# Energy-efficient UAV-based Edge Computing Systems for XR Applications

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***Abstract*—In this paper, we propose an energy-efficient unmanned aerial vehicle (UAV)-based mobile edge computing system to minimize the total energy consumption of mobile users (MUs) using X-Reality (XR) applications. Specifically, based on the characteristics of XR that have elements in common with neighboring users, we jointly optimize the UAV's trajectory and resources for communication and computation, whose performances are verified via simulations.**

***Index Terms*—Edge computing, unmanned aerial vehicle (UAV), X-Reality (XR), energy minimization, trajectory, resource allocation**

## I. Introduction

X-reality (XR) has recently been used in various fields such as entertainment, design, medical and construction that in general require high computation capability and high data traffic, yielding a significant amount of battery consumption. Accordingly, in order to execute the XR applications in the battery-limited mobile devices, edge computing becomes a promising solution. A series of recent works significantly reduce mobile energy consumptions under latency requirements by jointly optimizing communication and computing resources allocation [1], [2]. These studies are applied to cases, where the users independently execute general applications. However, AR applications have the unique property that the service users have the shared computational tasks and input and output data [3], [4]. [5] proposes an edge computing system for Augmented Reality (AR) applications, where the mobile users (MUs) to be served AR services have the common tasks due to the similar environmental factors, and process them at once for minimizing the energy consumption. In [6], with the assist of the UAV-mounted cloudlet, the mobile edge computing can be improved by allowing the good channel conditions to the desired users thanks to the mobility of UAVs.

In this paper, we develop an energy-efficient mobile edge computing system via UAV-mounted cloudlet for serving the XR applications of $K$ MUs. To this end, we formulate the problem to minimize the total energy consumption of MUs by optimizing the UAV's trajectory along with the computation and communication resources based on Majorization Minimization (MM) algorithms [7]. Via simulations, the performances of the proposed method are verified. Section II introduces the system model. The problem formulation and the proposed algorithm for the optimal UAV's trajectory and resource allocation are provided in Section III. Simulation results and concluding remarks are presented in Section IV and V.

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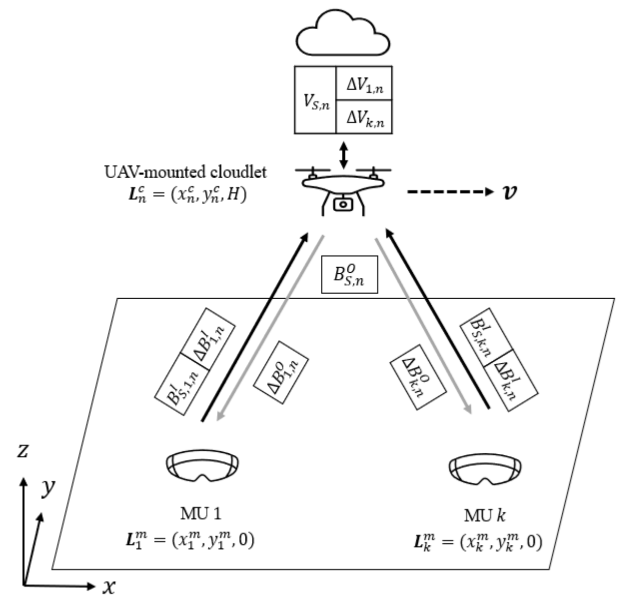


Fig. 1. Illustration of the considered UAV-based edge computing systems.

## II. System model

We consider the mobile edge computing system as shown in Fig. 1, where the $K$ MUs run the computation-intensive XR applications on their single-antenna mobile devices with the aid of a single-antenna UAV-mounted cloudlet. The UAV-mounted cloudlet provides the services to all MUs within its coverage via Time Division Duplex (TDD). Following [5], based the characteristics of XR applications, the offloaded tasks of MUs are supposed to be composed of shared and

