Multi-tier ON/OFF Scheduling Algorithm for Small Cell Networks with Renewable Energy

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Abstract. In the future cellular network, densifying the multi-tier heterogeneous cellular network (HetNet) via viral deployment of small cell base stations (SBSs) can increase energy consumption. In order to solve the energy problem in the future, SBSs that rely solely on energy harvesting can be adopted. In this paper, we focus on problem about multi-tier ON/OFF scheduling of SBSs and the goal is to minimize the overall cost of the network, including energy consumption costs and transmission delay costs of a HetNet. Finally, simulation results show, proposed algorithm can improve the overall performance of the network.

Keywords: Energy consumption · Transmission delay

1 Introduction

In order to face a large amount of transmission data growth, the need for high-capacity wireless networks has spurred a variety of new technologies in recent years. One solution is to deploy SBSs intensively, which reduce the blind spot area and improve the performance of network. SBSs are employed to improve the overall wireless quality-of-service (QoS).

Several recent works study ON/OFF scheduling for improve the energy efficiency by intelligently turning BSs ON and OFF. For instance, the authors in [1] solve the online ON/OFF scheduling issues through consider energy harvesting and the influence of transmission delays in a two-tier heterogeneous network. The proposed algorithm considers two states of SBSs and macro cell base stations (MBSs) in cellular networks. However, in multi-tier HetNet, there are multi-tier BSs, each tier of BSs has a different transmission range and energy arrival. For multiple states, the UE is faced with a variety of options, and ON/OFF scheduling of the SBS is determined by the connection state of the UE.

In this paper, we derive a novel framework to optimize the user association and switch SBSs in a HetNet, in which exist multiple types of SBSs and a MBS which located in the center. To solve the optimization problem for each user

group online, a multi-tier ON/OFF scheduling algorithm is proposed. The multi-tier ON/OFF scheduling algorithm solves the new difficulties when compared to the traditional online problem. We show that under an illustrative case, a multi-tier ON/OFF scheduling algorithm achieves a competitive ratio of 1.52. Simulation results are provided to verify the theoretical analysis, and our results show that the proposed multi-tier ON/OFF scheduling algorithm has superior performance to the traditional fixed-time algorithm.

For the rest of this paper. In Sect. 2, the system model and performance model are presented. In Sect. 3, the algorithm process is given. In Sect. 4, the performance of the proposed algorithm is demonstrated with using simulations. Finally, Sect. 5 concludes the paper.

2   System Model and Problem Formulation

We consider a multi-tier HetNet that consists of k types of transmit BSs belonging to different tiers [2]. Each tier is independent, and the BSs differ in terms of transmit power and spatial density.

Next, we discuss the user association policy. If one of the UEs leaves SBS j^k, other UEs in same user group will leave SBS j^k at the same time. We call these UEs connected to the BS in tier k user group $\mathcal{I}_{j^k}$. The set of UEs associated with the same SBS j^x is denoted by

$$\mathcal{I}_{j^x} = \{i | j^x = \mathrm{argmin}\varepsilon_{ij^x}, \forall_i \in \mathcal{I}\}. \tag{1}$$

In the paper, we consider a continuous-time system. Within period T, we can use time t to represent the operation time. When time $t = 0$, we assume that user association is done by (1). At time t, the UEs associated with SBS j^x are given by the set $\mathcal{I}_{j^x,t}$. In particular, we let $\mathcal{I}_{0,t}$ be the set of UEs connect to the MBS at time t and $\mathcal{I}_{j^x,t}, j \in \mathcal{J}^x$ be the set of UEs connect to SBS j^x at time t. Then, the UEs belong to same user group should connect to the $(x-1)th$ level BSs at time $t \in [0, T]$ from (1), so $\cup_{x=1}^{k} \cup_{i=1}^{J} \mathcal{I}_{j^x,t} \cup \mathcal{I}_{0,t}$.

