Green-Parallel Online Offloading for DSCI-Type Tasks in IoT-Edge Systems

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Abstract

In order to meet people's demands for intelligent and user-friendly Internet of Things (IoT) services, the amount of computation is increasing rapidly, and the requirements of task delay are becoming increasingly more stringent. However, the constrained battery capacity of IoT devices greatly limits the user experience. Energy Harvesting (EH) technologies enable green energy to provide continuous energy support for devices in the IoT environment. Together with the maturity of Mobile Edge Computing (MEC) technology and the development of parallel computing, it provides a strong guarantee for the normal operation of resource-constrained IoT devices. In this paper, we design a parallel offloading strategy based on Lyapunov optimization, which is conducive to efficiently finding the optimal decision for Delay-Sensitive and Compute-Intensive (DSCI) tasks. We establish a stochastic optimization problem on a discrete-time slot system and propose a Green Parallel Online Offloading Algorithm (GPOOA). By decoupling the target problem three times, the joint optimization of green energy, task division factor, CPU frequency and transmission power is realized. Experimental results demonstrate that under the constraints of strict task deadlines and limited server computing resources, GPOOA performs well in terms of system cost and task drop ratio, far superior to several existing offloading algorithms.

Index Terms

Mobile Edge Computing, Internet of Things, Task Offloading, Energy Harvesting, Perturbed Lyapunov Optimization

I. Introduction

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FIFTH-Generation (5G) mobile communication has paved the way for the rapid proliferation of the Internet of Things (IoT) [1]. With the increasingly diversified and user-friendly functions of IoT devices, various compute-intensive and delay-sensitive applications have emerged, e.g., Augmented Reality (AR), Virtual Reality (VR), speech recognition, video analysis [2], and smart homes. The underlying IoT tasks generated by these applications usually require high computational demands and short delays [3], which are referred to as **Delay-Sensitive and Compute-Intensive (DSCI)** tasks [4]. In most cases, the limited computing resources and battery capacity of the device itself are difficult to support DSCI-type tasks. This can easily lead to tasks not being executed smoothly due to battery depletion or long response times. Regardless of transmission latency, it is ideal to offload the workload to a cloud server with abundant computing resources for processing. However, it is unrealistic to offload all tasks to remote clouds. On the one hand, large-scale and long-distance transmission of tasks will consume a lot of energy. On the other hand, frequent communication with the cloud may also cause greater communication delays [5]. As a result, not only has today's already congested network become worse [6], [7], but the entire IoT system has also become unstable.

The emergence of Mobile Edge Computing (MEC) has made up for the deficiencies of cloud computing and can support the needs of mission-critical computing for low latency, intensive computing, and mass storage [8], [9]. However, there exist several bottlenecks restricting the further development of IoT technology. For instance, battery life has become one of the main factors affecting user experience. Limited battery life increases the maintenance cost of IoT devices, and the cost of replacing batteries is often higher than the cost of IoT devices themselves. For instance, in an industrial environment with only 10,000 sensors, the battery needs to be replaced nearly 3,333 times each year [10]. Not to mention how to deal with today's huge IoT system where everything is interconnected. Fortunately, Energy Harvesting (EH), a promising technology that obtains harvested green energy from the external environment (e.g., solar and wind energy) and converts the captured renewable energy into electrical energy through an energy harvesting device, provides a new opportunity for powering IoT-edge systems [11]. The working range of most IoT devices and sensors is between 0.1 μW and 1 W, which can be easily handled by EH devices [12]. While EH extends the life cycle of the equipment, it also eliminates the limitation of fixed rechargeable batteries as energy sources. Despite the obvious advantages of using green energy for power supply, the energy collection process is highly intermittent and random, which poses a huge challenge for making full use of green energy. In addition, although the edge server has more abundant computing resources than the device itself, e.g., faster CPU frequency and higher parallel computing power [13]. However, most MEC servers in the real world have limited computing capacities and cannot match cloud computing, especially in a multi-device IoT environment.

To address the above challenges, several Lyapunov optimization-based solutions, e.g., DBWA [14] and EEDTO [15] have been proposed to minimize system energy consumption by optimizing the workload distribution based on IoT-Edge-Cloud computing architecture. Chen *et al.* [16] transformed the energy minimization problem into a knapsack problem and proposed an Energy-Efficient Dynamic Offloading algorithm (EEDOA), which can approximate the minimum transmission energy consumption while ensuring the stability of the system. Although the aforementioned approaches strive for energy-efficient algorithms, they do not take into account green energy harvesting techniques or the mobility of the devices. Using execution delays and task failures as execution costs, Mao *et al.* [17] developed a low-complexity Lyapunov Optimization-based Dynamic Computation Offloading (LODCO) algorithm for models from a single device to a single edge. Zhao *et al.* [13] inherited the advantages of the LODCO algorithm and migrated it to the multi-device multi-server scenario that is more in line with the real world. Inspired by the above practices, we try to apply the Lyapunov optimization technique combined with the mobility of the device in the multi-device multi-server model.

Regarding how to reduce latency to meet the needs of different types of tasks, Yousefpour *et al.* [18] utilized the concept of Load Sharing to reduce service latency by sharing load among fog nodes. Mukherjee *et al.* [19] used Quadratic Constrained Quadratic Programming (QCQP) to solve the delay-sensitive task offloading problem when considering local execution delay and transmission delay. Liu *et al.* [20] developed an efficient one-dimensional search algorithm to solve the power-constrained delay minimization problem under different time scales. Instead, in this paper, we use parallel offloading for DSCI-type tasks to achieve this goal.

Green computing and communication have become the new darlings of researchers. Taking advantage of EH and Device-to-Device (D2D) communication, Zhou *et al.* [21] proposed GreenEdge, a novel framework for sustainable edge computing, and verified its feasibility. Deng *et al.* [22] designed a green sustainable MEC framework for dynamic and parallel computing offloading and energy management (DPCOEM) algorithms. However, this work was carried out under the ideal state of MEC server computing resources, ignoring the mobility of IoT devices. We consider more scenarios where the edge server has limited computing resources and the devices can move freely. Hu *et al.* [23] proposed an Online Mobile-aware

Offloading and Resource Allocation (OMORA) algorithm, which combined Lyapunov optimization and Semi-Definite Programming (SDP) methods. Although the task drop rate and migration cost are considered, the main optimization is the total energy consumption. Inspired by the above, we attempt to apply the EH technology to deal with system energy consumption, while placing more emphasis on the optimization of latency.

In this paper, we design a Green Parallel Online Offloading Algorithm (GPOOA) for DSCI-type tasks. GPOOA is based on the Lyapunov optimization framework to offload tasks in a parallel manner in multi-device and multi-server scenarios, and combines EH technology to power the devices. Our goal is to optimize the user experience and system robustness by reducing system costs. The main contributions of this paper are summarized below.

- We establish a multi-device and multi-server MEC system model for DSCI-type tasks and formally define the stochastic optimization problem on a discrete-time slot system, taking the mobility of the device into account.
- To meet the delay requirements of DSCI-type tasks, we propose a parallel offloading strategy with the close collaboration between IoT devices and edge servers. To ensure the robustness of task processing, we take the drop ratio into consideration to motivate the system to perform tasks as many as possible.
- We apply the EH technology to IoT devices to make full use of the advantages of green energy, and further propose a Lyapunov-guided solution to maintain the continuity of energy supply in IoT-edge systems. Meanwhile, we decoupled the optimization problem three times and designed the GPOOA algorithm.

II. System Model and Problem Formulation

In this section, we first introduce the system model, computation offloading and energy harvesting models, and then formulate the online decision problem for task offloading in MEC environments.

A. System Model

As shown in Fig. 1, we consider a 5G-based MEC environment with multiple IoT devices and multiple MEC servers, where IoT devices $\mathcal{M} = \{1, 2, \cdots, M\}$ can move freely in the environment, while MEC servers $\mathcal{N} = \{1, 2, \cdots, N\}$ are statically deployed. According to the EH technology, each device in the scenario is equipped with an energy harvester. The energy harvester will collect green energy (e.g., solar, wind) from the environment and convert it into electricity to power the device itself. According to the divisible load theory [24], we assume that the unit task $A(L, \tau)$ generated by the device is divisible and of DSCI type, where L (in bit) is the task size, and τ (in ms) is the deadline of the task. Divisible here means that the task $A(L, \tau)$ can be divided into two parts arbitrarily. And we adopt the cooperation of local devices and edge servers to process tasks in parallel.

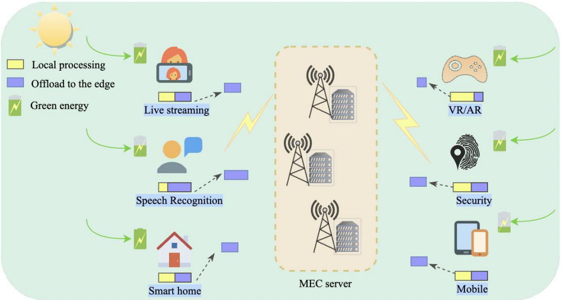


Fig. 1. The system model with energy harvesting technology.