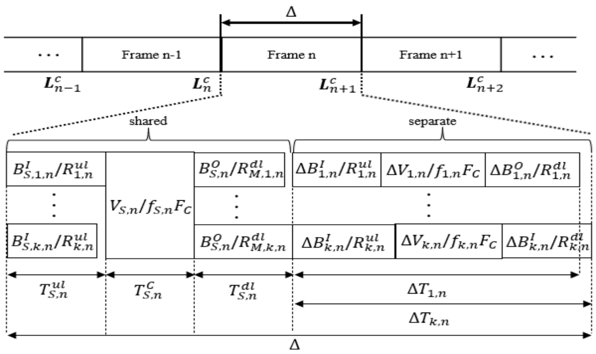


Fig. 2. Frame structure.

non-shared data, which are transmitted via uplink and are processed at the UAV-mounted cloudlet. The computation results are transferred to the MUs via downlink. A three-dimensional Cartesian coordinate system is applied, where the coordinate is measured in meters. We assume that all MUs exist on the ground, regarded as the $xy$-plane. Consequently, the MU $k$'s position is denoted as $\mathbf{L}_k^m = (x_k^m, y_k^m, 0)$, where $k \in \mathcal{K} = \{1, \ldots, K\}$. For the stable services and due to the operational capability, the UAV flies along a trajectory over time $0 < t < T$ at a fixed altitude of $H$, whose initial position, final position and maximum speed are assumed to be predetermined as $\mathbf{L}_I^c = (x_I^c, y_I^c, H), \mathbf{L}_F^c = (x_F^c, y_F^c, H)$ and $v_{max}$, respectively.

As shown in Fig. 2, the time horizon $T$ is divided into $N$ intervals, and the duration of each interval is $\Delta$ seconds, i.e., $T = N\Delta$, during which UAV flies continuously communicating and computing for providing the offloading services to MUs. The frame duration $\Delta$ is assumed to be sufficiently small so that the UAV can be considered as being fixed, allowing the channel for each frame to be constant. Accordingly, the UAV's trajectory $\mathbf{L}_n^c$ can be described as $\mathbf{L}_n^c = (x_n^c, y_n^c, H)$ for $n \in \mathcal{N} = \{1, \ldots, N\}$, where $\mathbf{L}_1^c = \mathbf{L}_I^c$ and $\mathbf{L}_{N+1}^c = \mathbf{L}_F^c$. Also, we can define the UAV's speed at the $n$th frame as $\mathbf{v}_n^c = \frac{\mathbf{L}_{n+1}^c - \mathbf{L}_n^c}{\Delta}$ with satisfying the speed constraint $\|\mathbf{v}_n^c\| \leq v_{max}$. The input bits of the $n$th frame of the MU $k$ can be expressed as $B_{k,n}^I = B_{S,k,n}^I + \Delta B_{k,n}^I$, where $B_{S,k,n}^I$ indicates the input bits shared between MUs, while $\Delta B_{k,n}^I$ represents the input bits, which are not shared. Similarly, the CPU cycles for processing the input bits and the resultant output bits are defined as $V_{k,n} = \Delta V_{k,n} + V_{S,n}$ and $B_{k,n}^O = \Delta B_{k,n}^O + B_{S,n}^O$, respectively, where $V_{S,n}$ and $\Delta V_{k,n}$ indicate the CPU cycles for shared and non-shared input bits, respectively, and $B_{S,n}^O$ and $\Delta B_{k,n}^O$ represent the shared output bits and non-shared output bits, respectively. By following [8]–[10], the communication channel between MU $k$ and UAV is assumed to be Line-of-sight (LOS) link, and then in the $n$th frame, the channel gain between MU $k$ and UAV can be represented as $g_{k,n(\mathbf{L}_n^c)} = \frac{g_0}{d_{k,U,n}^2}$, where $g_0$ is the received power at a reference distance $d_0 = 1$m with respect to the transmission power of 1 W, and $d_{k,U,n}$ is the interdistance between MU $k$ and UAV in the $n$th frame.

