Latency-aware Service Provisioning in UAV Mobile Edge Computing

Presenter: Liang Zhang

Ph.D, IEEE Member

Ying Wu College of Computing,

New Jersey Institute of Technology,

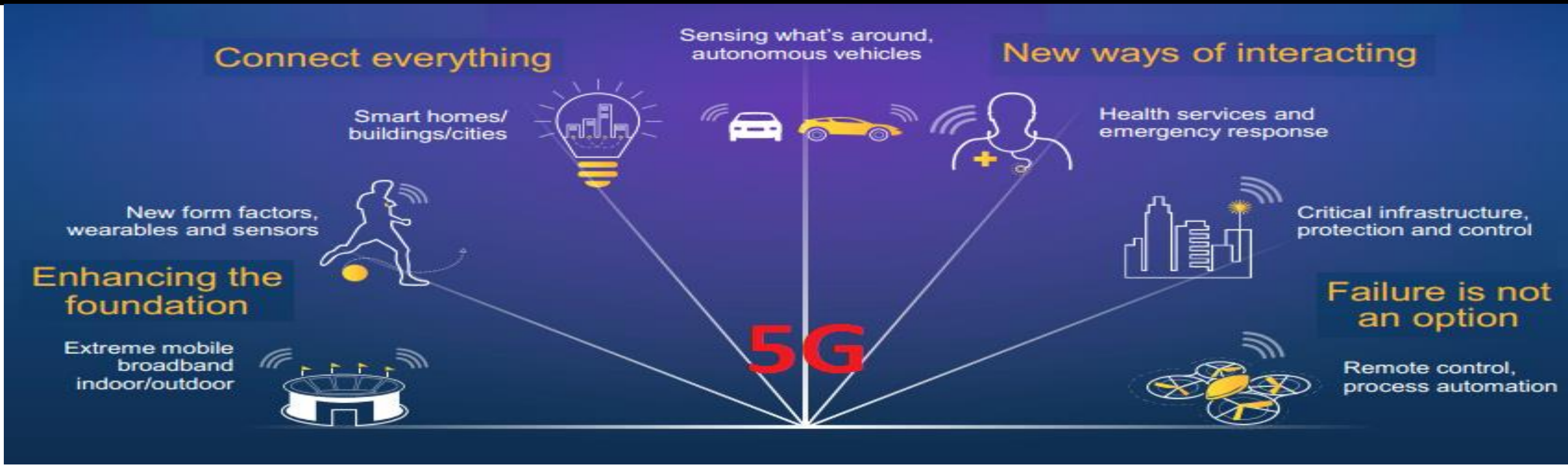
Email: lz284 AT njit.edu

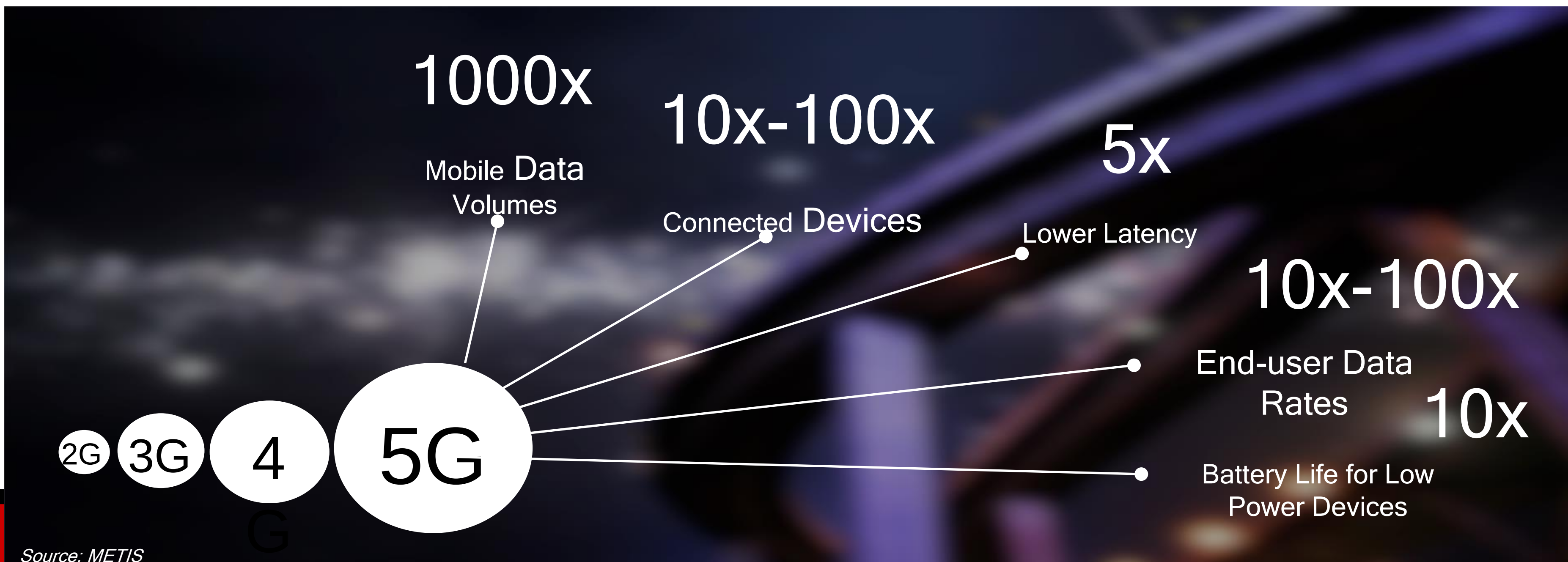
L. Zhang and N. Ansari, "Latency-aware Service Provisioning in UAV Mobile Edge Computing," *IEEE Internet of Things Journal*, vol. 7, no. 10, pp. 10573-10580, Oct. 2020.

Outline

- Mobile Edge Computing and UAV Communications
- System Model and Problem Formulation
- Algorithms and Analysis
- Evaluation Results
- Conclusions
- Future Work

5G is a Fully Mobile Connected Society





What is Mobile Edge Computing?

- MEC is a network architecture that pushes cloud computing capabilities at edge nodes that are close to users and connected to cloud servers via a core network.
- Users receive computing service locally without traversing the remote core network, and thus the latency of users can be reduced.