We perform parallel offloading on a discrete-time slot system, where the time slot set is $\mathcal{T} = \{0, 1, \cdots, T-1\}$ with the slot length τ_0. Tasks are randomly generated with Bernoulli distribution in the time slots, and the task arrival rate is defined as ρ $(0 \leq \rho \leq 1)$. Let ζ_i^t denote a task generation indicator, and $\zeta_i^t = 1$ means that the i-th IoT device has a task generated in the time slot t. And $\zeta_i^t = 0$ indicates no task is generated. In addition, we define the task division factors of i-th device in time slot t as follows:

$$I_{i,l}^t + I_{i,e}^t + I_{i,d}^t = 1, \tag{1}$$

$$I_{i,l}^t, I_{i,e}^t \in [0, 1], \ I_{i,d}^t \in \{0, 1\}. \tag{2}$$

where $I_{i,l}^t$ and $I_{i,e}^t$ indicate the ratio of the task processed locally and offloaded to the edge server, respectively. The value of $I_{i,d}^t$ is either 1 or 0, indicating that the task is either completely discarded or executed. The symbols and their definitions commonly used in this paper are summarized in Table I.

B. Computation Offloading and Energy Harvesting Models

1) Local Execution Model: Dynamic Voltage and Frequency Adjustment (DVFS) technology [25] can adjust execution time and energy consumption by controlling the CPU cycle frequency to achieve low power consumption. Using DVFS, the local execution delay of the i-th device in time slot t can be obtained by:

$$T_{i,l}^t = \sum_{k=1}^{K} \left(f_{i,k}^t \right)^{-1}, \ \forall t \in \mathcal{T}, \forall i \in \mathcal{M}, \tag{3}$$

TABLE I
NOTATIONS AND DEFINITIONS

Notation	**Definition**
$A(L, \tau)$	A unit task
τ_0 τ'	The slot length of system A temporary time variable
$I_{i,l}^t$, $I_{i,e}^t$, $I_{i,d}^t$	The task division factors
$T_{i,l}^t$ $T_{i,e}^t$	The delay to process a unit task locally The delay to offload a unit task
$E_{i,l}^t$ $E_{i,e}^t$	The energy consumption to process a unit task locally The energy consumption to offload a unit task
f_{local}^{max}	The maximum CPU-cycle frequency of local devices
K	The number of CPU cycles required for a unit task
E_H^{max}	The maximum energy can grab from the outside
$E^{\max}$	The maximum discharge energy of the battery
p^{max}	The maximum transmission power allowed by the device
b_i^t	The battery level of the i-th device in the time slot t
χ_i^t	The task drop indicator
ζ_i^t	The task generation indicator
ψ	The penalty weight (the system cost of dropping the task)
D_i^t	The delay of the i-th device in the time slot t
e_i^t	The green energy level collected through the energy harvester in the time slot t
ε_i^t	The total energy consumption of the i-th device in the time slot t
Q	The maximum number of devices that the edge server can connect to in a time slot

where $K = LW$ is the number of CPU cycles required for a unit task $A(L, \tau)$ and W is the number of CPU cycles required to perform one bit locally. $f_{i,k}^t$ is the frequency allocated by the i-th device to the k-th CPU cycle in the time slot t. The corresponding local execution energy consumption is :

$$E_{i,l}^t = \theta \sum_{k=1}^{K} \left(f_{i,k}^t \right)^2, \ \forall t \in \mathcal{T}, \forall i \in \mathcal{M}, \tag{4}$$

where θ is the capacitance constant [17] that depends on the chip architecture. Here, $f_{i,k}^t \leq f_{local}^{max}, \forall k \in \{1, 2, \cdots, K\}$, where f_{local}^{max} (in cycle/s) represents the maximum CPU-cycle frequency of local devices.

2) MEC Offloading Model: The Shannon-Hartley formula shows that the channel transmission rate is determined by the channel gain $h_{i,j}^t$ and the transmission power p_i^t of the device. So the transmission rate

$v_{i,j}^t$ from the i-th device to the j-th MEC server can be expressed as [26]:

$$v_{i,j}^t = v\left(h_{i,j}^t, p_i^t\right) = \omega \log_2\left(1 + \frac{h_{i,j}^t p_i^t}{\sigma}\right), \tag{5}$$

where $h_{i,j}^t = \gamma_{i,j}^t g_0 \left(\frac{d_0}{d_{i,j}^t}\right)^\alpha$ represents the channel gain from the i-th device to the j-th MEC server, $\gamma_{i,j}^t$ is the small-scale fading channel power gain, d_0 represents the reference distance, $d_{i,j}^t$ is the distance from the device i to the MEC server j. g_0 is the pass-loss constant, and α is the pass-loss exponent. The bandwidth of the channel is denoted as ω. σ is the noise power at the MEC server.

Typically, the downlink transmission rate is much higher than the uplink rate. And the size of the output result is usually much smaller than the input, so our model ignores the return time of the result. Inspired by [13], [17], [22], our model inherits the delay assumptions in these works. That is, we do not consider the execution delay of the MEC server for simplicity. If a unit task generated by the i-th device is processed by the j-th MEC server, the corresponding offloading delay is calculated by:

$$T_{i,e}^t = \frac{L}{v_{i,j}^t}, \ \forall t \in \mathcal{T}, i \in \mathcal{M}, \tag{6}$$

And the corresponding energy consumed by the i-th device of offloading tasks is:

$$E_{i,e}^t = p_i^t T_{i,e}^t, \ \forall t \in \mathcal{T}, \forall i \in \mathcal{M}. \tag{7}$$

3) Energy Harvesting Model: We adopt EH technology to make full use of green energy to provide energy support for IoT devices. The energy harvester converts green energy such as solar, wind and mechanical energy obtained from the outside into electrical energy and stores it in the battery to ensure the normal operation of the device. However, the process of obtaining green energy in the real world is stochastic.

Assuming that the green energy arrives at the i-th device in the time slot t with $E_{i,H}^t$, which is independent and identically distributed, and $E_{i,H}^t \leq E_H^{max}$. Here, E_H^{max} is the maximum energy that the device can grab from the outside world. Define the green energy level collected through the energy harvester of the i-th device in the time slot t as e_i^t, and the captured energy e_i^t cannot exceed the randomly arrived green energy level:

$$0 \leq e_i^t \leq E_{i,H}^t. \tag{8}$$

In our model, the generated tasks are either executed in parallel or dropped (satisfy Eq. (1)). Dropping tasks will not generate energy consumption. Therefore, the total energy consumption of the i-th device in the time slot t consists of two parts (local part $I_{i,l}^{t}E_{i,l}^{t}$ and edge part $I_{i,e}^{t}E_{i,e}^{t}$):

$$\varepsilon_i^t = I_{i,l}^{t}E_{i,l}^{t} + I_{i,e}^{t}E_{i,e}^{t}. \tag{9}$$

In order to prolong the service life of the battery and prevent the battery from over-discharging, the battery output energy of each time slot should not exceed E^{max}:

$$0 \leq \varepsilon_i^t \leq E^{max}, \tag{10}$$

where $E^{\max}$ is the maximum discharge energy of the battery in each time slot.

Define the battery level of the i-th device in the time slot t as b_i^t. It needs to be emphasized that the energy consumed in each time slot cannot exceed the current battery level, which satisfies:

$$\varepsilon_i^t \leq b_i^t < \infty. \tag{11}$$

In other words, if the energy consumed by the processing task exceeds the current battery level, the system will drop the task due to insufficient energy supply. In summary, the battery level of device i in time slot $t+1$ is updated according to:

$$b_i^{t+1} = b_i^t - \varepsilon_i^t + e_i^t. \tag{12}$$

C. Problem Formulation

Our goal is to optimize user experience (reduce delay) and improve system stability (reduce task drop ratio) by reducing the total system cost. For DSCI-type tasks, we use a parallel offload strategy to cope with DS (delay-sensitive) features, and we use EH techniques to power devices for compute-intensive (CI) features. Before defining the system cost, we first define a task drop indicator as: $\chi_i^t = \zeta_i^t I_{i,d}^t$ (if the i-th device has a task to generate in time slot t while it is dropped).

