcal{M}_0. \tag{8}$$

and the energy harvesting causal constraint for a user in $\mathcal{M}_0$ as

$$\frac{T}{N} \sum_{k=1}^{n} \gamma_c f_i^3 [k] \leq \frac{\eta_0 T}{N} \sum_{k=1}^{n} h_i [k] P_0, n \in \mathcal{N}, i \in \mathcal{M}_i. \tag{9}$$

- The TDMA protocol is applied,

$$\sum_{j\in\mathcal{M}_1} t_j\left[n\right] \leq 1, n \in \mathcal{N}. \tag{10}$$

- R_j^O denotes the total computation rate of the jth user in the set $\mathcal{M}_1$,

$$R_j^O = \sum_{n=1}^{N} \frac{BTt_j\left[n\right]}{\nu_j N} \log_2\left(1 + \frac{h_j\left[n\right]P_j\left[n\right]}{\sigma_0^2}\right), j \in \mathcal{M}_1. \tag{11}$$

- The energy harvesting causal constraint for a user in $\mathcal{M}_1$ can be given as

$$\frac{T}{N}\sum_{k=1}^{n} t_j\left[k\right]P_j\left[k\right] \leq \frac{\eta_0 T}{N}\sum_{k=1}^{n} h_j\left[k\right]P_0, n \in \mathcal{N}, j \in \mathcal{M}_1. \tag{12}$$

The weighted sum computation bits maximization problem is formulated as P_1,

$$\mathrm{P}_1: \max_{f_m[n], P_m[n], \mathrm{q}_u[n], t_m[n]} \sum_{m=1}^{M} w_m \times \left[\sum_{n=1}^{N} \frac{T f_m[n]}{NC} + \frac{BT t_m[n]}{\nu_m N} \log_2 \left(1 + \frac{h_m[n] P_m[n]}{\sigma_0^2} \right) \right]$$

$$\text{s.t. } C1: f_m[n] \geq 0, P_m[n] \geq 0, m \in \mathcal{M}, n \in \mathcal{N}, \tag{13a}$$

$$C2: \frac{T}{N} \sum_{k=1}^{n} \left[\gamma_c f_m^3[k] + t_m[k] P_m[k] \right] \leq \frac{\eta_0 T}{N} \sum_{k=1}^{n} h_m[k] P_0 \qquad m \in \mathcal{M}, n \in \mathcal{N}, \tag{13b}$$

$$C3: \sum_{m=1}^{M} t_m[n] \leq 1, n \in \mathcal{N}, \tag{13c}$$

$$C4: \left\| \mathrm{q}_u[n+1] - \mathrm{q}_u[n] \right\|^2 \leq V_{\max} \frac{T}{N}, n \in \mathcal{N}, \tag{13d}$$

$$C5: \mathrm{q}_u[1] = \mathrm{q}_0, \mathrm{q}_u[N+1] = \mathrm{q}_F, \tag{13e}$$

where $V_{\max}$ denotes the maximum speed of the UAV; q_0 and q_F are the initial and final horizontal locations of the UAV, w_m denotes the weight of the mth user, which takes the priority and the fairness among users into consideration.

Let $z_m[n] = t_m[n] P_m[n], n \in \mathcal{N}$. For a given trajectory, P_1 can be transformed into P_2.

$$\mathrm{P}_2: \max_{f_m[n], z_m[n], t_m[n]} \sum_{m=1}^{M} w_m \times \left[\sum_{n=1}^{N} \frac{T f_m[n]}{NC} + \frac{BT t_m[n]}{\nu_m N} \log_2 \left(1 + \frac{h_m[n] z_m[n]}{t_m[n] \sigma_0^2} \right) \right]$$

$$\text{s.t. } C1, C3,$$

$$C5: \frac{T}{N} \sum_{k=1}^{n} \left[\gamma_c f_m^3[k] + z_m[k] \right] \leq \frac{\eta_0 T}{N} \sum_{k=1}^{n} h_m[k] P_0, \; m \in \mathcal{M}, n \in \mathcal{N}. \quad (14a)$$

P_2 is convex and can be solved by using the Lagrange duality method.

For a given trajectory $\mathrm{q}_u[n]$, the optimal CPU frequency and transmit power of users can be respectively expressed as

$$f_m^{opt}[n] = \sqrt{\frac{w_m}{3C\gamma_c \sum\limits_{k=n}^{N} \lambda_{m,k}}}, \quad P_m^{opt}[n] = \begin{cases} 0, \quad \text{if } t_m[n] = 0, \\ \left[\frac{w_m B}{\nu_m \ln 2 \sum\limits_{k=n}^{N} \lambda_{m,k}} - \frac{\sigma_0^2}{h_m[n]} \right]^+, \quad \text{otherwise,} \end{cases} \tag{15a}$$

The optimal user offloading time can be obtained by solving the following equation.

$$\log_2\left(1 + \frac{h_m[n]\, z_m[n]}{\sigma_0^2 t_m[n]}\right) - \frac{h_m[n]\, z_m[n]}{\ln 2\left\{\sigma_0^2 t_m[n] + h_m[n]\, z_m[n]\right\}} - \frac{\nu_m N \alpha_n}{BT} = 0. \tag{16}$$

where $\lambda_{m,n} \geq 0$ is the dual variable associated with the constraint $C2$; $[a]^+ = \max(a, 0)$ and $\max(a, 0)$ denotes the bigger value of a and 0.