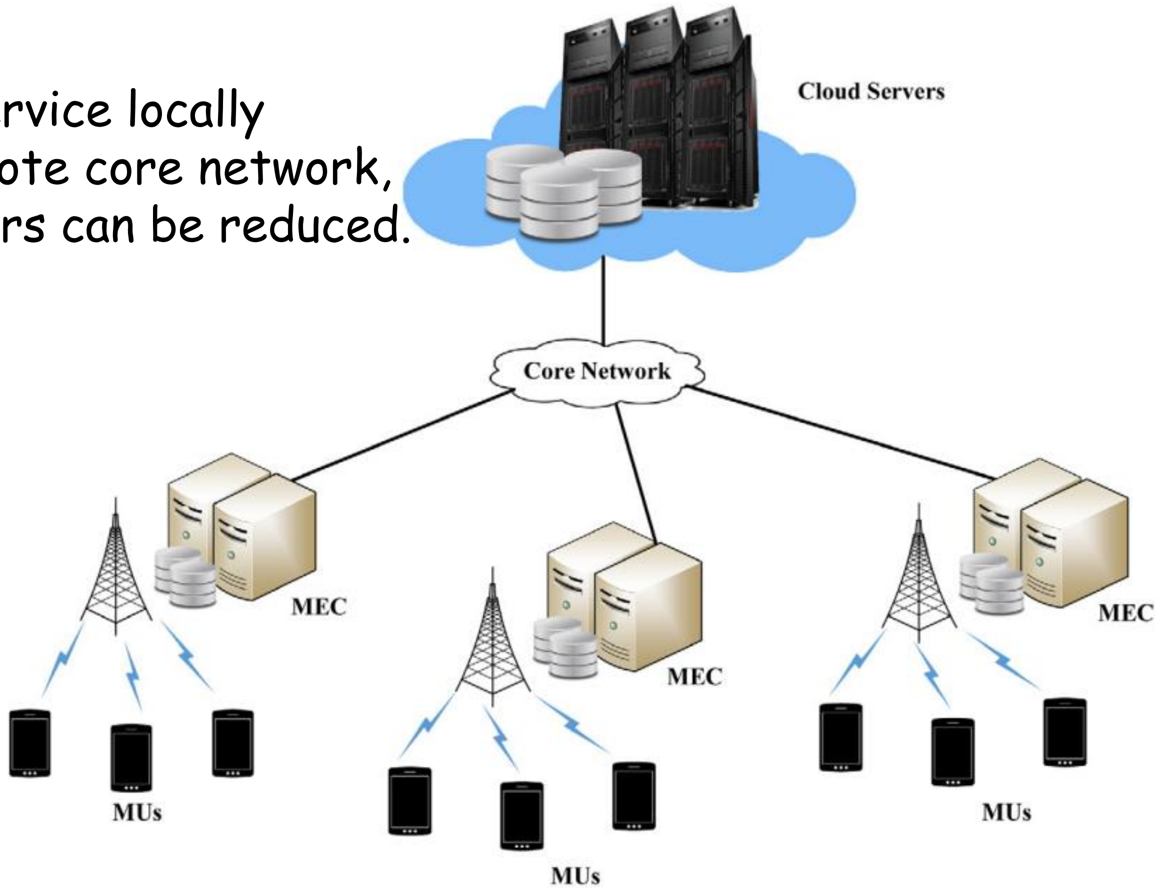


Fig. 1. A mobile edge computing architecture.

Source: I.A. Elgendy, et al. / Future Generation Computer Systems, 100 (2019) 531–541.

Advantages of Using UAV communications?

- UAVs/Drone-mounted base-stations (DBSs) have several advantages:

  i) environmental care-free,

  ii) high maneuverability

  iii) flexible deployment,

  iv) good channel conditions and enhance network capacity.

- Cellular is well suited for drone operation: Ubiquitous coverage, high reliability, and Seamless mobility.

- Sample use cases of using UAVs/DBSs for communication:

temporary large-scale or unexpected events such as Olympic games, football games, concerts, and some other application scenarios.

Source: https://www.qualcomm.com/media/documents/files/leading-the-world-to-5g-evolving-cellular-technologies-for-safer-drone-operation.pdf

Source: I. Bucaille, S. Hethuin, A. Munari, R. Hermenier, T. Rasheed, and S. Allsopp, "Rapidly deployable network for tactical applications: Aerial base station with opportunistic links for unattended and temporary events absolute example," in *IEEE Military Communications Conference*, Nov. 2013.

Unmanned Aircraft Vehicle (UAV) Classifications

- Drone: an unmanned aircraft system

- Unmanned Aerial System (UAS)

UAV Classification: Fixed-Wing vs. Rotar

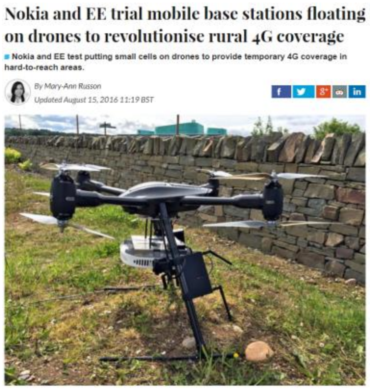
	Fixed-Wing	Rotary-Wing
Mechanism	lift generated using wings with forward airspeed	lift generated using blades revolving around a rotor shaft
Advantages	simpler structure, usually higher payload, higher speed	can hover, able to move in any direction, vertical takeoff and landing
Limitations	need to maintain forward motion, need a runway for takeoff and landing	usually lower payload, lower speed, shorter range

Source: Rui Zhang, Wireless Communications with Unmanned Aerial Vehicles: Opportunities and Challenges, 2016. [Online] https://www.ece.nus.edu.sg/stfpage/elezhang/Publications/UAV%20Communications.pdf

Prototypes of UAV Communications

- Nokia had developed a 4G base station weighing only 2Kg in 2016, which was successfully mounted on a commercial quad-copter to provide coverage over a remote area in Scotland.

- Several projects by the industry have already been initiated, such as Project Aquila by Facebook, Cell on Wings (COW) by ATT, and Google projects such as SKYBENDER that are designed for drone-based internet services.


Nokia and EE trial mobile base stations floating on drones to revolutionise rural 4G coverage

Nokia and EE test putting small cells on drones to provide temporary 4G coverage in hard-to-reach areas.

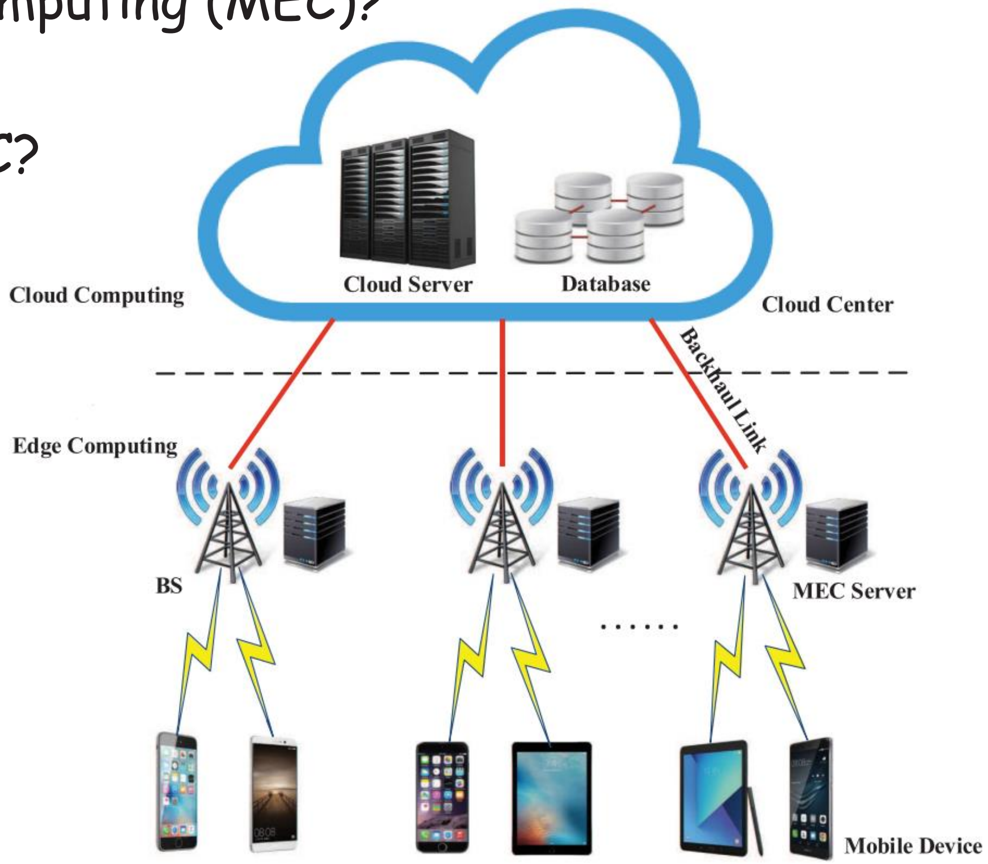
By Mary-Ann Russon

Updated August 15, 2016 11:19 BST

Source: I. B. Times, "Nokia and EE trial mobile base stations floating on drones to revolutionise rural 4G coverage," url: http://www. ibtimes.co.uk/nokia-ee-trial-mobile-base-stations-floatingdrones-revolutionise-rural-4g-coverage-1575795, 2016.
Source: D. Bharadia, E. McMilin, and S. Katti, "Full duplex radios," in Proc. *ACM SIGCOMM*, pp. 375–386, Aug. 2013.

Why Do We Need UAV-aided MEC?

- Why do we need Mobile Edge Computing (MEC)?
- Why do we need UAV-aided MEC?
- UAV-aided MEC:
  line-of-sight communications, high mobility, high flexibility, and high maneuverability.