The energy consumption for both uplink and downlink transmission of $n$th frame of MU $k$ is defined as $E_{k,n}^{ul} = (\frac{P_{k,n}^{ul}}{R_{k,n}^{ul}} + l_k^{ul})(B_{S,k,n}^I + \Delta B_{k,n}^I)$ and $E_{k,n}^{dl} = (\frac{\Delta B_{k,n}^O}{R_{k,n}^{dl}} + \frac{B_{S,n}^O}{R_{M,k,n}^{dl}})l_k^{dl}$, respectively, where $l_k^{ul}$ and $l_k^{dl}$ are parameters used to calculate the energy consumed during uplink and downlink transmission [5], $P_{k,n}^{ul}$ and $P_{k,n}^{dl}$ are the transmit powers used for uplink and downlink transmission, respectively, and $R_{k,n}^{ul}$,$R_{k,n}^{dl}$ and $R_{M,k,n}^{dl}$ are the achievable transmission rates between MU $k$ and UAV with the 20 MHz bandwidth, for uplink and for broadcasting and multicasting in downlink as defined in [5].

## III. Optimal energy consumption for mobile users

In this section, we formulate the problem to minimize the total energy consumed by all MUs for offloading as follows:

$$\underset{B_{S,k,n}^I, T_{S,n}^{ul}, T_{S,n}^{dl}, \mathbf{L}_n^c, \mathbf{v}_n^c}{\text{minimize}} \sum_{k \in \mathcal{K}} \sum_{n \in \mathcal{N}} \{E_{k,n}^{ul} + E_{k,n}^{dl}\} \tag{1a}$$

$$\text{s.t.} \quad \frac{\Delta B_{k,n}^I}{R_{k,n}^{ul}(\mathbf{L}_n^c)} + \frac{\Delta V_{k,n}}{f_{k,n} F_c} + \frac{V_{S,n}}{f_{S,n} F_c} + \frac{\Delta B_{k,n}^O}{R_{k,n}^{dl}(\mathbf{L}_n^c)}$$

$$\leq T_{max} - T_{S,n}^{ul} - T_{S,n}^{dl}, \tag{1b}$$

$$\frac{B_{S,k,n}^I}{R_{k,n}^{ul}(\mathbf{L}_n^c)} \leq T_{S,n}^{ul}, \tag{1c}$$

$$\frac{B_{S,n}^O}{R_{M,k,n}^{ul}(\mathbf{L}_n^c)} \leq T_{S,n}^{dl}, \tag{1d}$$

$$\gamma^c V_{S,n}(f_{S,n}F_c)^2 + \sum_{k \in \mathcal{K}} \sum_{n \in \mathcal{N}} \Delta V_{k,n}(f_{k,n}F_c)^2$$

$$+ \sum_{k \in \mathcal{K}} \sum_{n \in \mathcal{N}} (\frac{P_{M,n}^{dl}}{R_{M,k,n}^{dl}(\mathbf{L}_n^c)} + l_k^{ul}) B_{S,n}^O$$

$$+ \sum_{k \in \mathcal{K}} \sum_{n \in \mathcal{N}} (\frac{P_{k,n}^{dl}}{R_{k,n}^{dl}(\mathbf{L}_n^c)} + l_k^{ul}) \Delta B_{k,n}^O$$

$$+ \sum_{k \in \mathcal{K}} \sum_{n \in \mathcal{N}} (\frac{\Delta B_{k,n}^I + B_{S,k,n}^I}{R_{k,n}^{ul}(\mathbf{L}_n^c)}) l_k^{dl} + \kappa ||\mathbf{v}_n^c||^2 \leq \mathcal{E}, \tag{1e}$$

$$\sum_{k \in \mathcal{K}} \sum_{n \in \mathcal{N}} B_{S,k,n}^I = B_{S,n}^I, \tag{1f}$$

$$\mathbf{L}_1^c = \mathbf{L}_I^c, \mathbf{L}_{N+1}^c = \mathbf{L}_F^c, \tag{1g}$$

$$\mathbf{v}_n^c = \frac{\mathbf{L}_{n+1}^c - \mathbf{L}_n^c}{\Delta} \tag{1h}$$

$$||\mathbf{v}_n^c||^2 \leq v_{max}, \tag{1i}$$

for $n \in \mathcal{N}$ and $k \in \mathcal{K}$, where $T_{S,n}^{ul}$ and $T_{S,n}^{dl}$ are transmission and reception times of common tasks, respectively, $F_C$ represents the capacity of the cloudlet in terms of CPU cycles per second, $f_{S,n}$ and $f_{k,n}$ are the ratios of $F_C$ allocated for shared and non-shared tasks, respectively, $\gamma_c$ is the actual switched capacity of the cloudlet, and $\mathcal{E}$ is the energy budget of the UAV. The minimization problem (1) is non-convex due to the coupling of optimization variables, whose optimal solution is obtained by using the Block Coordinate Descent (BCD) method [11] detailed in the following.