For any given CPU frequency, transmit power, and offloading time of users, the trajectory optimization problem can be formulated as P_3.

$$\mathrm{P}_3: \max_{\mathrm{q}_u[n]} \sum_{m=1}^{M} w_m \times \left[\sum_{n=1}^{N} \frac{BTt_m[n]}{\nu_m N} \log_2 \left(1 + \frac{\beta_0 P_m[n]}{\sigma_0^2 \left(H^2 + \|\mathrm{q}_u[n] - \mathrm{q}_m\|^2 \right)} \right) \right]$$
$$\text{s.t. } C2: \frac{T}{N} \sum_{k=1}^{n} \left[\gamma_c f_m^3[k] + t_m[k] P_m[k] \right] \le \frac{\eta_0 T}{N} \sum_{k=1}^{n} \frac{\beta_0 P_0}{H^2 + \|\mathrm{q}_u[k] - \mathrm{q}_m\|^2},$$
$$C4 \text{ and } C5.$$

P_3 is non-convex, by using the SCA technique, P_3 can be solved by iteratively solving the approximate problem P_4.

$$\mathrm{P}_4: \max_{\mathrm{q}_u[n]} \sum_{m=1}^{M} w_m \left[\sum_{n=1}^{N} \frac{BTt_m[n]\, y_{m,\jmath}(\{\mathrm{q}_u[n]\})}{\nu_m N} \right] \quad (18a)$$
$$\text{s.t. } \quad C4 \text{ and } C5, \quad (18b)$$
$$\sum_{k=1}^{n} \left[\gamma_c f_m^3[k] + t_m[k] P_m[k] \right] \le \eta_0 P_0 \beta_0 \overline{h_m}[n].$$

Problem Formulation: Binary Offloading

Under the binary computation offloading mode, the problem is formulated as P_5,

$$\mathrm{P}_5 : \max_{\substack{f_i[n], P_j[n], q[n],\\ t_j[n], \mathcal{M}_0, \mathcal{M}_1}} \sum_{i \in \mathcal{M}_0} \sum_{n=1}^{N} w_i \frac{f_i[n] T}{CN} + \sum_{j \in \mathcal{M}_1} \frac{w_j B T}{\nu_j N} \sum_{n=1}^{N} t_j[n] \log_2 \left(1 + \frac{h_j[n] P_j[n]}{\sigma_0^2}\right)$$

$$\text{s.t. } \frac{T}{N} \sum_{k=1}^{n} \gamma_c f_i^3[k] \le \frac{\eta_0 T}{N} \sum_{k=1}^{n} h_i[k] P_0, n \in \mathcal{N}, i \in \mathcal{M}_0, \tag{19a}$$

$$\frac{T}{N} \sum_{k=1}^{n} t_j[k] P_j[k] \le \frac{\eta_0 T}{N} \sum_{k=1}^{n} h_j[k] P_0, n \in \mathcal{N}, j \in \mathcal{M}_1, \tag{19b}$$

$$\sum_{j \in \mathcal{M}_1} t_j[n] \le 1, n \in \mathcal{N}, \tag{19c}$$

$$\mathcal{M} = \mathcal{M}_0 \cup \mathcal{M}_1, \mathcal{M}_0 \cap \mathcal{M}_1 = \Theta, \tag{19d}$$

$$f_i[n] \ge 0, P_j[n] \ge 0, i \in \mathcal{M}_0, j \in \mathcal{M}_1, \tag{19e}$$

$$C4 \text{ and } C5. \tag{19f}$$

P_5 has a similar structure as P_1 when the operation modes of users are determined. As such, a three-stage alternative optimization algorithm is proposed.

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Three-Stage Alternative Optimization Algorithm

To solve P_5, a binary variable denoted by ρ_m is introduced, where $\rho_m \in \{0,1\}$ and $m \in \mathcal{M}$. Moreover, ρ_m is relaxed as a sharing factor $\rho_m \in [0,1]$. Thus, P_5 can be rewritten as

$$P_6: \max_{\substack{f_m[n], P_n[n], q[n], \\ t_m[n], \rho_m}} \sum_{m=1}^{M} \sum_{n=1}^{N} w_m \left\{ (1-\rho_m) \frac{f_m[n]\,T}{CN} + \frac{BT t_m[n]\,\rho_m}{\nu_m N} \log_2 \left(1 + \frac{h_m[n]\,P_m[n]}{\sigma_0^2} \right) \right\}$$

$$\text{s.t. } (1-\rho_m) \frac{T}{N} \sum_{k=1}^{n} \gamma_c f_m^3[k] + \rho_m \frac{T}{N} \sum_{k=1}^{n} t_m[k]\,P_m[k] \le \frac{\eta_0 T}{N} \sum_{k=1}^{n} h_m[k]\,P_0, \tag{20a}$$

$$\sum_{m=1}^{M} \rho_m t_m[n] \le 1, n \in \mathcal{N}, \tag{20b}$$

$$f_m[n] \ge 0, P_m[n] \ge 0, n \in \mathcal{N}, m \in \mathcal{M}, \tag{20c}$$

$C4$ and $C5$.