Source: J. Ren, G. Yu, Y. He, and G. Y. Li, “Collaborative cloud and edge computing for latency minimization,” IEEE Trans. Veh. Technol., vol. 68, no. 5, pp. 5031–5044, May 2019.
Source: Q. Hu, Y. Cai, G. Yu, Z. Qin, M. Zhao and G. Y. Li, "Joint Offloading and Trajectory Design for UAV-Enabled Mobile Edge Computing Systems," in *IEEE Internet of Things Journal*, vol. 6, no. 2, pp. 1879-1892, Apr. 2019.

Outline

- Mobile Edge Computing and UAV Communications
- System Model and Problem Formulation
- Algorithms and Analysis
- Evaluation Results
- Conclusions
- Future Work

A UAV-MEC Network

- Low latency UAV-MEC architecture
- UAV → relay or edge computing

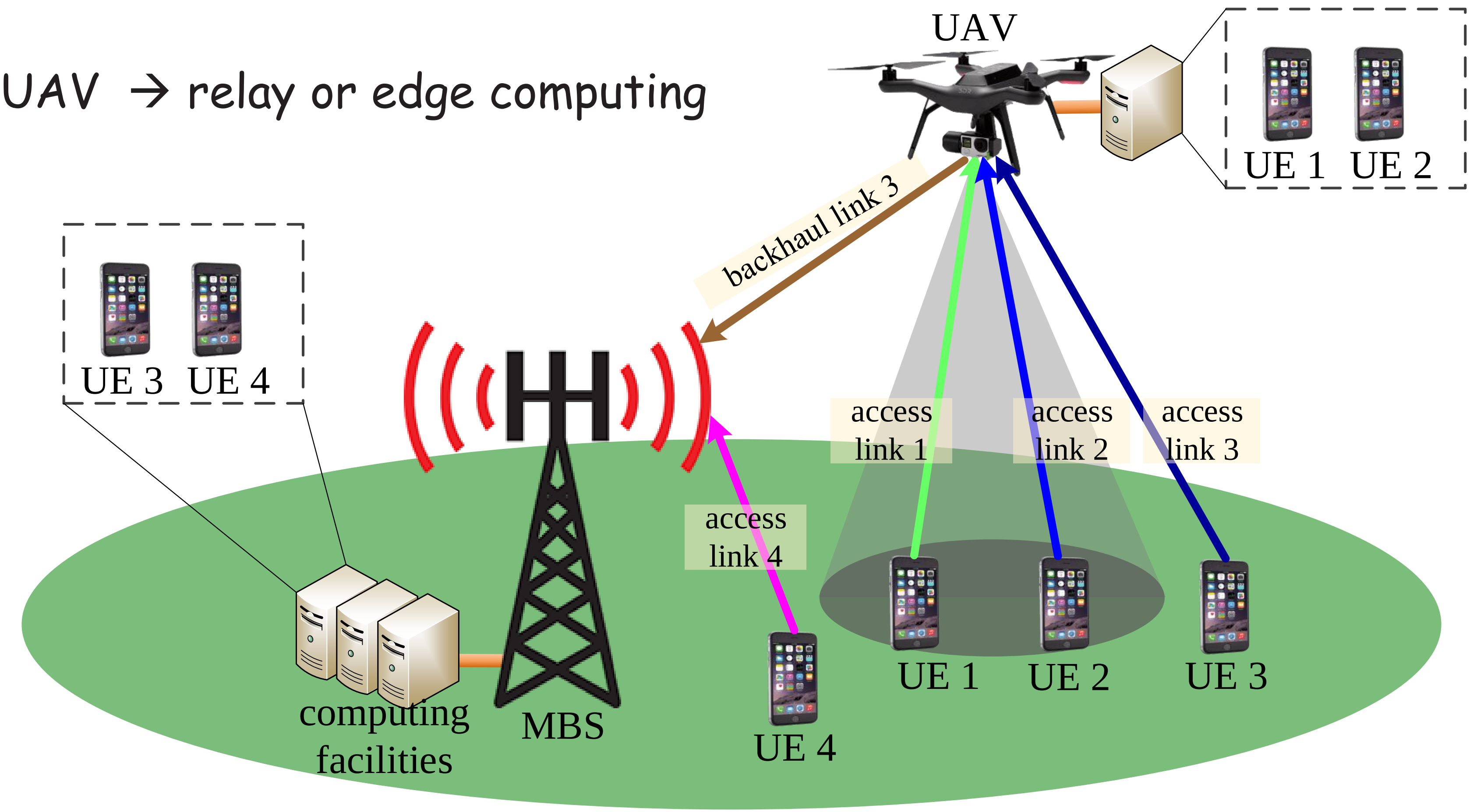


Fig. 2. UAV mobile edge computing.

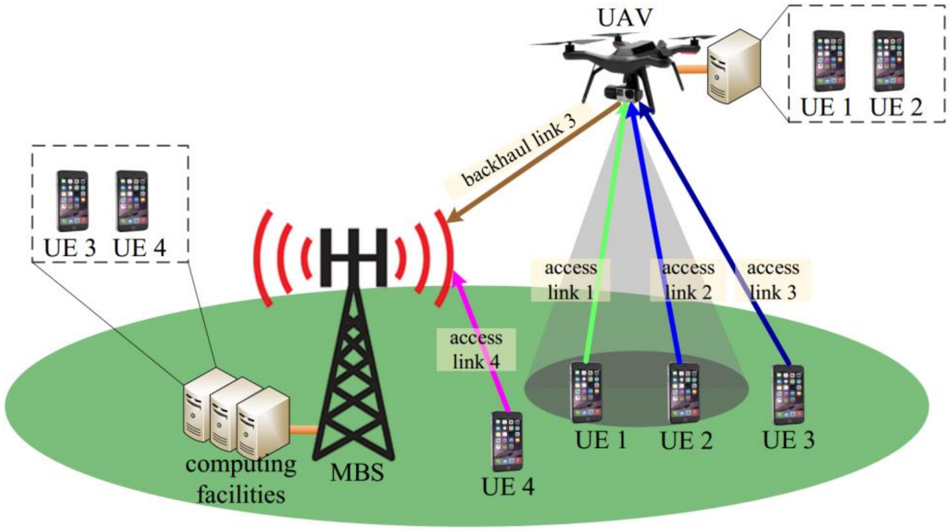
Communication Model

- Assume $\beta_{i,j}$ is the data rate from the ith user to the jth BS:

$$\beta_{i,j} = \begin{cases} \max(\beta_{i,j}^{d}, \beta_{i,j}^{b}), & j = 1 \\ \beta_{i,j}^{b}, & j > 1 \end{cases} \qquad (3)$$

- The propagation delay is:

$$t_{i,j} = \frac{l_i}{\beta_{i,j}} \qquad (4)$$



Computing Model

- r_i is the required computing resources (CPU cycles/bit), and l_i is the *i*th user's data size in bits to be processed.
- C_j is the computing capacity (CPU cycles/s) of the MEC server in the *j*th BS.
- Let $T_{i,j}$ be the total latency of the ith user provisioned by the jth BS:

$$T_{i,j} = \kappa_{i,j} T_0 + q_{i,j} + \tau_{i,j} \quad (5)$$

Here, $\kappa_{i,j} = \lceil t'_{i,j} / T_0 \rceil$ is the index of the time frame, and $t'_{i,j} = t_{i,j} + (k-1)T_0$;

$t'_{i,j}$ is the time allotted for transmission from user i to BS j;

$(k-1)T_0$ is the waiting time for transmission;

$\tau_{i,j} = r_i l_i / C_j$ is the computing time;

$q_{i,j}$ is the waiting time for obtaining the computing service.