Based on the characteristics of the parallel computing framework, the delay of the i-th device in time slot t is the larger of the delays between the local side $I_{i,l}^{t}T_{i,l}^{t}$ and the offload to the edge server side $I_{i,e}^{t}T_{i,e}^{t}$:

$$D_i^t = \zeta_i^t \cdot \max\left\{I_{i,l}^{t}T_{i,l}^{t}, I_{i,e}^{t}T_{i,e}^{t}\right\}. \tag{13}$$

The cost of the i-th device in time slot t is defined as the weighted sum of the delay D_i^t and the task drop indicator χ_i^t:

$$cost_i^t = D_i^t + \psi \chi_i^t, \tag{14}$$

where ψ (in second) is the penalty weight, i.e., the system cost of dropping the task. Therefore, the total cost of the system in time slot t is:

$$cost_{total}^t = \sum_{i=1}^{M} cost_i^t. \tag{15}$$

Considering that there are many random factors in the system, such as the arrival of tasks, the location of devices, the state of the channel, and the energy harvesting situation, etc. First, we formulate the problem as a random optimization problem. And we want to minimize the response time and task drop ratio in the sense of time average through resource allocation and parallel offloading. So we first get optimization problem $\mathcal{P}_1$:

$$\begin{aligned}
\boldsymbol{\mathcal{P}_1}: \quad & \min \lim_{T\to\infty} \frac{1}{T}\mathbb{E}\left[\sum_{t=0}^{T-1} cost_{total}^t\right] \\
\text{s.t.}: \quad & (1),\ (2),\ (8),\ (10) \text{ and } (11) \\
& D_i^t \leq \tau \qquad (16) \\
& I_{i,l}^t + I_{i,e}^t \leq \zeta_i^t \qquad (17) \\
& 0 \leq f_{i,k}^t \leq f_{local}^{max},\ \forall t \in \mathcal{T}, \forall i \in \mathcal{M} \qquad (18) \\
& 0 \leq p_i^t \leq p^{max},\ \forall t \in \mathcal{T}, \forall i \in \mathcal{M} \qquad (19)
\end{aligned}$$

where Eqs. (1) and (2) are task division factor constraints. Eqs. (8), (10) and (11) are energy consumption constraints (the task will be dropped if the energy consumed to perform the task exceeds the current battery level). Eq. (16) indicates that the response time constraints (the task will be dropped if it is not executed before the deadline). Eq. (17) indicates that parallel offloading can only occur when there are tasks generated. Eqs. (18) and (19) are the constraints of the device's CPU frequency and transmission power, respectively, where p^{max} represents the maximum transmission power allowed by the device.

D. Modified System Cost Minimization Problem

It is worth noting that the energy constraint in Eq. (11) makes the system coupled between different time slots when making decisions, which is challenging to directly apply the traditional Lyapunov method. In order to eliminate this coupling effect, similar to [17], we introduce a non-zero energy consumption

E^{min} as the minimum discharge energy of the battery in each time slot to tighten the constraints of the problem $\mathcal{P}_1$, so that an improved stochastic optimization problem can be obtained by:

$$\begin{aligned} \boldsymbol{\mathcal{P}_2}: \quad & \min \lim_{T\to\infty} \frac{1}{T}\mathbb{E}\left[\sum_{t=0}^{T-1} cost_{total}^{t}\right] \\ \text{s.t.}: \quad & (1),\ (2),\ (8),\ (11) \text{ and } (16)-(19) \\ & \varepsilon_i^t \in \{0\} \cup \left[E^{min}, E^{max}\right] \end{aligned} \tag{20}$$

where the constraints of $\mathcal{P}_2$ are much stricter than that of $\mathcal{P}_1$. By forcing E^{min} to tend to zero, the optimal solution of $\mathcal{P}_2$ will tend to that of $\mathcal{P}_1$. The relationship between the optimal solutions of the two problems is as shown in **Lemma 1**. According to Lemma 1, we transform how to solve problem $\mathcal{P}_1$ into how to solve problem $\mathcal{P}_2$.

Lemma 1: Let the optimal value corresponding to the optimal solution of problem $\mathcal{P}_1$ and problem $\mathcal{P}_2$ be $\mathcal{SP}_1^*$ and $\mathcal{SP}_2^*$, respectively, then we have $\mathcal{SP}_1^* \le \mathcal{SP}_2^* \le \mathcal{SP}_1^* + \sum_{m=1}^{M}\left(\psi - \tau_m^{min}\right)\cdot 1_{\{E^{min} > E_{\tau,\mathrm{m}}^{min}\}}$, where $\tau_m^{min} = \min_\tau \left\{\arg\left\{E_{\tau,l,m}^{min} = E^{min}\right\}, \arg\left\{E_{\tau,e,m}^{min} = E^{min}\right\}\right\}$, $E_{\tau,e,m}^{min} = \tau\sigma\frac{2^{\frac{LI_{m,e}^t}{\omega\tau}}-1}{h_{i,j}^t}$ and $E_{\tau,l,m}^{min} = \frac{\theta K^3 I_{m,l}^t}{\tau^2}$.

Proof: Since the constraint condition of $\mathcal{P}_2$ is more stringent than that of $\mathcal{P}_1$, it is easy to draw $\mathcal{SP}_1^* \le \mathcal{SP}_2^*$. The other side of the inequality can be obtained by constructing a feasible solution of $\mathcal{P}_2$ according to problem $\mathcal{P}_1$. Let $\left\langle Q_m^{P_1}(t)\right\rangle$ be the optimal solution of the m-th IoT device in the value space $\mathcal{SP}_1$, the following is to construct an optimal solution in the value space $\mathcal{SP}_2$ for each IoT device. We have, when $\varepsilon\left(Q_m^{P_1}(t)\right) \in \{0\} \cup \left[E^{min}, E^{max}\right]$, let $\left\langle Q_m^{P_1}(t)\right\rangle = \left\langle Q_m^{P_2}(t)\right\rangle$. Next, we will discuss the situation when $\varepsilon\left(Q_m^{P_1}(t)\right) \in \left(0, E^{min}\right)$. For the optimization problem $\mathcal{P}_2$, the energy consumption at this time is not within its constraint range, and the tasks in this state will be dropped, i.e., the corresponding optimization value $\mathcal{SP}_2 = \psi$.

Let the minimum energy consumption of the m-th IoT device meet the task deadline τ as $E_{\tau,m}^{min} = E_{\tau,l,m}^{min} + E_{\tau,e,m}^{min}$, where $E_{\tau,e,m}^{min} = \tau\sigma\frac{2^{\frac{LI_{m,e}^t}{\omega\tau}}-1}{h_{i,j}^t}$ represents the minimum energy consumption required for the task to be executed on the device side, $E_{\tau,l,m}^{min} = \frac{\theta K^3 I_{m,l}^t}{\tau^2}$ represents the minimum energy consumption required for the task to be executed on the MEC side. If $E^{min} \ge E_{\tau,m}^{min}$, the newly constructed task drop cost is set to ψ, and the corresponding cost of $\mathcal{P}_1$ is at least τ_m^{min}, where $\tau_m^{min} = \min_\tau \left\{\arg\left\{E_{\tau,l,m}^{min} = E^{min}\right\}, \arg\left\{E_{\tau,e,m}^{min} = E^{min}\right\}\right\}$. Thus, the optimal values of these two problems may differ by $\psi - \tau_m^{min}$ at most. If $E^{min} < E_{\tau,m}^{min}$, the generated task will also be dropped for $\mathcal{P}_1$. In summary, there is no difference between the optimal values of the two problems in a discrete-time slot system. ■

III. Perturbed Lyapunov Optimization-based Approach

A. Lyapunov Optimization Framework

Because Lyapunov optimization does not require many a priori parameters, it can realize real-time control in dynamic systems with relatively low algorithm complexity, which is in line with the characteristics of task generation and the characteristics of capturing green energy. In our model, Lyapunov optimization is combined with parallel offloading and energy harvesting, this method does not directly calculate the optimal value, but uses an upper bound to guarantee the stability of the system.

The energy flow is constructed as an energy queue to provide continuous and stable energy support for the normal operation of devices. Each energy queue corresponds to a virtual queue defined as:

$$\tilde{b}_i^t = b_i^t - \beta, \quad \forall t \in \mathcal{T}, \forall i \in \mathcal{M}, \tag{21}$$

where the virtual queue vector formed by all IoT devices is $\tilde{B}^t \triangleq \left[\tilde{b}_1^t, \tilde{b}_2^t, \cdots, \tilde{b}_M^t\right]$. The disturbance parameter β of IoT devices with EH technology is a bounded constant that satisfies:

$$\beta \geq \tilde{E}^{max} + \frac{V\psi}{E^{min}}, \tag{22}$$

where $\tilde{E}^{max} \triangleq \min\left\{\max_i \left\{\varepsilon_i^t\right\}, E^{max}\right\} = \min\left\{\max\left\{\beta K \left(f_{local}^{max}\right)^2, p^{max}\tau_0\right\}, E^{max}\right\}$ is the upper bound of the available energy. V is the non-negative weight control parameter.