### A. Resource allocation for computation and communication

In this section, we develop the optimal allocation of computational and communication resources, given the fixed UAV's flight trajectory. With the given UAV's trajectory, the problem (1) can be reformulated as

$$\underset{B^I_{S,k,n}, T^{ul}_{S,n}, T^{dl}_{S,n},}{\text{minimize}} \sum_{k\in\mathcal{K}}\sum_{n\in\mathcal{N}}\{E^{ul}_{k,n}(B^I_{S,k,n}) + E^{dl}_{k,n}\} \tag{2a}$$

$$\text{s.t.} \quad \text{(1b), (1c), (1d), (1e), (1f).} \tag{2b}$$

Since (2) is convex, the optimal solution can be obtained via the CVX tool [12], [13].

### B. Optimization of UAV's trajectory

When the resource allocation of $B^I_{S,k,n}, T^{ul}_{S,n}$ and $T^{dl}_{S,n}$ is given, the problem (1) can be expressed as

$$\underset{\mathbf{L}^c_n, \mathbf{v}^c_n}{\text{minimize}} \sum_{k\in\mathcal{K}}\sum_{n\in\mathcal{N}}\{E^{ul}_{k,n}(\mathbf{L}^c_n) + E^{dl}_{k,n}(\mathbf{L}^c_n)\} \tag{3a}$$

$$\text{s.t.} \quad \text{(1b), (1c), (1d), (1e), (1g), (1h), (1i).} \tag{3b}$$

The problem (3) is a non-convex problem owing to the non-convexity of (3a) and (3b). By adopting the MM algorithms and introducing the slack variables $X^1_{k,n}$, $X^2_{k,n}$, $X^3_{k,n}$ and $p_{k,n}$, we can reformulate it as

$$\underset{\mathbf{L}^c_n, \mathbf{v}^c_n, X^1_{k,n}, X^2_{k,n}, X^3_{k,n}, p_{k,n}}{\text{minimize}} \sum_{k\in\mathcal{K}}\sum_{n\in\mathcal{N}}\{E^{ul}_{k,n} + E^{dl}_{k,n}\} \tag{4a}$$

$$\text{s.t.} \quad \frac{\Delta B^I_{k,n}}{X^1_{k,n}} + \frac{\Delta V_{k,n}}{f_{k,n}F_c} + \frac{V_{S,n}}{f_{S,n}F_c} + \frac{\Delta B^O_{k,n}}{X^2_{k,n}} \le T_{max} - T^{ul}_{S,n} - T^{dl}_{S,n}, \tag{4b}$$

$$\frac{B^I_{S,k,n}}{X^1_{k,n}} \le T^{ul}_{S,n} \tag{4c}$$

$$\frac{B^O_{S,n}}{X^3_{k,n}} \le T^{dl}_{S,n}, \tag{4d}$$

$$\gamma^c V_{S,n}(f_{S,n}F_c)^2 + \sum_{k\in\mathcal{K}}\sum_{n\in\mathcal{N}}\Delta V_{k,n}(f_{k,n}F_C)^2 + \sum_{k\in\mathcal{K}}\sum_{n\in\mathcal{N}}\left(\frac{P^{dl}_{M,n}}{X^3_{k,n}} + l^{ul}_k\right)B^O_{S,n} + \sum_{k\in\mathcal{K}}\sum_{n\in\mathcal{N}}\left(\frac{P^{dl}_{k,n}}{X^2_{k,n}} + l^{ul}_k\right)\Delta B^O_{k,n} + \sum_{k\in\mathcal{K}}\sum_{n\in\mathcal{N}}\left(\frac{\Delta B^I_{k,n} + B^I_{k,n}}{X^1_{k,n}}\right)l^{dl}_k + \kappa||\mathbf{v}^c_n||^2 \le \mathcal{E} \tag{4e}$$