- In this article, we focus on the problem of provisioning services via the UAV-aided MEC network (UAV-MEC) .
- The objective to minimize the average latency of all users.

$$\mathscr{P}_1: \min_{\omega_{i,j}, t_{i,j}, \tau_{i,j}, \gamma_j} \sum_i \sum_j \alpha_i \omega_{i,j} T_{i,j}$$

s.t. :

$$C1: \sum_j \omega_{i,j} \leq 1 \quad \forall i \in \mathscr{U}$$

$$C2: \sum_i \sum_j \omega_{i,j} t_{i,j} \leq T_0$$

$$C3: \omega_{i,j} \in \{0,1\} \quad \forall i \in \mathcal{U}, j \in \mathscr{B}$$

$$C4: t_{i,j} \geq 0 \quad \forall i \in \mathcal{U}, j \in \mathscr{B}$$

$$C5: \tau_{i,j} \geq 0 \quad \forall i \in \mathcal{U}, j \in \mathscr{B}$$

$$C6: \gamma_j \in \Gamma \quad \forall j \in \tilde{\mathscr{B}}.$$

- C1: Provisioning Constraint
- C2, C4: Communication Constraint
- C5: Computing Constraint
- C6: UAV Placement Constraint

Outline

- Mobile Edge Computing and UAV Communications
- System Model and Problem Formulation
- Algorithms and Analysis
- Evaluation Results
- Conclusions
- Future Work

Analysis

- The UAV-MEC problem is strongly NP-hard as the multiprocessor scheduling problem is strongly NP-hard [A1].
- The UAV-MEC problem is decomposed into three sub-problems:

  1) the joint UE association and computing resource assignment (JCRA) problem;

  2) the communication resource assignment problem;

  3) the UAV placement problem.

- The JCRA problem:

$$\mathscr{P}_2 : \min_{\omega_{i,j}} \quad \sum_i \sum_j \alpha_i \omega_{i,j} \tau_{i,j}$$

$$\text{s.t. :}$$

$$C1 : \sum_j \omega_{i,j} = 1 \quad \forall i \in \mathscr{U}$$

$$C2 : \omega_{i,j} \in \{0, 1\} \quad \forall i \in \mathcal{U}, j \in \mathscr{B}$$

$$C3 : \tau_{i,j} \geq 0 \quad \forall i \in \mathcal{U}, j \in \mathscr{B}. \qquad (12)$$

$$\sum_i \sum_j \tau_{i,j} \approx N \cdot L$$

- $\sum_i \sum_j \tau_{i,j} = N \cdot L$ when the makespan of all servers are the same.

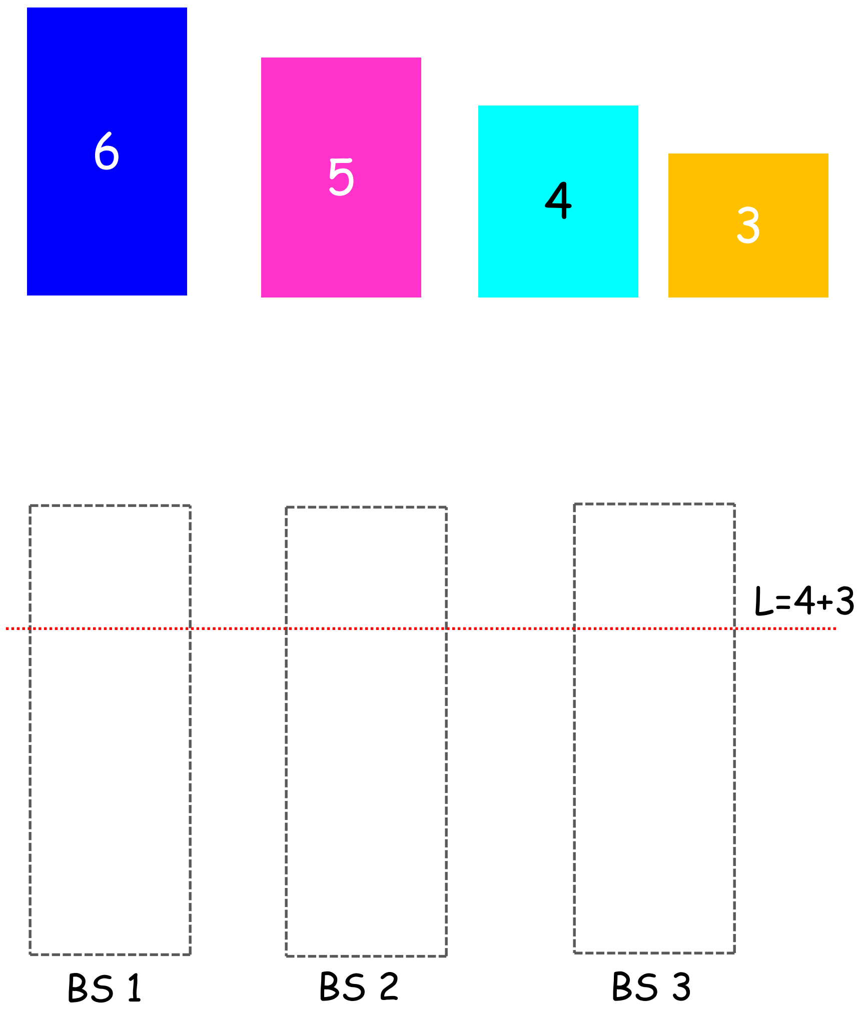
Joint UE Association and Computing Resource Assignment

- Problem P3 is the classical makespan scheduling problem (the multiprocessor scheduling problem).

$$
\begin{aligned}
&\mathscr{P}_3 : \min_{\omega_{i,j}} \quad L \\
&s.t. : \\
&\quad C1 : \sum_j \omega_{i,j} = 1, \quad \forall i \in \mathscr{U}, \\
&\quad C2 : \sum_i \omega_{i,j}\tau_{i,j} \le L, \quad \forall j \in \mathscr{B} \\
&\quad C3 : \omega_{i,j} \in \{0,1\}, \quad \forall i \in \mathcal{U}, j \in \mathscr{B}, \\
&\quad C4 : \tau_{i,j} \ge 0, \quad \forall i \in \mathcal{U}, j \in \mathscr{B}. \qquad (13)
\end{aligned}
$$

Joint UE Association and Computing Resource Assignment

- Problem P3 is the classical makespan scheduling problem (the multiprocessor scheduling problem).
- An approximation algorithm is proposed to solve problem *P3* and referred to *AA-JCRA*.



Algorithm 1: AA-JCRA

Input : $\mathscr{B}$, $\mathscr{U}$, C_j, l_i, r_i and γ_j;
Output: $\omega_{i,j}$, $\tau_{i,j}$ and Λ_j;

sort all UE demands in $\mathscr{U}_0$ by the decreasing order based on the required computing resources;
$i = 1$, $\omega_{i,j} = 0$, and $\Lambda_j = 0$, $\forall j \in \mathscr{B}$;
for $i \in \mathscr{U}_0$ **do**
  get the BS index $\tilde{j}$ with the least completion time after serving the ith UE, $\tilde{j} = \underset{j}{\operatorname{argmin}}(\Lambda_j + \tau_{i,j})$;
  assign the ith UE to the $\tilde{j}$th BS;
  update $\tau_{i,\tilde{j}}$ and set $\omega_{i,\tilde{j}} = 1$;
  update the workload, $\Lambda_{\tilde{j}} = \Lambda_{\tilde{j}} + \tau_{i,\tilde{j}}$;
return $\omega_{i,j}$, $\tau_{i,j}$ and Λ_j;

Proof of the Approximation Ratio for Identical Servers

Theorem 1. The AA-JCRA algorithm achieves a $(1+\varepsilon)$-approximation for problem *P3*. Here, $\varepsilon = \frac{1}{2}(1 - \frac{1}{|B|+m-1})$ and $0 \le \varepsilon < \frac{1}{2}$. Here, *m* is a ratio, viz., computing capacity of a BS versus the minimum computing capacity of a BS. If the servers in all BS have identical computing capacity, $\varepsilon = \frac{1}{2}(1 - \frac{1}{|B|})$.

$$\sum_i \sum_j \tau_{i,j} C_j - \tau_{i',j'} C_{j'} \ge \sum_j (L - \tau_{i',j'}) C_j$$