Then define the Lyapunov function of the virtual energy queue as:

$$\mathcal{L}(t) = \frac{1}{2}\sum_{i=1}^{M}\left(\tilde{b}_i^t\right)^2 = \frac{1}{2}\sum_{i=1}^{M}\left(b_i^t - \beta\right)^2, \quad \forall t \in \mathcal{T}. \tag{23}$$

Next, we introduce a one-step conditional Lyapunov drift function to push the quadratic Lyapunov function to a bounded level to form a stable virtual queue, which is formulated as:

$$\Delta(t) = \mathbb{E}\left[\mathcal{L}(t+1) - \mathcal{L}(t) \mid \tilde{B}^t\right], \quad \forall t \in \mathcal{T}. \tag{24}$$

Finally, by combining the queue stability with the system cost required to execute the task, we obtain a Lyapunov drift plus penalty function:

$$\Delta_V(t) = \Delta(t) + V\mathbb{E}\left[cost_{total}^t \mid \tilde{B}^t\right], \quad \forall t \in \mathcal{T}. \tag{25}$$

The parameter V here is consistent with Eq. (22), which shows the trade-off relationship between the energy queue backlog and the system cost. Use the classic Lyapunov technique [27] to scale the upper bound of Eq. (25), we have:

$$\begin{aligned}\Delta_V(t) \le &\mathbb{E}\left[\sum_{i=1}^{M}\left(\tilde{b}_i^t\left(e_i^t-\varepsilon_i^t\right)\right) \mid \tilde{B}^t\right]+C\\ &+V\mathbb{E}\left[\sum_{i=1}^{M}\left(D_i^t+\psi\chi_i^t\right) \mid \tilde{B}^t\right],\end{aligned} \tag{26}$$

where $C=M\frac{\left(E_H^{max}\right)^2+\left(\tilde{E}^{max}\right)^2}{2}$. The detailed proof of Eq. (26) is shown as follows:

Proof: We first introduce a statement. Let A, B and C be non-negative real numbers and $W=A-B+C$, then $W^2 \le A^2+B^2+C^2+2A(C-B)$. Recall the definition of battery level in Eq. (12), we have:

$$\begin{aligned}\left(\tilde{b}_i^{t+1}\right)^2 &\le \left(\tilde{b}_i^t\right)^2+\left(\varepsilon_i^t\right)^2+\left(e_i^t\right)^2+2\tilde{b}_i^t\left(e_i^t-\varepsilon_i^t\right)\\ &\le \left(\tilde{b}_i^t\right)^2+2\tilde{b}_i^t\left(e_i^t-\varepsilon_i^t\right)+\left(E_H^{max}\right)^2+\left(\widetilde{E}^{max}\right)^2\end{aligned}$$

Reorganizing the above formula, we can obtain:

$$\left(\tilde{b}_i^{t+1}\right)^2-\left(\tilde{b}_i^t\right)^2 \le 2\tilde{b}_i^t\left(e_i^t-\varepsilon_i^t\right)+\left(E_H^{max}\right)^2+\left(\widetilde{E}^{max}\right)^2.$$

Summing all devices over time slot t, it holds:

$$\begin{aligned}\sum_{i=1}^{M}\left[(\tilde{b}_i^{t+1})^2-(\tilde{b}_i^t)^2\right] \le\ &2\sum_{i=1}^{M}\tilde{b}_i^t(e_i^t-\varepsilon_i^t)\\ &+M\left[(E_H^{max})^2+(\tilde{E}^{max})^2\right].\end{aligned}$$

By dividing both sides of the above inequality by two:

$$\Delta(t) \le \sum_{i=1}^{M}\tilde{b}_i^t(e_i^t-\varepsilon_i^t)+M\left[\frac{\left(E_H^{max}\right)^2+\left(\tilde{E}^{max}\right)^2}{2}\right].$$

Finally, by taking the expectation on the above inequality and adding the item $V\mathbb{E}\left[cost_{total}^t \mid \tilde{B}^t\right]$, it further yields Eq. (26). ■

By scaling Eq. (25) with Lyapunov optimization, we embed the constraint on the stability of the energy queue into Eq. (26). Solving problem $\mathcal{P}_2$ is transformed into how to solve problem $\mathcal{P}_3$:

$$\boldsymbol{\mathcal{P}_3}: \min \sum_{i=1}^{M} \left(\tilde{b}_i^t \left(e_i^t - \varepsilon_i^t\right)\right) + V \sum_{i=1}^{M} \left(D_i^t + \psi \chi_i^t\right) + C.$$

$$\text{s.t.}: \quad (1),\ (2),\ (3),\ (8),\ (11) \text{ and } (16)-(20)$$

Doing so not only minimizes the total system cost in a time-averaged sense, but also stabilizes the battery charge of each device.

B. Decoupling and Problem Solving

The problem $\mathcal{P}_3$ contains four variables to be determined: green energy, task division factor, CPU frequency, and transmission power. It is challenging to solve by traditional convex optimization algorithms. Our main idea is to decompose the problem $\mathcal{P}_3$ into a series of sub-optimization problems at each time slot. In this part, we give the decoupling process of the problem theoretically and summarize it into Fig. 2.

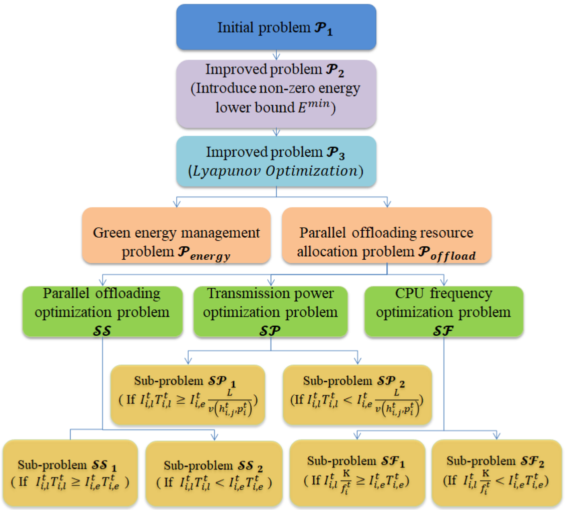

Initial problem $\mathcal{P}_1$
Improved problem $\mathcal{P}_2$ (Introduce non-zero energy lower bound E^{min})
Improved problem $\mathcal{P}_3$ (Lyapunov Optimization)
Green energy management problem $\mathcal{P}_{energy}$
Parallel offloading resource allocation problem $\mathcal{P}_{offload}$
Parallel offloading optimization problem $\mathcal{SS}$
Transmission power optimization problem $\mathcal{SP}$
CPU frequency optimization problem $\mathcal{SF}$
Sub-problem $\mathcal{SP}_1$ (If $I_{i,l}^t T_{i,l}^t \geq I_{i,e}^t \frac{L}{v\left(h_{i,j}^t, p_i^t\right)}$)
Sub-problem $\mathcal{SP}_2$ (If $I_{i,l}^t T_{i,l}^t < I_{i,e}^t \frac{L}{v\left(h_{i,j}^t, p_i^t\right)}$)
Sub-problem $\mathcal{SS}_1$ (If $I_{i,l}^t T_{i,l}^t \geq I_{i,e}^t T_{i,e}^t$)
Sub-problem $\mathcal{SS}_2$ (If $I_{i,l}^t T_{i,l}^t < I_{i,e}^t T_{i,e}^t$)
Sub-problem $\mathcal{SF}_1$ (If $I_{i,l}^t \frac{K}{f_i^t} \geq I_{i,e}^t T_{i,e}^t$)
Sub-problem $\mathcal{SF}_2$ (If $I_{i,l}^t \frac{K}{f_i^t} < I_{i,e}^t T_{i,e}^t$)

Fig. 2. The decoupling process of the problem.

1) The First Decoupling of the Problem: We can find that problem $\mathcal{P}_3$ can be decomposed into two sub-problems, namely, $\mathcal{P}_{energy}$ and $\mathcal{P}_{offload}$. The former is to optimize the energy harvesting decision, that is, how to determine e_i^t, while the latter is to optimize parallel decision-making $S_i^t \triangleq \left[I_{i,l}^t, I_{i,e}^t\right]$, the CPU frequency $f_{i,k}^t$ and the transmission power p_i^t for resource allocation. We will give the optimal solution to the problem in each slot. Before discussing the problem further, we need to give a **Lemma 2** [17] as follows:

Lemma 2: If the task is executed on the device side (locally) in the time slot t ($t \in \mathcal{T}$), the allocation of the CPU frequency will be optimal when K CPU cycles are equal, i.e., $f_{i,k}^t = f_i^t$, $i \in \mathcal{M}$, $k = 1, 2, \cdots, K$.

According to Lemma 2, we will use $T_{i,l}^t = K(f_i^t)^{-1}$, $E_{i,l}^t = \theta K(f_i^t)^2$, $t \in \mathcal{T}$, $i \in \mathcal{M}$ to optimize the objective problem. For the energy optimization problem $\mathcal{P}_{energy}$, it is easy to obtain the optimal amount of energy harvesting e^{*t}_i by solving the following Linear Programming (LP) problem:

$$\begin{aligned} \mathcal{P}_{energy}: \quad & \min \sum_{i=1}^{M} \tilde{b}_i^t e_i^t \\ \text{s.t.}: \quad & 0 \le e_i^t \le E_H^t \\ & e_i^t + b_i^t \le \Lambda_i \end{aligned}$$

where

$$e^{*t}_i = \begin{cases} \min\left\{\Lambda_i - b_i^t, E_H^t\right\}, & \tilde{b}_i^t \le 0 \\ 0, & \tilde{b}_i^t > 0 \end{cases} \tag{27}$$

Considering the remaining terms except for e_i^t in problem $\mathcal{P}_3$, we can get the problem $\mathcal{P}_{offload}$ as following:

$$\begin{aligned} \mathcal{P}_{offload}: \quad & \min - \sum_{i=1}^{M} \tilde{b}_i^t \varepsilon_i^t + V \sum_{i=1}^{M} \left(D_i^t + \psi \chi_i^t\right) + C \\ \text{s.t.}: \quad & (1),\ (2),\ (3),\ (11) \text{ and } (16) - (20) \end{aligned}$$

which includes three phases of operations in each time slot: i) Scheduling of CPU cycle frequency $f_{i,k}^t$; ii) Distribution of transmission power p_i^t; iii) Determination of parallel offloading decision S_i^t. Since there are both continuous and discrete variables in the constraints, and the coupling between different variables is very high, it is still difficult to solve them directly. So we try to decouple the problem a second time.