For any given $f_m[n]$, $P_m[n]$, $t_m[n]$ and $\mathrm{q}_u[n]$, the user operation selection scheme can be obtained by

$$\rho_m^{opt} = \begin{cases} 0 & \text{if } G_1 \geq G_2, \\ 1 & \text{otherwise;} \end{cases} \tag{21a}$$

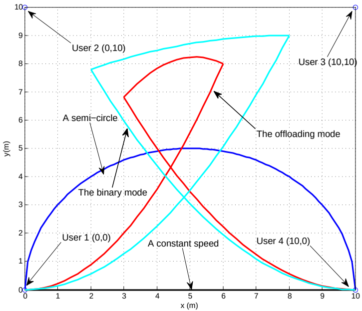
$$G_1 = \sum_{n=1}^{N} \left\{ \frac{w_m f_m[n]}{C} - \upsilon_{m,n} \sum_{k=1}^{n} \gamma_c f_m^3[k] \right\}, \tag{21b}$$

$$G_2 = \sum_{n=1}^{N} \left\{ \frac{B t_m[n]}{\nu_m} \log_2 \left(1 + \frac{h_m[n] P_m[n]}{\sigma_0^2} \right) \right.$$

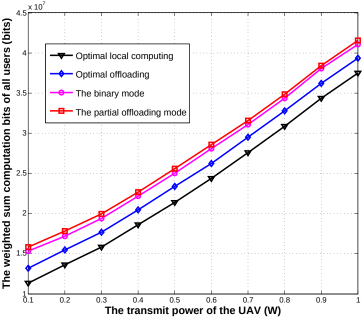
$$\left. - \upsilon_{m,n} \sum_{k=1}^{n} t_m[k] P_m[k] - \frac{N}{T} \varepsilon_n t_m[n] \right\}, \tag{21c}$$

where $\upsilon_{m,n} \geq 0$ and $\varepsilon_n \geq 0$ are the dual variables associated with the constraints given by $(21b)$ and $(21c)$, respectively.

Simulation Results

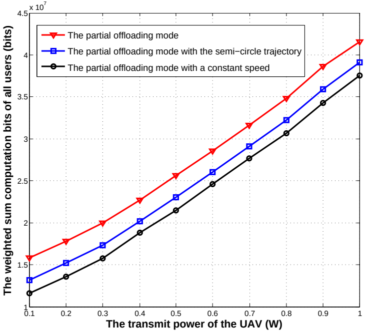


(a) The trajectory of the UAV under different schemes with $T = 2$ seconds.

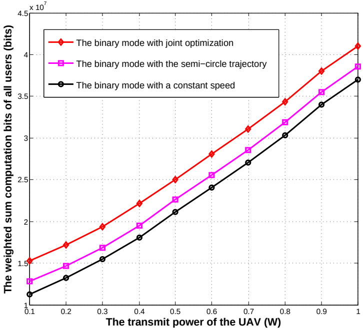


(b) The weighted sum computation bits versus the transmit power.

Simulation Results

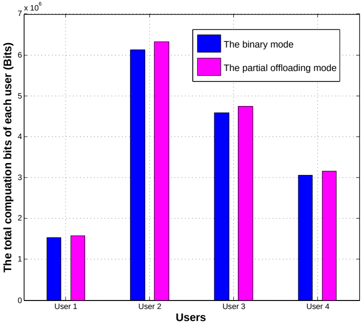


(a) The weighted sum computation bits versus the transmit power with the Partial computation offloading mode.

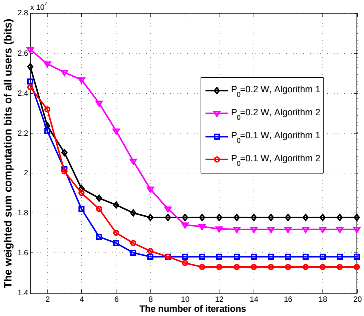


(b) The weighted sum computation bits versus the transmit power with the binary computation offloading mode.

Simulation Results



(a) The total computation bits with $P_0 = 0.1$ W.



(b) The weighted sum computation bits versus the number of iterations.

Conclusions

- The resource allocation problems were studied for UAV-enabled wireless powered MEC systems under both the partial and binary computation offloading modes.
- MEC and wireless power transfer are two promising techniques to enhance the computation capability and to support the operation of low power wireless devices.
- UAV based MEC has been demonstrated to offer more flexibility due to possible better channel conditions and location movement.

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Thanks!

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