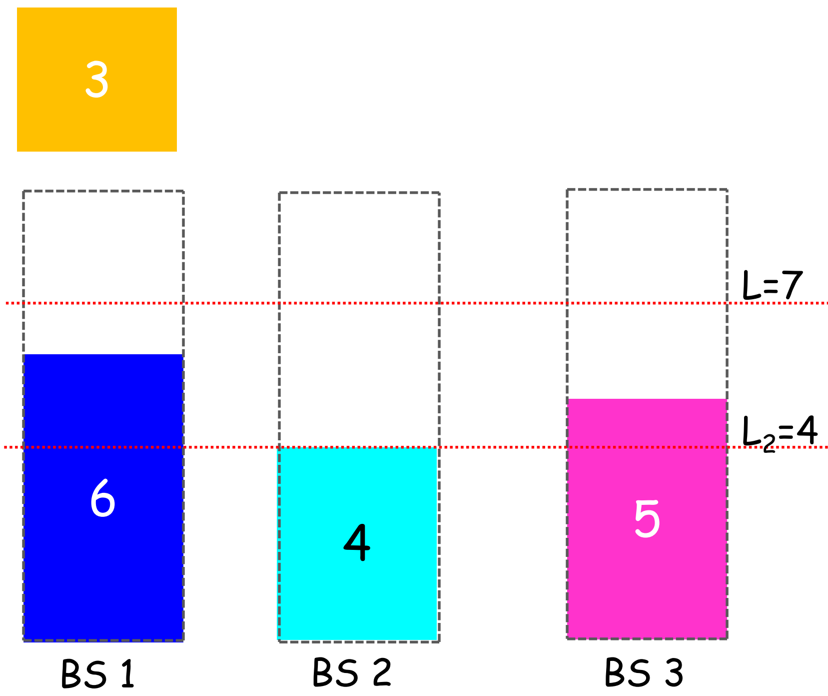
$$L \sum_j C_j \le \sum_i \sum_j \tau_{i,j} C_j + \tau_{i',j'} \sum_j C_j - \tau_{i',j'} C_{j'}$$

$$L \le \frac{1}{\sum_j C_j}\left(\sum_i \sum_j \tau_{i,j} C_j\right) + \tau_{i',j'} - \frac{1}{\sum_j C_j}(\tau_{i',j'} C_{j'})$$

$$L \le OPT + \frac{1}{2} OPT \left(1 - \frac{C_{j'}}{\sum_j C_j}\right)$$

$$L \le \left(\frac{3}{2} - \frac{1}{2(|\mathscr{B}| + m - 1)}\right) OPT$$

$$L \le (1+\epsilon) OPT, \quad \epsilon = \frac{1}{2}\left(1 - \frac{1}{|\mathscr{B}| + m - 1}\right).$$



Proof of the Approximation Ratio for Non-identical Servers

Theorem 1. The *AA-JCRA* algorithm achieves a $(1+\varepsilon)$-approximation for problem *P3*. Here, $\varepsilon = \frac{1}{2}(1 - \frac{1}{|B|+m-1})$ and $0 \le \varepsilon < \frac{1}{2}$. Here, *m* is a ratio, viz., computing capacity of a BS versus the minimum computing capacity of a BS. If the servers in all BS have identical computing capacity, $\varepsilon = \frac{1}{2}(1 - \frac{1}{|B|})$.

$A^d < A^e$

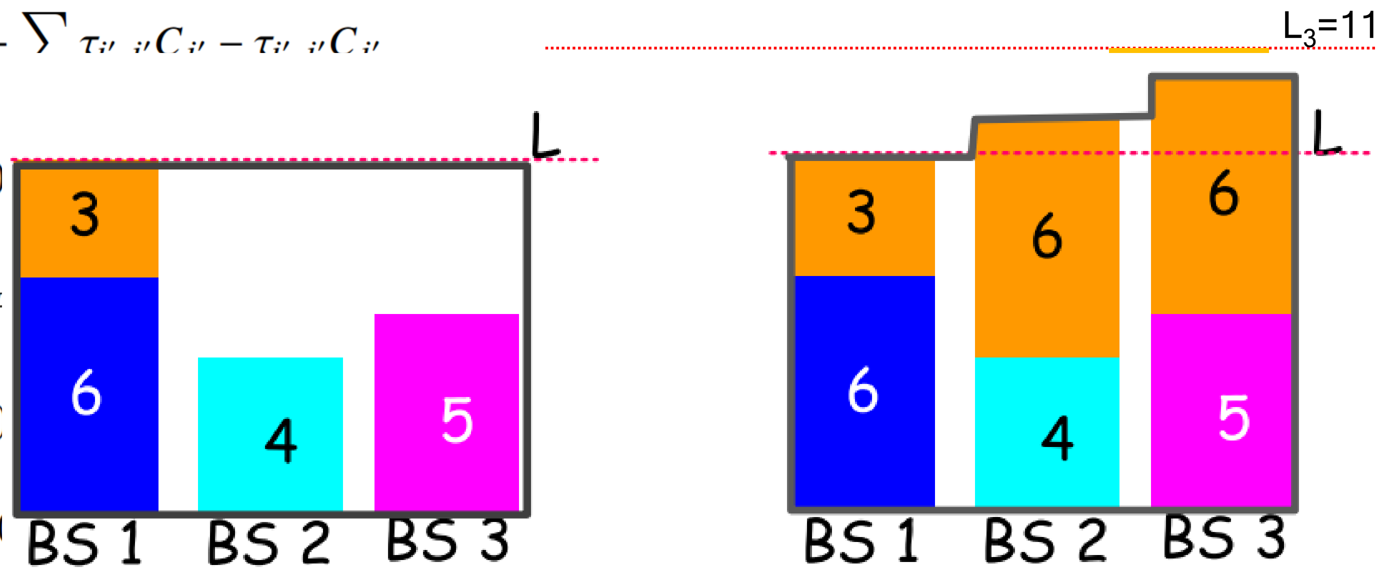
$L\sum_j C_j \le \sum_i \sum_j \tau_{i,j} C_j + \sum \tau_{i',j'} C_{j'} - \tau_{i',j'} C_{j'}$

$L \le \frac{1}{\sum_j C_j}(\sum_i \sum_j \tau_{i,j} C_j)$

$L \le OPT + \frac{1}{2}OPT - \frac{1}{2}OI$

$L \le (\frac{3}{2} - \frac{1}{2(|\mathscr{B}| + m - 1)}$

$L \le (1+\epsilon)OPT, \quad \epsilon = \frac{1}{2}($



BS 1 BS 2 BS 3

The Communication Resource Assignment Problem

- Time resource is assigned to users in order to transmit the data to the MBS or UAVs.
- In P4, $\kappa_{i,j} = \lceil t'_{i,j}/T_0 \rceil = \kappa'_{i,j} + (k-1)T_0$ is the index of the time frame; $t'_{i,j} = t_{i,j} + (k-1)T_0$ is the time allotted for transmission from user i to BS j; $(k-1)T_0$ is the waiting time for transmission.

$$
\begin{aligned}
\mathscr{P}_4 : \min_{t_{i,j}} \quad & \sum_j \sum_i \omega_{i,j} \kappa_{i,j} T_0 \\
s.t. : \quad & \\
& C1 : \sum_i \sum_j \omega_{i,j} t_{i,j} \le \kappa_{i,j} T_0, \\
& C2 : t_{i,j} \ge 0, \quad \forall i \in \mathcal{U}, j \in \mathscr{B}, \\
& C3 : t_{i,j} \le \kappa'_{i,j} \le t_{i,j} \xi, \quad \forall i \in \mathcal{U}, j \in \mathscr{B}. \qquad (15)
\end{aligned}
$$

The UAV Placement Problem

- The position of a UAV greatly affects communications, viz., a poor link between a UAV and a user results in low data rate transmission and increased latency.