2) The Second Decoupling of the Problem: Similar to [22], we convert $\mathcal{P}_{offload}$ into three equivalent sub-problems in each time slot for the second decoupling. Taking the task division factor as the starting point, when the generated tasks is dropped, i.e., $I_{i,d}^t = 1$, $I_{i,l}^t = I_{i,e}^t = 0$, the device neither needs to process the task nor send it to the edge server. Thus, we have $f_{i,k}^t = 0$ and $p_i^t = 0$. Next, we consider the case that the task is not dropped, and the following three equivalent sub-problems can be obtained:

Parallel offloading problem $\mathcal{SS}$: When the transmission power and CPU frequency are given, i.e.,

$p_i^t = p_0^t$ and $f_i^t = f_0^t$, we can get the optimal solution $S{*}_i^t$.

$$
\begin{aligned}
\mathcal{SS}:\ & \min_{S_i^t} -\tilde{b}_i^t \left(I_{i,1}^t E_{i,l}^t + I_{i,e}^t E_{i,e}^t \right) + V \cdot \max \left\{ I_{i,1}^t T_{i,l}^t, I_{i,e}^t T_{i,e}^t \right\} \\
\text{s.t.}:\ & (1),\ (2),\ (16),\ \text{and}\ (20)
\end{aligned}
$$

Transmission power problem $\mathcal{SP}$: When parallel offloading decision and CPU frequency are given, i.e., $S_i^t = S_0^t$ and $f_i^t = f_0^t$, the optimal solution $p{*}_i^t$ can be obtained.

$$
\begin{aligned}
\mathcal{SP}:\ & \min_{p_i^t} -\tilde{b}_i^t \left[I_{i,l}^t E_{i,l}^t + I_{i,e}^t \frac{p_i^t L}{\omega \log_2 \left(1 + \frac{h_{i,j}^t p_i^t}{\sigma}\right)} \right] \\
& + V \cdot \max \left\{ I_{i,l}^t T_{i,l}^t, I_{i,e}^t \frac{L}{\omega \log_2 \left(1 + \frac{h_{i,j}^t p_i^t}{\sigma}\right)} \right\} \\
\text{s.t.}:\ & (16)\ \text{and}\ (19) \\
& I_{i,e}^t E_{i,e}^t \in \left[\max \left\{ 0, E^{min} - I_{i,l}^t E_{i,l}^t \right\}, E^{max} - I_{i,l}^t E_{i,l}^t \right]
\end{aligned}
$$

CPU frequency problem $\mathcal{SF}$: When parallel offloading decision and transmission power are given, i.e., $S_i^t = S_0^t$ and $p_i^t = p_0^t$, the optimal solution $f{*}_i^t$ can be obtained.

$$
\begin{aligned}
\mathcal{SF}:& \min_{f_i^t} -\tilde{b}_i^t \left(\theta I_{i,l}^t K \left(f_i^t\right)^2 + I_{i,e}^t E_{i,e}^t \right) + V \cdot \max \left\{ I_{i,l}^t \frac{K}{f_i^t}, I_{i,e}^t T_{i,e}^t \right\} \\
\text{s.t.}:\ & (16)\ \text{and}\ (18) \\
& I_{i,l}^t E_{i,l}^t \in \left[\max \left\{ 0, E^{min} - I_{i,e}^t E_{i,e}^t \right\}, E^{max} - I_{i,e}^t E_{i,e}^t \right]
\end{aligned}
$$

3) The Third Decoupling of the Problem: We found that the way in which tasks are offloaded in parallel makes D_i^t (in Eq. (13)) difficult to solve on the three sub-problems. Here, we take D_i^t as the starting point to decouple the above series of problems for the third time and give the expression of the optimal solution.

The parallel offloading problem $\mathcal{SS}$ is a convex optimization problem about the variable S_i^t, which consists of several convex functions added together and can be further transformed into sub-problem $\mathcal{SS}_1$ and sub-problem $\mathcal{SS}_2$:

Sub-problem $\mathcal{SS}_1$ for case $I^t_{i,l}T^t_{i,l} \geq I^t_{i,e}T^t_{i,e}$:

$$\mathcal{SS}_1 : \min_{S^t_i} -\tilde{b}^t_i \left(I^t_{i,1}E^t_{i,l} + I^t_{i,e}E^t_{i,e} \right) + VI^t_{i,1}T^t_{i,l}.$$
$$\text{s.t.} : \quad (1), \ (2), \ (16), \ \text{and} \ (20)$$

Sub-problem $\mathcal{SS}_2$ for case $I^t_{i,l}T^t_{i,l} < I^t_{i,e}T^t_{i,e}$:

$$\mathcal{SS}_2 : \min_{S^t_i} -\tilde{b}^t_i \left(I^t_{i,1}E^t_{i,l} + I^t_{i,e}E^t_{i,e} \right) + VI^t_{i,e}T^t_{i,e}.$$
$$\text{s.t.} : \quad (1), \ (2), \ (16), \ \text{and} \ (20)$$

We can use linear programming tools to obtain the optimal solution for each problem easily, and apply the contradiction method to verify whether the result meets the assumptions, so as to obtain the optimal offloading decision S^{*t}_i.

The transmission power problem $\mathcal{SP}$ can be further reduced to sub-problem $\mathcal{SP}_1$ and sub-problem $\mathcal{SP}_2$:

Sub-problem $\mathcal{SP}_1$ for case $I^t_{i,l}T^t_{i,l} \geq I^t_{i,e}\frac{L, v\left(h^t_{i,j}, p^t_i\right)}{\omega h^t_{i,j}}$:

$$\mathcal{SP}_1 : \min_{p^t_i} -\tilde{b}^t_i \left[I^t_{i,l}E^t_{i,l} + I^t_{i,e}\frac{p^t_i L}{v\left(h^t_{i,j}, p^t_i\right)} \right] + VI^t_{i,l}T^t_{i,l}$$
$$\begin{aligned} \text{s.t.} : &\ 0 \leq p^t_i \leq p^{max} \\ & I^t_{i,e}\frac{L}{v\left(h^t_{i,j}, p^t_i\right)} \leq I^t_{i,l}T^t_{i,l} \leq \tau \\ & I^t_{i,e}E^t_{i,e} \in \left[\max\left\{0, E^{min} - I^t_{i,l}E^t_{i,l}\right\}, E^{max} - I^t_{i,l}E^t_{i,l} \right] \end{aligned}$$

where $\tau' = I^t_{i,l}T^t_{i,l}$ in this case, and

$$p^{*t}_i = \begin{cases} p_U, & \tilde{b}^t_i \geq 0 \\ p_L, & \tilde{b}^t_i < 0 \end{cases} \tag{28}$$

Sub-problem $\mathcal{SP}_2$ for case $I_{i,l}^tT_{i,l}^t < I_{i,e}^t\frac{L,v\left(h_{i,j}^t,p_i^t\right)}{\omega h_{i,j}^t}$:

$$\begin{aligned}
\mathcal{SP}_2:\ &\min_{p_i^t} -\tilde{b}_i^t\left[I_{i,l}^tE_{i,l}^t + I_{i,e}^t\frac{p_i^tL}{v\left(h_{i,j}^t,p_i^t\right)}\right] + VI_{i,e}^t\frac{L}{v\left(h_{i,j}^t,p_i^t\right)}\\
\text{s.t.}:\ &I_{i,e}^t\frac{L}{v\left(h_{i,j}^t,p_i^t\right)} \le \tau\\
&0 \le p_i^t \le p^{max}\\
&I_{i,e}^tE_{i,e}^t \in \left[\max\left\{0, E^{min} - I_{i,l}^tE_{i,l}^t\right\}, E^{max} - I_{i,l}^tE_{i,l}^t\right]
\end{aligned}$$

where $\tau' = \tau$ in this case, and

$$p^{*t}_i = \begin{cases} p_U, & \tilde{b}_i^t \ge 0 \text{ or } \tilde{b}_i^t < 0 \ \&\ p_0 > p_U \\ p_0, & \tilde{b}_i^t < 0 \ \&\ p_L < p_0 < p_U \\ p_L, & \tilde{b}_i^t < 0 \ \&\ p_0 < p_L \end{cases} \tag{29}$$