Then, we consider the network delay performance model. In this model, we consider the each tier transmission delay cost. Whenever a file containing $\mathcal{K}$ bits is transferred to each UE, we can define the transmission delay cost between each tier SBS and all UEs in $\mathcal{I}_{j^x,t}$ at time t as

$$\phi_{j^x}^{\mathcal{I}_{j^x,t}} = \sum_{i \in \mathcal{I}_{j^x,t}} \frac{\mathcal{K}}{\mathbb{E}[c_{ij^x}(l_{ij^x})]}. \tag{2}$$

Similarly, the transmission delay cost about UE associated with MBS in time t can be defined as follows:

$$\phi_0^{\mathcal{I}_{0,t}} = \sum_{i \in \mathcal{I}_{0,t}} \frac{\mathcal{K}}{c_{i0}}. \tag{3}$$

For balance the power cost and delay cost, we define the new punishment cost as follows:

$$\Phi_{x \to x-1}^j = \ln(\tau(\phi_{j^{x-1}}^{\mathcal{I}_{j^x,t}} - \phi_{j^x}^{\mathcal{I}_{j^x,t}})), \tag{4}$$

where $\Phi^j_{x\to x-1}$ is the delay cost for the UE to change its connection state (from SBS j^x to SBS j^{x-1}). τ is a weighting parameter that balances the delay cost and the QoS.

When the UE switches from SBS j^k to the MBS, the UE needs to transfer from j^k to j^{k-1}, then from j^{k-1} to j^{k-2} and finally to the MBS. The delay cost in user group $\mathcal{I}_{j^k}$ can be written as follows:

$$\Phi^j_{k\to 0} = \Phi^j_{k\to k-1} + \Phi^j_{x-1\to x-2} + \cdots + \Phi^j_{1\to 0}. \tag{5}$$

For each user group $\mathcal{I}_{j^k}$ has its own delay cost and is not associated with each other. We accumulate these delay cost and obtain the total delay cost function as follows:

$$\Phi_t = \sum_{x=1}^{k} \sum_{j=1}^{|\mathcal{J}^x|} \left(\Phi^j_{x\to x-1} \right). \tag{6}$$

Next, we consider the power consumption model. For each user group $\mathcal{I}_{j^k}$, when a user group connects to the MBS, the power cost of $\mathcal{I}_{j^k}$ connected to the MBS at time t can be defined as:

$$\varphi^t_{j,0} = \frac{|\mathcal{I}_{j^k}|}{M} P^{\mathrm{op}}_{j^x} \sigma^t_{j^x} (1-q) P^{\mathrm{op}}_0. \tag{7}$$

For SBSs, because of its simple structure, we consider the operational power $P^{\mathrm{op}}_{j^x}$ when SBS in ON state and standby power consumption when SBS in OFF state. In particular, we assume the standby power is 0. In other words, SBSs only generate power cost when in ON state. Hence, the power consumption of the SBS j^x at time t is

$$\psi^t_{j^x} = P^{\mathrm{op}}_{j^x} \sigma^t_{j^x}, \tag{8}$$

where $\sigma^t_{j^x}$ is represent ON/OFF state of SBS j^x, and it is defined as:

$$\sigma^t_{j^x} = \begin{cases} 1, & \text{if SBS } j^x \text{ in ON states at time } t, \\ 0, & \text{other cases.} \end{cases} \tag{9}$$

Let M^x be the maximum number of UE connections for an SBS in tier x. For each user group $\mathcal{I}_{j^k}$, when the user group connects to SBS j^x, the power cost for the UEs to connect to SBS j^x at time t can be defined as follows:

$$\varphi^t_{j,x} = \frac{|\mathcal{I}_{j^k}|}{M^x} P^{\mathrm{op}}_{j^x} \sigma^t_{j^x}, \tag{10}$$

For energy storage system, we can use energy storage modules (ESMs) store the energy. Thus, plus new sources of energy acquired through nature and subtract the resources that have been consumed, the value of $\mathcal{E}^t_{j^x}$ at time t is given by

$$\mathcal{E}^t_{j^x} = \min(\mathcal{E}^{t-\Delta t}_{j^x} - \psi^t_{j^x} \Delta t + \Theta^t_{j^x}, \mathcal{E}^x_{\max}), \tag{11}$$

where $\psi_{j^x}^t \Delta t$ is the energy resources consumption of SBS j^x during a short interval of time Δt, $\Theta_{j^x}^t$ represents increased energy about SBS j^x during time Δt, and $\mathcal{E}_{\max}^x$ is the maximum capacity of the ESMs in x tier.