- An exhaustive search method is used to solve the UAV placement problem P5.

$$\mathscr{P}_5 : \min_{\gamma_j} \quad \psi_5(\gamma_j)$$
$$\text{s.t.} :$$
$$C1 : \gamma_j \in \Gamma \quad \forall j \in \tilde{\mathscr{B}} \tag{17}$$

$$\psi_5(\gamma_j) = \psi_1\Big|_{\omega_{i,j}=\omega'_{i,j}, t_{i,j}=t'_{i,j}, \tau_{i,j}=\tau'_{i,j}}$$

The UAV-MEC Problem

- We propose an approximation algorithm, named *AA-UAV-MEC* algorithm, to solve the UAV-MEC problem based on the solutions to the sub-problems.

- Theorem 3. The approximation algorithm for the UAVMEC problem, *AA-UAV-MEC* algorithm, has a $(1+\varepsilon)$-approximation ratio of solving the UAV-MEC problem, where $\varepsilon = \frac{1}{2}(1 - \frac{1}{|B|+m-1})$ and $0 \le \varepsilon < \frac{1}{2}$. The approximation ratio of the *AA-UAV-MEC* algorithm is $(\frac{3}{2} - \frac{1}{2|B|})$ if the servers in all BSs have identical computing capacity, $\varepsilon = \frac{1}{2}(1 - \frac{1}{|B|})$.

Algorithm 3: AA-UAV-MEC

```
Input  : 𝓑, 𝓤, C_j, l_i, r_i and Γ;
Output: ω_{i,j}, τ_{i,j}, Λ_j, t_{i,j} and γ_j;
for γ_j ∈ Γ do
    update positions of UAVs γ_j;
    obtain ω_{i,j} and Λ_j by Algorithm 1;
    calculate τ_{i,j} and t_{i,j};
find γ_j* by γ_j* = argmin_{γ_j} Σ_i Σ_j α_i ω_{i,j} T_{i,j};
return ω_{i,j}, τ_{i,j}, Λ_j, t_{i,j} and γ_j.
```

Outline

- Mobile Edge Computing and UAV Communications
- System Model and Problem Formulation
- Algorithms and Analysis
- Evaluation Results
- Conclusions
- Future Work

Evaluation Settings

- MATLAB is used to run the simulation, and the average results are obtained by 100 repeated runs.
- For each simulation, the coverage area of the MBS is 1000 m × 1000 m; and this area is divided into 36 equal areas.
- All UAVs fly at the same fixed altitude, 100 m. The weights of UEs are the same, the total bandwidth is 20 MHz, and the time frame is set as 100 ms [10].

Table I: Simulation Parameters

T_0, length of the time frame	100 ms [10]
the input data size	$[0.1, 0.3]$ MB
required number of CPU cycles per bit	[500, 1500] CPU cycle/bit
UAV computing capacity	5×10^9 CPU cycle/s
Edge computing capacity	1×10^9 CPU cycle/s
(a, b, η_L, η_N), environment parameters	$(9.61, 0.16, 1, 20)$
h_j	100 m
path loss between the MBS and the UE	$131.1 + 42.8log10(d_{i,j})$, $d_{i,j}$ in km [27]
Rayleigh fading between a UE and the MBS	8 dB
N_0	-174 dBm/Hz
$\|\mathcal{U}\|$	$\{10, 15, \cdots, 40\}$
P^V	27 dBm
P^U	23 dBm
β^M	20 MHz

Baseline Algorithms

- *Least-BW:*
  the same number of UAVs is used as Algorithm 3;
  all UEs are assigned to a BS with the highest weight (similar to the best SINR strategy);
  the weight is defined as the required data of the user over the required transmission time to a BS.

- *UAV-Relay*:
  the same number of UAVs is utilized as Algorithm 3;
  all UEs are assigned to the BS with the least workload and the UAVs are working as relay nodes.

- *No-UAV*:
  all UEs are provisioned by the MBS.

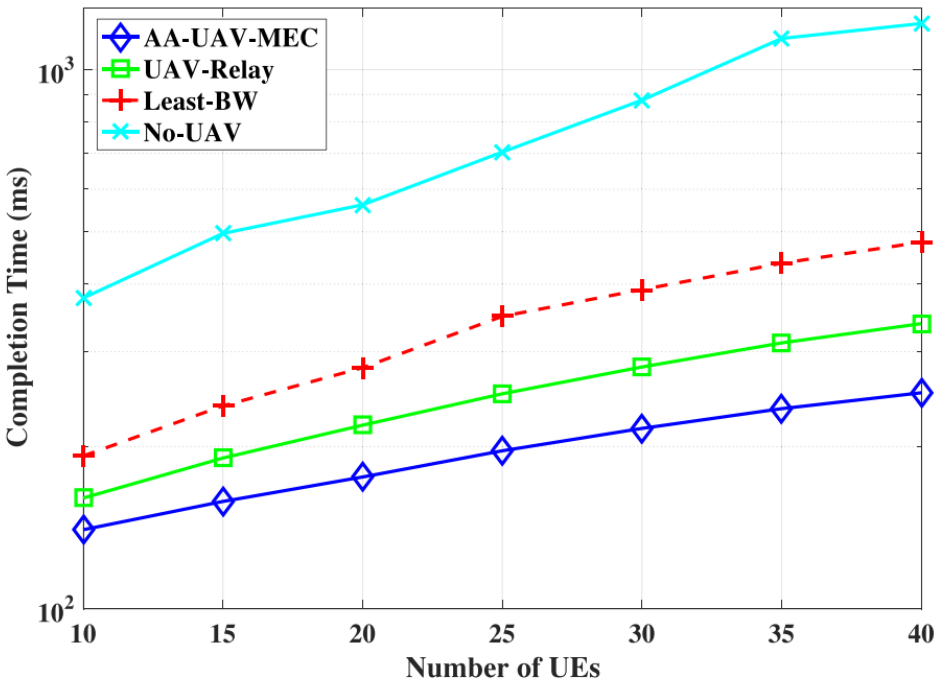


Fig. 3. Maximum completion time versus UEs with three UAVs.

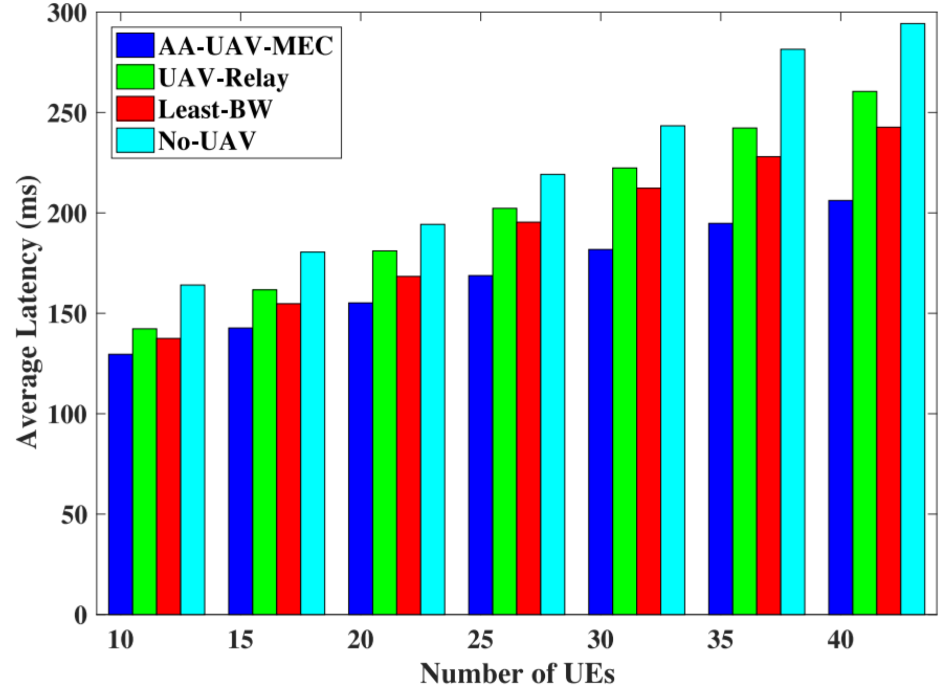


Fig. 4. Average UE latency versus UEs with three UAVs.