$$\frac{W^{ul}}{K}\{\log_2(p_{k,n}N_0(W^{ul}/K) + kg_0P^{ul}_{k,n}) - \frac{1}{p_{k,n}(v)N_0(W^{ul}/K)\ln 2}(p_{k,n} - p_{k,n}(v)) - \log_2(p_{k,n}(v)N_0(W^{ul}/K)\} \ge X^1_{k,n}, \tag{4f}$$

$$\frac{W^{dl}}{K}\{\log_2(p_{k,n}N_0(W^{dl}/K) + kg_0P^{dl}_{k,n}) - \frac{1}{p_{k,n}(v)N_0(W^{dl}/K)\ln 2}(p_{k,n} - p_{k,n}(v)) - \log_2(p_{k,n}(v)N_0(W^{dl}/K)\} \ge X^2_{k,n}, \tag{4g}$$

$$W^{dl}\{\log_2(p_{k,n}N_0(W^{dl}) + kg_0P^{dl}_{M,n}) - \frac{1}{p_{k,n}(v)N_0W^{dl}\ln 2}(p_{k,n} - p_{k,n}(v)) - \log_2(p_{k,n}(v)N_0W^{dl})\} \ge X^3_{k,n}, \tag{4h}$$

$$d^2_{k,U,n} \le p_{k,n}, \tag{4i}$$

$$\text{(1g), (1h), (1i),} \tag{4j}$$

for $n \in \mathcal{N}$ and $k \in \mathcal{K}$, where the parameters with $v$ represents the values of the current feasible iterate. Since the problem (4) is convex, the optimal solution can be achieved through CVX tool [12], [13].

### C. Proposed Algorithm

The proposed algorithm is detailed in Algorithm 1, whose convergence is guaranteed because each iteration of Algorithm 1 can obtain the minimum value of the problem (1) by using the approximated expression in the convex form, converging to the optimal resource allocation and UAV's trajectory of the problem (1).

**[Algorithm 1]**

**Input**: $\mathbf{\Theta}_n(i)$ with $\mathbf{\Theta}_n(i) \triangleq (\mathbf{B}^I_S(i), \mathbf{T}^{ul}_S(i), \mathbf{T}^{dl}_S(i))$, and $\mathbf{U}_n(i)$ with $\mathbf{U}_n(i) \triangleq (\mathbf{L}^c_n(i), \mathbf{v}^c_n(i))$. Set $i = 0$.

**Iterate**

With $\mathbf{\Theta}_n(i)$ and $\mathbf{U}_n(i)$, find the optimal solution $\mathbf{\Theta}_n(i+1)$ by using (2).

With $\mathbf{\Theta}_n(i+1)$ and $\mathbf{U}_n(i)$, find the optimal solution $\mathbf{U}_n(i+1)$ by using (4).

$i \leftarrow i + 1$

**until** convergence.

**Output**: optimal $\mathbf{\Theta}_n(i)$ and $\mathbf{U}_n(i)$

## IV. Simulation results

In this section, we consider the simulations with $K = 5$, $\eta = 0.8$, $g_0 = 0.01$, $B^I_{k,n} =$ 100Kbits, $N_0 =$ -174dBm, $P^{ul}_{k,n} =$ 45dBm, $P^{dl}_{k,n} =$ 48dBm, $P^{dl}_{M,n} =$ 55dBm, $\Delta =$ 0.05s, $v_{max} =$ 50m/s, $H =$ 20m, $F_c = 10^{10}$CPU cycles/s, $f_{S,n} = 1$, $f_{k,n} =$ 1/5, $l^{ul}_k = 1.78 \times 10^{-6}$J/bit, $l^{dl}_k =$ 0.625J/s, $V_{k,n} = 2640 \times B^I_{k,n}$, $V_{S,n} = \eta V_{k,n}$, $B^I_{S,n} = B^O_{S,n} = \eta B^I_{k,n}$, $\gamma^c = 10^{-28}$, $\kappa = 0.2413$ and $\mathcal{E} =$ 500KJ, where $\eta$ is the parameter representing the degree of commonality of input bits.