Let $\mathrm{g}_1\left(p_i^t, h_{i,j}^t, \tilde{b}_i^t\right) = \frac{-\tilde{b}_i^tp_i^t}{v\left(h_{i,j}^t,p_i^t\right)} + \frac{V}{v\left(h_{i,j}^t,p_i^t\right)}$, we take the first-order partial derivative of g_1: $\frac{\mathrm{dg}_1\left(p_i^t,h_{i,j}^t,\tilde{b}_i^t\right)}{\mathrm{d}p_i^t} = \frac{-\tilde{b}_i^t\log_2\left(1+\frac{h_{i,j}^tp_i^t}{\sigma}\right)-\frac{h_{i,j}^t}{\left(\sigma+h_{i,j}^tp_i^t\right)\ln 2}\left(V-p_i^t\tilde{b}_i^t\right)}{\omega\log_2^2\left(1+\frac{h_{i,j}^tp_i^t}{\sigma}\right)}$ and p_0 is the solution of $\tilde{b}_i^t\log_2\left(1+\frac{h_{i,j}^tp_i^t}{\sigma}\right) + \frac{h_{i,j}^t}{\left(\sigma+h_{i,j}^tp_i^t\right)\ln 2}\left(V - p_i^t\tilde{b}_i^t\right) = 0$. In addition, we define p_L and p_U as follows:

$$p_L = \begin{cases} p_{L,\tau'}, & E_0 \ge E^{min} - I_{i,l}^tE_{i,l}^t \\ \max\left\{p_{L,\tau'}, p_{E^{min}}\right\}, & E_0 < E^{min} - I_{i,l}^tE_{i,l}^t \end{cases} \tag{30}$$

$$p_U = \begin{cases} 0, & E_0 \ge E^{max} - I_{i,l}^tE_{i,l}^t \\ \min\left\{p^{max}, p_{E^{max}}\right\}, & E_0 < E^{max} - I_{i,l}^tE_{i,l}^t \end{cases} \tag{31}$$

where $E_0 = \frac{\sigma I_{i,e}^tL\ln 2}{\omega h_{i,j}^t}$, and $p_{L,\tau'} = \frac{\sigma\left(2^{\frac{LI_{i,e}}{\omega\tau'}}-1\right)}{h_{i,j}^t}$ is the solution when $T_{i,e}^t = \tau'$. Besides, $p_{E^{min}}$ and $p_{E^{max}}$ are the solutions of $I_{i,e}^tE_{i,e}^t = E^{min}$ and $I_{i,e}^tE_{i,e}^t = E^{max}$, respectively. That is, $p_{E^{min}}I_{i,e}^tL = v\left(h_{i,j}^t, p_{E^{min}}\right)E^{min}$ and $p_{E^{max}}I_{i,e}^tL = v\left(h_{i,j}^t, p_{E^{max}}\right)E^{max}$.

Furthermore, the CPU frequency allocation problem $\mathcal{SF}$ can be further reduced to sub-problem $\mathcal{SF}_1$ and sub-problem $\mathcal{SF}_2$.

Sub-problem $\mathcal{SF}_1$ for case $I_{i,l}^t \frac{K}{f_i^t} \geq I_{i,e}^t T_{i,e}^t$:

$$\begin{aligned}
\mathcal{SF}_1 :\ & \min_{f_i^t} -\tilde{b}_i^t \left[I_{i,l}^t \theta K \left(f_i^t\right)^2 + I_{i,e}^t E_{i,e}^t \right] + V I_{i,l}^t \frac{K}{f_i^t} \\
\text{s.t.} :\ & I_{i,l}^t \frac{K}{f_i^t} \leq \tau \\
& 0 \leq f_i^t \leq f_{local}^{max} \\
& I_{i,l}^t E_{i,l}^t \in \left[\max\left\{0, E^{min} - I_{i,e}^t E_{i,e}^t\right\}, E^{max} - I_{i,e}^t E_{i,e}^t \right]
\end{aligned}$$

where $\tau' = \tau$ in this case, and

$$f^{*t}_i = \begin{cases} f_U, & \tilde{b}_i^t \geq 0 \text{ or } \tilde{b}_i^t < 0, f_0 > f_U \\ f_0, & \tilde{b}_i^t < 0, f_L < f_0 < f_U \\ f_L, & \tilde{b}_i^t < 0, f_0 < f_L \end{cases} \tag{32}$$

Let $\mathrm{g}_2(f_i^t, \tilde{b}_i^t) = -\tilde{b}_i^t \theta K \left(f_i^t\right)^2 + V \frac{K}{f_i^t}$, we take the first-order partial derivative of g_2: $\frac{\mathrm{d}\mathrm{g}_2\left(f_i^t, \tilde{b}_i^t\right)}{\mathrm{d}p_i^t} = -2\tilde{b}_i^t \theta K f_i^t - V \frac{K}{f_i^t}$ and f_0 is the solution of $\mathrm{g}_3(f_i^t, \tilde{b}_i^t)$, i.e., $f_0 = \sqrt[3]{\frac{V}{-2\theta \tilde{b}_i^t}}$. Besides, $f_L = \max\left\{ \frac{K I_{i,l}^t}{\tau'}, \max\left\{0, \sqrt{\frac{E^{min} - I_{i,e}^t E_{i,e}^t}{I_{i,l}^t \theta K}}\right\}\right\}$ and $f_U = \min\left\{ f_{local}^{max}, \sqrt{\frac{E^{max} - I_{i,e}^t E_{i,e}^t}{I_{i,l}^t \theta K}} \right\}$.

Sub-problem $\mathcal{SF}_2$ for case $I_{i,l}^t \frac{K}{f_i^t} < I_{i,e}^t T_{i,e}^t$:

$$\begin{aligned}
\mathcal{SF}_2 :\ & \min_{f_i^t} -\tilde{b}_i^t \left(I_{i,l}^t \theta K \left(f_i^t\right)^2 + I_{i,e}^t E_{i,e}^t \right) + V I_{i,e}^t T_{i,e}^t \\
\text{s.t.} :\ & I_{i,l}^t \frac{K}{f_i^t} < I_{i,e}^t T_{i,e}^t \leq \tau \\
& 0 \leq f_i^t \leq f_{local}^{max} \\
& I_{i,l}^t E_{i,l}^t \in \left[\max\left\{0, E^{min} - I_{i,e}^t E_{i,e}^t\right\}, E^{max} - I_{i,e}^t E_{i,e}^t \right]
\end{aligned}$$

where $\tau' = I_{i,e}^t T_{i,e}^t$ in this case, and

$$f^{*t}_i = \begin{cases} f_U, & \tilde{b}_i^t \geq 0 \\ f_L, & \tilde{b}_i^t < 0 \end{cases} \tag{33}$$

C. Green-Parallel Online Offloading Algorithm

As we mentioned earlier, the computing resources of edge servers in the real world are usually limited. We assume that MEC servers in IoT-Edge system have limited computing resources, that is, in each time slot, at most $Q = \left\lfloor \frac{\tau f_{edge}^{max}}{K} \right\rfloor$ devices are allowed to connect to one MEC server at the same time. According to the optimal solution given in Section III, we design the GPOOA algorithm for DSCI-type tasks.

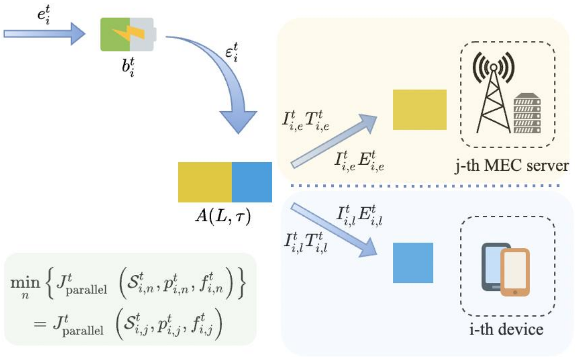

e_i^t
b_i^t
ε_i^t
$I_{i,e}^t T_{i,e}^t$
$I_{i,e}^t E_{i,e}^t$
j-th MEC server
$A(L,\tau)$
$I_{i,l}^t E_{i,l}^t$
$I_{i,l}^t T_{i,l}^t$
$\min_n \left\{ J_{\text{parallel}}^t \left(\mathcal{S}_{i,n}^t, p_{i,n}^t, f_{i,n}^t \right) \right\}$
$= J_{\text{parallel}}^t \left(\mathcal{S}_{i,j}^t, p_{i,j}^t, f_{i,j}^t \right)$
i-th device

Fig. 3. The task division process for the DSCI-type tasks.

GPOOA adopts the principle of minimum target value (J_{parallel}^t) first offloading, and seeks for parallel decision-making and resource allocation scheme to minimize the system cost. It is known that when given any two variables, the $\mathcal{P}_3$ turns into how to optimize $\mathcal{SF}$, $\mathcal{SP}$, or $\mathcal{SS}$. First, we get a random task division factor $\mathcal{S}_{i,j}^t$ by initializing $f_{i,j(0)}^t$ and $p_{i,j(0)}^t$, and get a random $p_{i,j}^t$ by $\mathcal{S}_{i,j}^t$ and $f_{i,j(0)}^t$. We use the obtained $\mathcal{S}_{i,j}^t$ and $p_{i,j}^t$ as the given two variables to optimize the problem $\mathcal{SF}$. Meanwhile, if the optimal offload object of task A generated by device i is MEC server j, and the number of devices connected to server j is less than Q, then task A will be completed by device i and server j together. If the server j has connected Q devices, then task A can only choose the suboptimal offload object. The details of the algorithmic process are described in **Algorithm 1**, where $J_{\text{parallel}}^t = -\tilde{b}_i^t \varepsilon_i^t + V\left(D_i^t + \psi\chi_i^t\right)$ and Q is the maximum number of devices that the edge server can connect to in a time slot. Fig. 3 shows the DSCI-type task division process.