- The maximum completion time of the AA-UAV-MEC algorithm has decreased by 25%, 47% and 79% as compared to those of the UAV-Relay, Least-BW and No-UAV algorithms, respectively.
- The average UE latency of the AA-UAV-MEC algorithm has decreased by 20%, 15% and 30% as compared to that of the UAV-Relay, Least-BW and No-UAV algorithms, respectively.

Evaluations

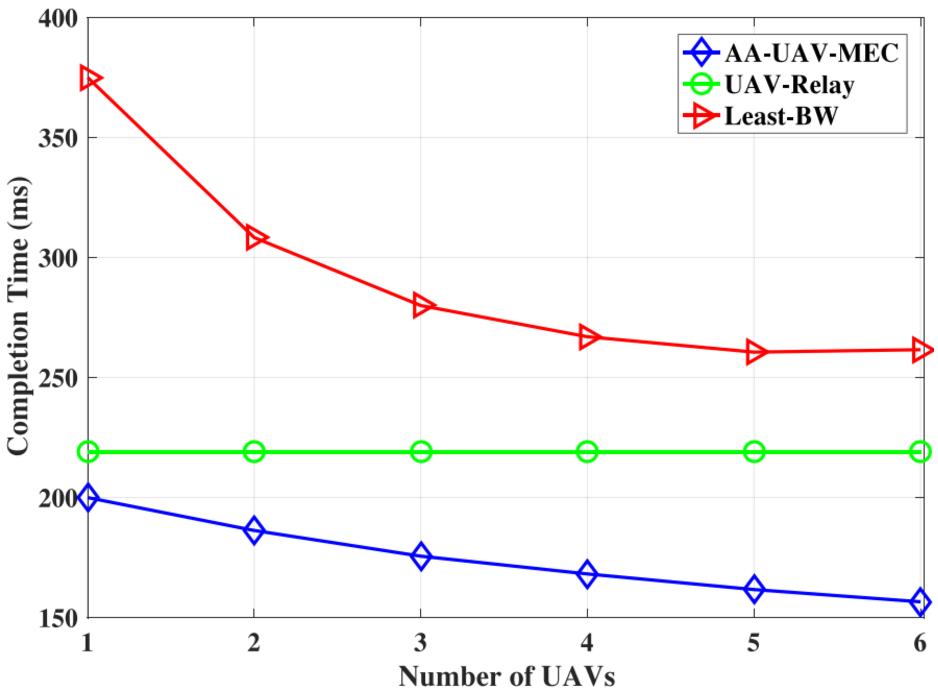


Fig. 5. Maximum completion time versus the number of UAVs..

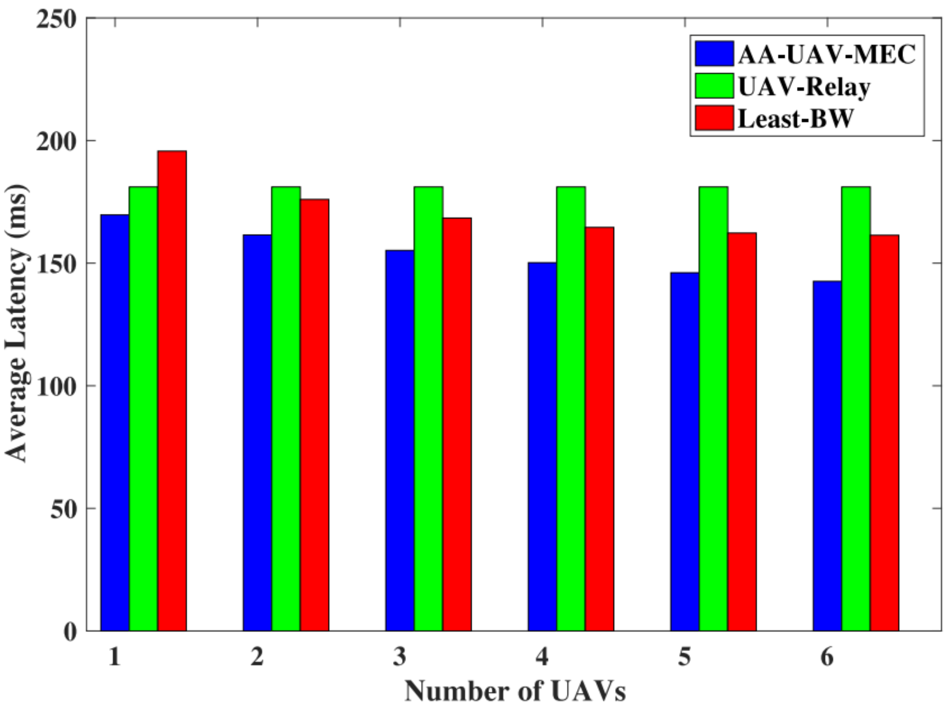


Fig. 6. Average UE latency versus the number of UAVs.

- Both the completion time and the average UE latency of the AA-UAV-MEC algorithm and the Least-BW algorithm decrease as the number of UAVs increases because the computing resource increases as the number of UAV increases.

Outline

- Mobile Edge Computing and UAV Communications
- System Model and Problem Formulation
- Algorithms and Analysis
- Evaluation Results
- Conclusions
- Future Work

Conclusions

- We have studied the service provisioning problem in the UAV-MEC, in which the UAV and the MBS are equipped with computing resources, including the UAV placement, the user association, the time assignment in the access links and the backhaul links, and the computing resource assignment in the MBS and UAVs.

- We have proposed one approximation algorithm to solve the joint user association and computing resource assignment problem and proved the approximation ratio of the proposed algorithm.

- We have proposed one approximation algorithm to solve the UAV-MEC problem by leveraging the solutions of the sub-problems and demonstrated its performance via extensive simulations.

Outline

- Mobile Edge Computing and UAV Communications
- System Model and Problem Formulation
- Algorithms and Analysis
- Evaluation Results
- Conclusions
- Future Work

Future Work

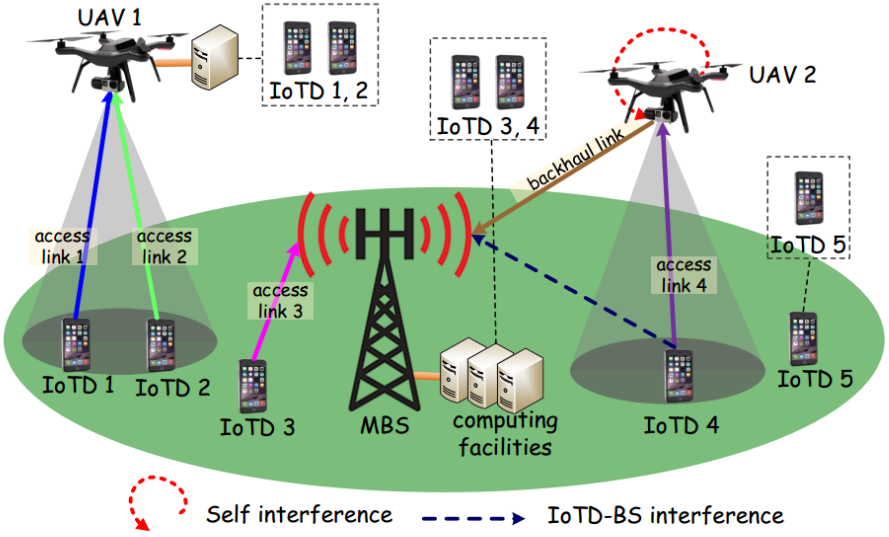


Fig. 7. A novel UAV-assisted mobile edge computing architecture.