Fig. 3 shows the convergence of the proposed Algorithm 1, which can be generally obtained within about ten iterations. Fig. 4, Fig. 5 and Fig. 6 show the optimal UAV's trajectory and resource allocation obtained by the proposed Algorithm 1. As in Fig. 4 and Fig. 5, the UAV tends to stay longer and closer to the spot, where the MUs are densely deployed. In Fig. 6, the more number of bits are allocated when the UAV is closer to the MUs, which allows to reduce the energy consumption of communication for offloading. Also, it is noticed that the optimized trajectory passes the center of gravity of the five MUs, where the amount of the allocated bits can be considered as the weighting factors of MUs when the same power is allocated.

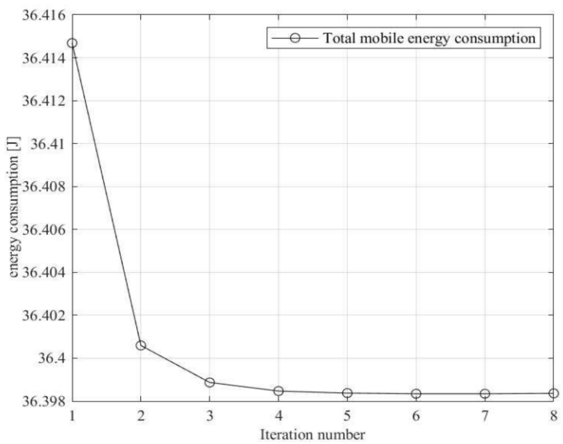


Fig. 3. Convergence of Algorithm 1.

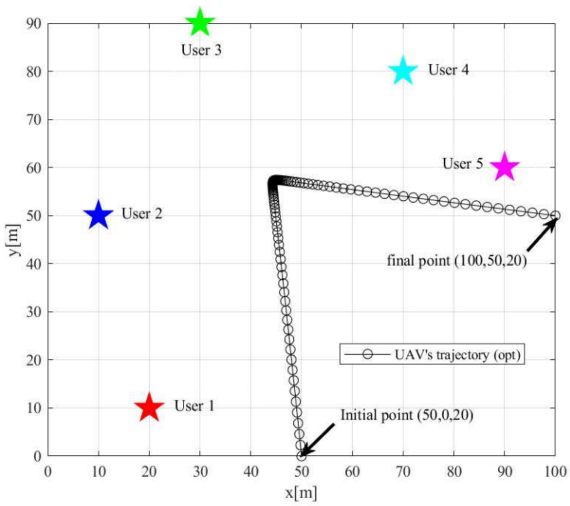


Fig. 4. The optimal UAV's trajectory obtained by proposed Algorithm 1, where each MU located at $\mathbf{L}_1^m = (20, 10, 0)$, $\mathbf{L}_2^m = (10, 50, 0)$, $\mathbf{L}_3^m = (30, 90, 0)$, $\mathbf{L}_4^m = (70, 80, 0)$ and $\mathbf{L}_5^m = (90, 60, 0)$.

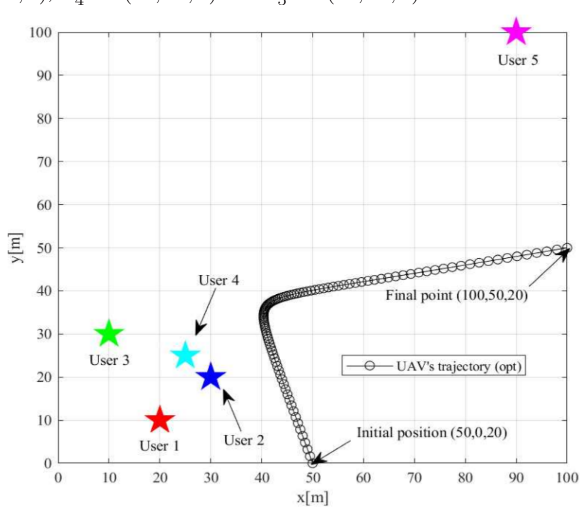


Fig. 5. The optimal UAV's trajectory obtained by proposed Algorithm 1, where each MU located at $\mathbf{L}_1^m = (20, 10, 0)$, $\mathbf{L}_2^m = (30, 20, 0)$, $\mathbf{L}_3^m = (10, 30, 0)$, $\mathbf{L}_4^m = (25, 25, 0)$ and $\mathbf{L}_5^m = (90, 100, 0)$.