IV. Performance Evaluation

In this section, we verify the effectiveness of GPOOA through MATLAB simulation with the adoption of the controlled variable method.

A. Simulation Setup

The parameter setting of the paper mainly refers to work [13], [17]. There are 3 MEC servers and 8 IoT devices placed in an area of $100m \times 100m$, where IoT devices can move arbitrarily in the area without affecting each other. Let $E_{i,H}^t$ be a uniform distribution on $\left[0, E_H^{max}\right]$ with the average EH power $p_H = E_H^{max}/2\tau$ (the range is between 7.5 mW and 10 mW). The unit task $A(L,\tau)$ with $L = 1$ kbits and

ALGORITHM 1: The GPOOA Algorithm

```
for time slots $t \in \mathcal{T}$ do
    for $i = 1$ to $M$ do
        Acquire $\zeta_i^t$, $\tilde{b}_i^t$ and $E_H^t$
        Solve the problem $\mathcal{P}_{energy}$ as Eq. (27) to get the $e{*}_i^t$
        for $j = 1$ to $N$ do
            Initialize $f_{i,j(0)}^t$ and $p_{i,j(0)}^t$
            Solve the problem $\mathcal{SS}$ to get the $\mathcal{S}_{i,j}^t$;
            Solve the problem $\mathcal{SP}$ as Eqs.(28) and (29) to get the $p_{i,j}^t$;
            Solve the problem $\mathcal{SF}$ as Eqs.(32) and (33) to get the $f_{i,j}^t$;
            Record optimal value $J_{\text{parallel}}^t\left(\mathcal{S}_{i,j}^t, p_{i,j}^t, f_{i,j}^t\right)$;
            If the battery energy level is insufficient for the $i$ IoT device and the $j$ MEC server to parallel offloading, set
            $J_{\text{parallel}}^t\left(\mathcal{S}_{i,j}^t, p_{i,j}^t, f_{i,j}^t\right)$ as inf;
            Choose the optimal $\mathcal{S}{*}_i^t$, $P{*}_i^t$ and $f{*}_i^t$ by selecting the minimum $J_{\text{parallel}}^t\left(\mathcal{S}_{i,j}^t, p_{i,j}^t, f_{i,j}^t\right)$, denote as $J_{\text{parallel}}^t\left(\mathcal{S}_i^t, p_i^t, f_i^t\right)$ and
            record $j$.
        end for
        Insert key-value pair into the map with key $i$ and value $j$;
    end for
    while map $\neq \emptyset$ do
        Find the key-value pair“$i$-$j$” with the smallest value $J_{\text{parallel}}^t\left(\mathcal{S}_i^t, p_i^t, f_i^t\right)$ and record $j$;
        if flag[$j$] $\leq Q$ then
            Remove the key-value pair “$i$-$j$” from the map;
            flag[$j$] = flag[$j$] + 1;
        else
            $J_{\text{parallel}}^t\left(\mathcal{S}_{:,j}^t, p_{:,j}^t, f_{:,j}^t\right) = \text{inf}$;
            if min $\left\{J_{\text{parallel}}^t\left(\mathcal{S}_{i,:}^t, p_{i,:}^t, f_{i,:}^t\right)\right\} \neq$ inf then
                Find the smallest $J_{\text{parallel}}^t\left(\mathcal{S}_{i,j'}^t, p_{i,j'}^t, f_{i,j'}^t\right)$, overwrite the server initially selected in the map with $j'$, and overwrite the
                value of $J_{\text{parallel}}^t\left(\mathcal{S}_i^t, p_i^t, f_i^t\right)$.
            else
                There is no server to choose, the task can only be dropped.
            end if
        end if
    end while
    Update the virtual energy queue $\tilde{b}_i^{t+1}$;
    Set $t = t + 1$;
end for
```

$\tau = 2$ ms. The channel power gains are exponential distribution with mean $g_0\left(\frac{d_0}{d_{i,j}^t}\right)^{\alpha}$, where the pass-loss exponent $\alpha = 4$, the path-loss constant $g_0 = -40$ dB and $d_0 = 1$. The small-scale fading channel power gains follow an exponential distribution, i.e., $\gamma_{i,j}^t \sim Exp(1)$. In addition, $\theta = 10^{-28}$, $f_{local}^{max} = 1.5$ GHz, $p^{max} = 1.8$ W, $\omega = 10^6$ Hz and $\sigma = 10^{-13}$. Penalty weight for dropping tasks cost $\psi = 2$ ms and $E^{min} = 0.04$ mJ, $f_{edge}^{max} = 1.5$ GHz, $W = 737.5$ cycle/bit. We verify the effectiveness of GPOOA through MATLAB simulation on 3,000 time slots with the slot length $\tau_0 = 2$ ms.

B. Performance Analysis

As depicted in Fig. 4, given the arrival rate $\rho = 0.5$, as V goes from 0 to 7×10^{-5}, the time-averaged system cost drops from 1.57 to 0.97 ms, and the average energy queue backlog increases from 1.48 to 2.70 mJ. It can be found that the average battery queue length increases linearly as V increases. Meanwhile, the system cost is inversely proportional to V and eventually converges to the optimal value of $\mathcal{P}_1$ as V increases. Thus, by adjusting V, the trade-off between the minimization of the system cost and the stability of the battery queue can be achieved.

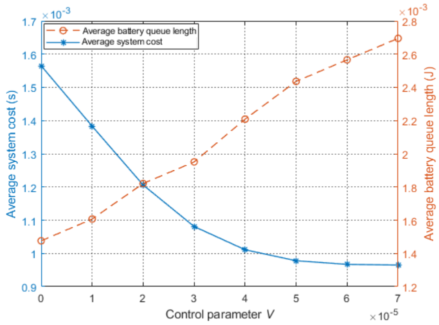


Fig. 4. The average system cost and average battery queue level under different control parameters V (in $J^2 \cdot s^{-1}$).

From Fig. 5, the system cost decreases rapidly at the beginning, then tends to decrease slowly, and finally stays within 1.1ms. As time increases, the energy buffer of the battery queue gradually increases and remains at a relatively stable level after the 1,000th time slot. That is, the green energy captured by the outside world and the energy consumed by the task have reached a balanced state. We can also find from the curve that the battery queue backlog fluctuates frequently. This is because when the energy harvester captures energy from the outside world, the process of green energy reaching the device at time slot t is random.

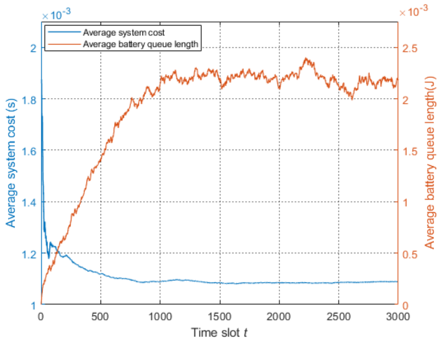
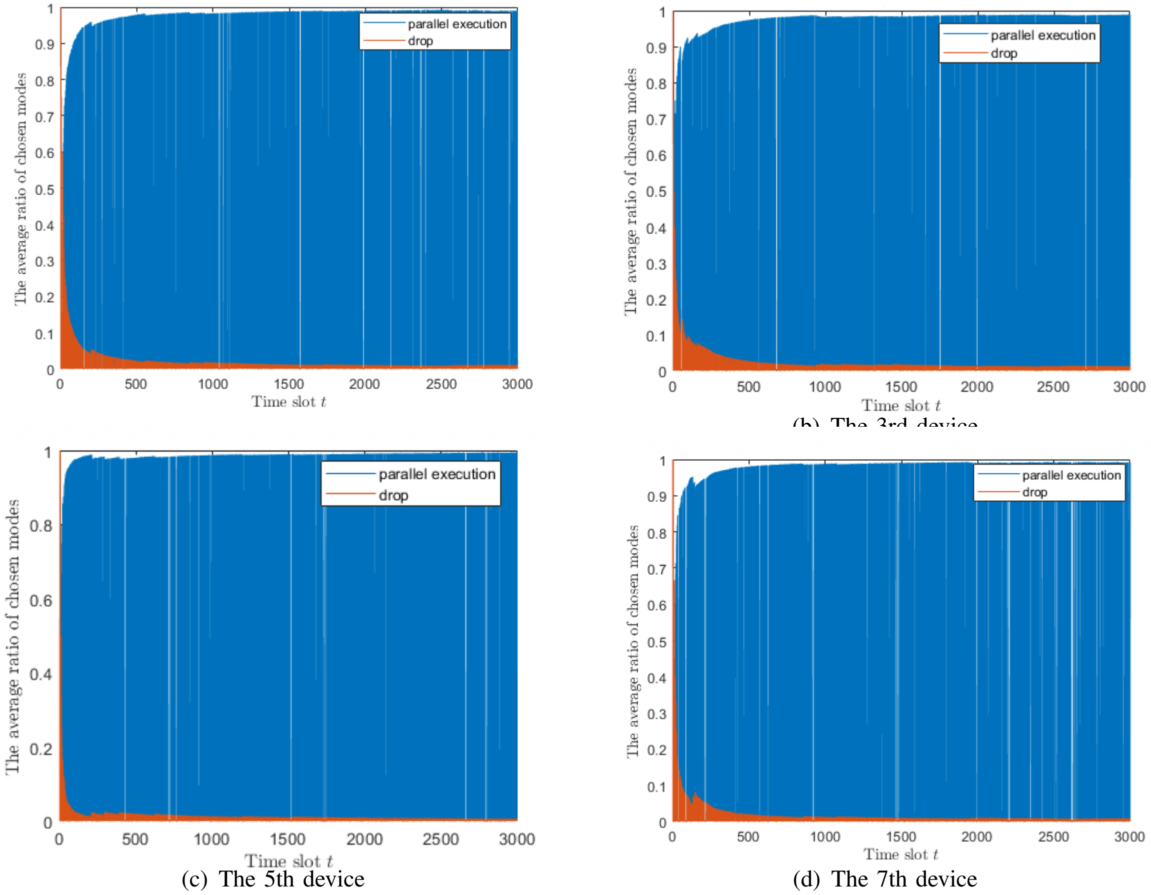