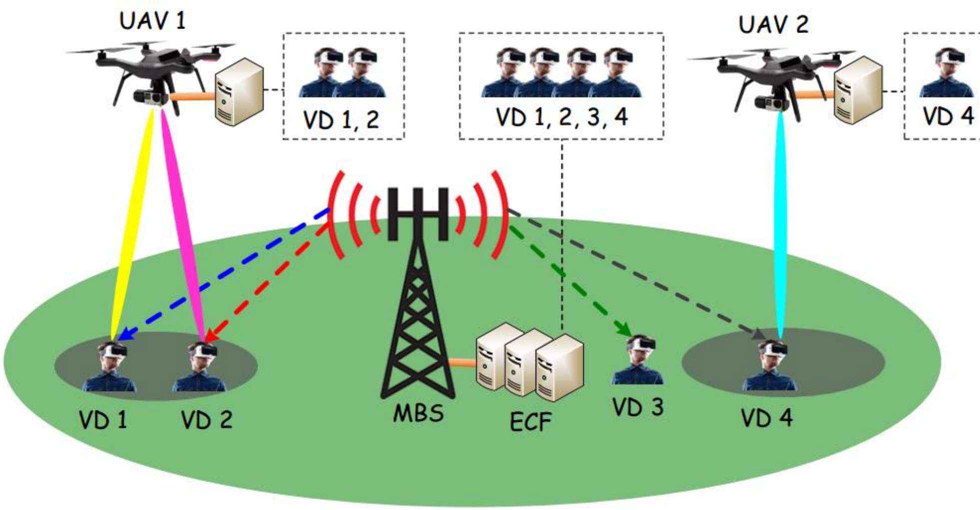


Fig. 8. A UAV-aided MEC framework over mmWave for the VR application.

- Fig. 7 shows a UAV-MEC architecture with the target to minimize the total cost of provisioning all users (IoTDs).
- Fig. 8 shows a UAV-MEC architecture with the target to minimize the average QoE of all users in all time slots.
- A deep reinforcement learning (Deep Deterministic Policy Gradient, DDPG) algorithm is used in the optimization.

Publications

Journal Articles:

- **L. Zhang** and N. Ansari, "Latency-aware Service Provisioning in UAV Mobile Edge Computing," *IEEE Internet of Things Journal*, vol. 7, no. 10, pp. 10573-10580, Oct. 2020.
- N. Ansari and **L. Zhang**, "Flexible backhaul-aware DBS-aided HetNet with IBFD communications," *ICT Express*, vol. 6, no. 1, pp. 48-56, Mar. 2020 (Invited Paper).
- **L. Zhang** and N. Ansari, "Optimizing the deployment and throughput of DBSs for uplink communications," *IEEE Open Journal of Vehicular Technology (OJVT)*, vol. 1, pp. 18-28, Jan. 2020 (Invited Paper).
- N. Ansari, Q. Fan, X. Sun and **L. Zhang**, "SoarNet," *IEEE Wireless Communications*, vol. 26, no. 6, pp. 37-43, Dec. 2019.
- **L. Zhang** and N. Ansari, "A framework for 5G Networks with in-band full-duplex enabled drone-mounted base-stations," *IEEE Wireless Communications*, vol. 26, no. 5, pp. 121-127, Oct. 2019.
- **L. Zhang** and N. Ansari, "Approximate algorithms for 3-D placement of IBFD enabled drone-mounted base-stations," *IEEE Transactions on Vehicular Technology*, vol. 68, no. 8, pp. 7715-7722, Jun. 2019.
- **L. Zhang** and N. Ansari, "On the number and 3-D placement of in-band full-duplex enabled drone-mounted base-stations," *IEEE Wireless Communications Letters*, vol. 8, no. 1, pp. 221-224, Feb. 2019.
- **L. Zhang**, Q. Fan and N. Ansari, "3-D drone-base-station placement with in-band full-duplex communications," *IEEE Communications Letters*, vol. 22, no. 9, pp. 1902-1905, Sept. 2018.
- **L. Zhang**, T. Han and N. Ansari, "Energy-aware virtual machine management in inter-datacenter networks over elastic optical infrastructure," *IEEE Transactions on Green Communications and Networking*, vol. 2, no. 1, pp. 305-315, Mar. 2018.
- **L. Zhang**, N. Ansari and A. Khreishah, "Anycast planning in space division multiplexing elastic optical networks with multi-core fibers," *IEEE Communications Letters*, vol. 20, no. 10, pp. 1983-1986, Oct. 2016.
- P. Lu, **L. Zhang**, X. Liu, J. Yao and Z. Zhu, "Highly efficient data migration and backup for big data applications in elastic optical inter-data-center networks," *IEEE Network*, vol. 29, no. 5, pp. 36-42, Sept. 2015.
- **L. Zhang** and Z. Zhu, "Spectrum-efficient anycast in elastic optical inter-datacenter networks," *Optical Switching and Networking (Elsevier)*, vol. 14, no. 3, pp. 250-259, Aug. 2014.
- Z. Zhu, W. Lu, **L. Zhang** and N. Ansari, "Dynamic service provisioning in elastic optical networks with hybrid single-/multi-path routing," *IEEE/OSA Journal of Lightwave Technology*, vol. 31, no. 1, pp. 15-22, Jan. 2013.

Under Review or Revision:

- **L. Zhang** and N. Ansari, "Optimizing the Operation Cost for UAV-aided Mobile Edge Computing," **submitted** to *IEEE Transactions on Vehicular Technology*, in review.
- W. Liu, **L. Zhang** and N. Ansari, "Joint Laser Charging and DBS Placement for Downlink Communications," IEEE Transaction on Network Science and Engineering, in review.

Publications (Cont'd)

Conference Papers:

- **L. Zhang** and N. Ansari, "Backhaul-aware uplink communications in full-duplex DBS-aided HetNets," *Proc. 2019 IEEE Global Communications Conference (GLOBECOM 2019)*, Waikoloa, HI, USA, Dec. 9-13, 2019.
- **L. Zhang**, Y. Luo, N. Anwari, B. Gao, X. Liu and F. Effenberger, "Enhancing next generation passive optical network stage2 (NG-PON2) with channel bonding," *International Conference on Networking, Architecture, and Storage*, pp. 1-6, Aug. 2017.
- **L. Zhang**, Y. Luo, N. Ansari, B. Gao, X. Liu and F. Effenberger, "Channel bonding for next generation passive optical network stage 2 (NG-PON2)," *International Conference on Computer, Information and Telecommunication Systems (CITS)*, pp. 103-107, Jul. 2017.
- Y. Luo, **L. Zhang**, N. Ansari, B. Gao, X. Liu and F. Effenberger, "Wavelength channel bonding for 100 Gb/s next generation passive optical networks," *Wireless and Optical Communication Conference (WOCC)*, pp. 1-6, Apr. 2017.
- **L. Zhang**, Y. Luo, B. Gao, X. Liu, F. Effenberger and N. Ansari, "Channel bonding design for 100 Gb/s PON based on FEC codeword alignment," *Optical Fiber Communications Conference and Exhibition (OFC)*, pp. 1-3, Mar. 2017.
- **L. Zhang**, T. Han and N. Ansari, "Revenue driven virtual machine management in green datacenter networks towards big data," *IEEE Global Communications Conference (GLOBECOM)*, pp. 1-6, Dec. 2016 (**NSF Travel Grant**).
- **L. Zhang**, T. Han and N. Ansari, "Renewable energy-aware inter-datacenter virtual machine migration over elastic optical networks," *IEEE International Conference on Cloud Computing Technology and Science (CloudCom)*, pp. 440-443, Dec. 2015.
- X. Liu, **L. Zhang**, M. Zhang and Z. Zhu, "Joint defragmentation of spectrum and computing resources in inter-datacenter networks over elastic optical infrastructure," *IEEE International Conference on Communications (ICC)*, pp. 3289-3294, Jun. 2014.
- **L. Zhang** and Z. Zhu, "Dynamic anycast in inter-datacenter networks over elastic optical infrastructure," *International Conference on Computing, Networking and Communications (ICNC)*, pp. 1-5, Feb. 2014 (**Best Paper Award**).
- **L. Zhang**, W. Lu, X. Zhou, and Z. Zhu, "Dynamic RMSA in spectrum-sliced elastic optical networks for high-throughput service provisioning," *International Conference on Computing, Networking and Communications (ICNC)*, pp. 380-384, Jan. 2013