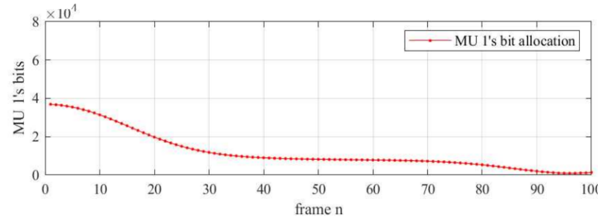


Fig. 6. MU 1's bit allocation of Fig. 4.

## V. Conclusion

In this paper, we propose the UAV-assisted mobile edge computing system for XR applications to minimize the total energy consumption of the ground MUs, whose performances are verified via simulations. As future works, the multiple UAVs and LEO satellites acting as cloudlets can be studied for providing the universal coverage.

## References

[1] A. Al-Shuwaili, O. Simeone, A. Bagheri, and G. Scutari, "Joint uplink/downlink optimization for backhaul-limited mobile cloud computing with user scheduling," *IEEE Transactions on Signal and Information Processing over Networks*, vol. 3, no. 4, pp. 787–802, 2017.

[2] S. Sardellitti, G. Scutari, and S. Barbarossa, "Joint optimization of radio and computational resources for multicell mobile-edge computing," *IEEE Transactions on Signal and Information Processing over Networks*, vol. 1, no. 2, pp. 89–103, 2015.

[3] T. Verbelen, P. Simoens, F. De Turck, and B. Dhoedt, "Leveraging cloudlets for immersive collaborative applications," *IEEE Pervasive Computing*, vol. 12, no. 4, pp. 30–38, 2013.

[4] S. Bohez, J. De Turck, T. Verbelen, P. Simoens, and B. Dhoedt, "Mobile, collaborative augmented reality using cloudlets," in *2013 International Conference on MOBILe Wireless MiddleWARE, Operating Systems, and Applications*, pp. 45–54, IEEE, 2013.

[5] A. Al-Shuwaili and O. Simeone, "Energy-efficient resource allocation for mobile edge computing-based augmented reality applications," *IEEE Wireless Communications Letters*, vol. 6, no. 3, pp. 398–401, 2017.

[6] S. Jeong, O. Simeone, and J. Kang, "Mobile edge computing via a uav-mounted cloudlet: Optimization of bit allocation and path planning," *IEEE Transactions on Vehicular Technology*, vol. 67, no. 3, pp. 2049–2063, 2017.

[7] D. R. Hunter and K. Lange, "A tutorial on mm algorithms," *The American Statistician*, vol. 58, no. 1, pp. 30–37, 2004.

[8] S. Jeong, O. Simeone, and J. Kang, "Mobile cloud computing with a uav-mounted cloudlet: optimal bit allocation for communication and computation," *IET Communications*, vol. 11, no. 7, pp. 969–974, 2017.

[9] Y. Zeng, R. Zhang, and T. J. Lim, "Throughput maximization for uav-enabled mobile relaying systems," *IEEE Transactions on communications*, vol. 64, no. 12, pp. 4983–4996, 2016.

[10] Y. Zeng and R. Zhang, "Energy-efficient uav communication with trajectory optimization," *IEEE Transactions on Wireless Communications*, vol. 16, no. 6, pp. 3747–3760, 2017.

[11] A. Beck and L. Tetruashvili, "On the convergence of block coordinate descent type methods," *SIAM journal on Optimization*, vol. 23, no. 4, pp. 2037–2060, 2013.

[12] M. Grant and S. Boyd, "CVX: Matlab software for disciplined convex programming, version 2.1." http://cvxr.com/cvx, Mar. 2014.

[13] M. Grant and S. Boyd, "Graph implementations for nonsmooth convex programs," in *Recent Advances in Learning and Control* (V. Blondel, S. Boyd, and H. Kimura, eds.), Lecture Notes in Control and Information Sciences, pp. 95–110, Springer-Verlag Limited, 2008. http://stanford.edu/ boyd/graph_dcp.html.