Fig. 5. The average system cost and the average battery queue length over 3,000 time slots with the arrival rate $\rho = 0.5$ and $V = 3 \times 10^{-5}$.

From Fig. 6, the task drop ratio tends to be very small after the 500th time slot, which indicates that most of the generated tasks can be completed within the deadline. This is because the GPOOA utilizes a combination of green energy to provide power and parallel offloading. Parallel offloading reduces the execution time of tasks and ensures that they are processed within the deadline as much as possible. Green energy solves the problem of limited local batteries and provides a constant source of energy support for smooth parallel offloading of tasks, which results in a significant reduction in task drop ratio.



(b) The 3rd device

(c) The 5th device

(d) The 7th device

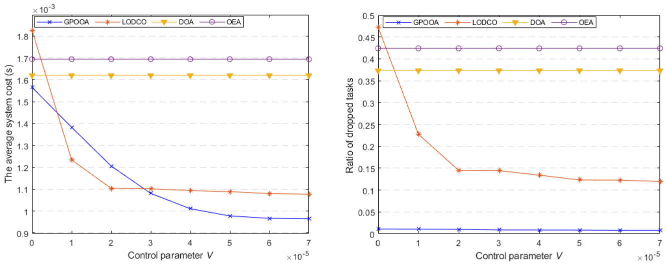
Fig. 6. Evolution of the average task drop ratio of devices (orange part), where the 1st, 3rd, 5th, and 7th devices are selected in turn.

C. Comparison of Different Offloading Schemes

We compare the proposed GPOOA with the following three offloading methods: LODCO [17], Only-Edge Algorithm (OEA) and Dynamic Offloading Algorithm (DOA). These algorithms are all performed on 3000-time slots. The devices are powered by the green energy collected by the EH. Tasks are generated with a Bernoulli distribution and are of the DSCI type. **Only-Edge Algorithm (OEA):** This algorithm adopts a method in which tasks are greedily offloaded to edge servers for processing. When i) $\frac{L}{v(h_{i,j}^t, p_i^t)} \leq \tau$ and ii) the energy required for the transmission task does not exceed the battery energy level of the current time slot, the task will be offloaded with the maximum transmission power p_i^t. Here $p_i^t = \min\left\{p^{max}, p^t_{\min\{b^t, E^{max}\}}\right\}$ if $\frac{\sigma L \ln 2}{\omega h^t} < \min\left\{b_i^t, E^{\max}\right\}$ and $p^t_{\min\left\{b_i^t, E^{max}\right\}}$ is the unique solution of $pL = v\left(h_{i,j}^t, p\right) \min\left\{b_i^t, E^{max}\right\}$. Otherwise, the task will be dropped.

Dynamic Offloading Algorithm (DOA): This algorithm adopts a calculation mode with a smaller delay within the delay requirement ($\frac{L}{v(h_{i,j}^t, p_i^t)} \leq \tau$ or $\frac{W}{f_i^t} \leq \tau$). That is, if the delay due to offloading is less than the local execution time, the task will be offloaded to the edge with the maximum transmission power p_i^t. Otherwise, it will be processed locally with the maximum CPU cycle frequency f_i^t. If neither of these two calculation modes is feasible, the task will be dropped. The maximum CPU cycle frequency available on the device side $f_i^t = \min\left\{f_{local}^{max}, \sqrt{\frac{\min\left\{b_i^t, E^{max}\right\}}{\theta W}}\right\}$ if $\frac{W}{f_i^t} \leq \tau$. The maximum transmission power p_i^t is the same as OEA algorithm.

1) Impact of the Control Parameter V: It can be observed from Fig. 7(a) that our proposed GPOOA performs better in minimizing system cost with V increases and outperforms the other three algorithms. As V increases, the system cost of the LODCO and the GPOOA decreases by $O(1/V)$ and gradually converges to the lowest level. This is because both the LODCO and the GPOOA are based on the Lyapunov optimization framework. In addition, this also confirms that GPOOA can reach the asymptotic optimum. Since DOA and OEA do not require V to regulate system costs and battery queues, their average system costs do not change with changes in V. At the same time, we found that the DOA is better than the OEA that only greedily offloads to the edge. As we envisioned, only greedy offloading on the device side or edge side cannot make full use of resources.

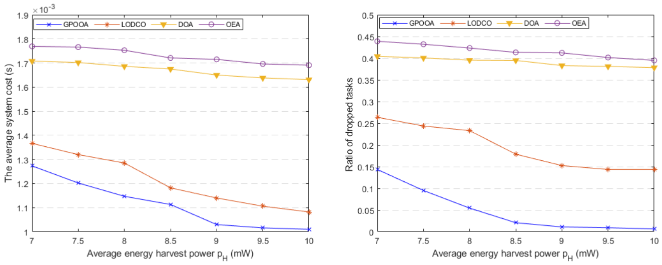


(a) The average system cost (b) The ratio of dropped tasks

Fig. 7. The average system cost and the ratio of dropped tasks under different control parameters V.

2) Impact of the Task Drop Ratio: From Fig. 7, the inability of DOA and OEA to make full use of system resources has resulted in large delays and high energy consumption. This caused a large number of tasks to be dropped due to excessive response time or insufficient energy supply. With the increase of V, LODCO suppresses the task drop ratio at the expense of a smaller system cost drop. However, compared with the other three schemes, the proposed GPOOA has outstanding performance in reducing the task drop ratio. Because GPOOA can flexibly select edge servers to parallel offloading for each IoT device based on the current channel status and user location. Not only does it take full advantage of the green energy on the device side, but it also takes advantage of the computing power of the edge server, so that more tasks can be executed within the deadline.

3) Impact of the EH Rate: Figs.8(a) and 8(b) show the relationship between the average system cost and the task drop ratio with p_H. With the increase of p_H, the average system cost and task drop ratio of all



(a) The average system cost (b) The ratio of dropped tasks

Fig. 8. The average system cost and the ratio of dropped tasks vs. p_H, where $V = 4 \times 10^{-5}$.

algorithms have decreased to varying degrees. Because the consumption of green energy does not incur system costs, the larger the p_H, the more sufficient energy is provided for the device in a unit time slot. Adequate energy will weaken the energy consumption constraints caused by offloading, so more tasks will be executed smoothly. Our GPOOA has outstanding performance in task drop ratio, which is less than 1% after $p_H = 8.5$ mW. The average system cost of GPOOA is much lower than that of the DOA and the OEA. Compared with the LODCO, the average system cost is reduced by 8.21%. This once again verifies the effectiveness of the GPOOA algorithm.

V. Conclusion

This paper proposes GPOOA, a green parallel offloading strategy based on Lyapunov optimization. Through three-time decoupling of the objective function, the joint optimization of green energy, CPU cycle frequency, transmission power, and task division factor is realized. Under the condition of little prior knowledge, the algorithm flexibly selects the target server for parallel offloading according to the current location and channel state of the device. In addition, we conducted a performance analysis and revealed that GPOOA can achieve asymptotically optimal results. Simulation results demonstrate that through parallel offloading, GPOOA is significantly superior to benchmark strategies in terms of system costs and task drop ratio. Future work includes applying Lyapunov-guided federated reinforcement learning [28] and digital twin [29] to simulate the energy harvesting process.

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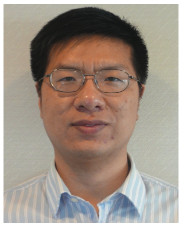

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