Then, we give the overall power cost of the HetNet at time t is

$$\Psi_t = \sum_{x=1}^{k} \sum_{j=1}^{|\mathcal{J}^x|} \psi_{j^x}^t \sigma_{j^x}^t + \psi_0^{\mathcal{I}_{0,t}}. \tag{12}$$

Next, we construct the objective function problem which consists of power cost and delay cost. And our goal is to minimize the objective function, the function is given by

$$\min_{\sigma_{j^x}^t} \quad \int_{t=0}^{T} \left(\Phi_t + \Psi_t \right) dt, \tag{13}$$

$$\mathcal{I}_{j^x,t} \cap \mathcal{I}_{m^x,t} = \varnothing, j^x \neq m^x, \forall j^x, m^x \in \mathcal{B}_t^{on}, \tag{14}$$

$$\mathcal{E}_{j^x}^t = \min(\mathcal{E}_{j^x}^{t-\Delta t} - \psi_{j^x}^t \Delta t + \Theta_{j^x}^t, \mathcal{E}_{\max}^x), \tag{15}$$

where $\mathcal{B}_t^{on}$ is the set of BSs in ON state at time t, $\mathcal{B}$ is the set of BSs in cellular networks, and $\mathcal{J}_t^{x+1,off}$ is the set of OFF BSs at time t in the $x+1$ tier. $\varepsilon_{j^x m^{x+1}}$ represents the Euclidean distance between SBS j^x and m^{x+1} in tiers x and $x+1$. The optimization variables are shown as vector $\sigma_{j^x}^t$, which indicates the ON and OFF states of the SBSs at time t.

3   Algorithm Description

In this section, we define the solution of the main problem in the form of a vector $\boldsymbol{\sigma}^t$, where the elements of the vector are vector $\boldsymbol{\sigma}_j^t$. $\boldsymbol{\sigma}_j^t$ represents the ON/OFF state of an SBS when associated with UEs in each tier, and the vector $\boldsymbol{\sigma}_j^t = [\sigma_{j^k}^t, \sigma_{j^{k-1}}^t, ..., \sigma_{j^x}^t, ..., \sigma_{j^1}^t]'$. Since $\boldsymbol{\sigma}_j^t$ is the solution of the sub-problems, $\boldsymbol{\sigma}^t$ can be found by solving the sub-problems. Thus, we can redefined the function (13) as follows:

$$\min_{\boldsymbol{t}_j} \sum_{j=1}^{|\mathcal{J}^k|} F_j \quad F_j(\boldsymbol{t}_j) = \boldsymbol{r}_j \boldsymbol{t}_j + \boldsymbol{b}_j, \tag{16}$$

$$s.t. \quad \mathcal{E}_{j^x}^t = \min(\mathcal{E}_{j^x}^{t-\Delta t} - \psi_{j^x}^t \Delta t + \Theta_{j^x}^t, \mathcal{E}_{\max}^x),$$

$$\boldsymbol{r}_j = [\varphi_{j,k} - \varphi_{j,0}, \cdots, \varphi_{j,1} - \varphi_{j,0}, \varphi_{j,0}], \tag{17}$$

$$\boldsymbol{b}_j = [0, \Phi_{k \to k-1}^j, \Phi_{k-1 \to k-2}^j, \cdots, \Phi_{1 \to 0}^j], \tag{18}$$

where $b_{j^x} \in \boldsymbol{b}_j$ is the delay cost of user group $\mathcal{I}_{j^k}$ to transfer SBS j^x to SBS j^{x-1}, $r_{j^x} \in \boldsymbol{r}_j$ is the power cost for user group $\mathcal{I}_{j^k}$ to connect to each SBS. For the renewable resources, such as solar energy, we can not predict when there is a sun and when there is no sun. For each tier SBS, the arrival of energy in the future is unknown. Hence, the SBS can not decide when to schedule.

So we propose an multi-tier online ON/OFF scheduling algorithm to solve this problem. In this system model, the network control center controls the connection state of the user group by the transition probability $p(t)$. Then, BS according to the UEs connection to the intelligent ON/OFF scheduling.

The algorithmic process can be described as follows. First, find the optimal the value of c (the minimum value that meets the conditions). Then, connect the UEs to SBS j^k (the boundary condition $p_1(0) = 0$). For each time point, the optimal power cost rate or the connection state of UEs changes (e.g., the UEs connect to SBS j^x at time t_1 and connect to SBS j^{x-1} at time t_2). This process results in a new differential equation with a new boundary condition. Finally, using this method, we can find each OFF time for the entire multi-tier base station energy harvesting system.

4   Simulation Results and Analysis

In the simulation, we assume MBS, multiple types of SBSs and UEs are randomly distributed in a $0.9\,\mathrm{km} \times 0.9\,\mathrm{km}$ area. We reference and adjust relevant parameters from [3]. We assume that available energy resources satisfy a Poisson process and different levels have different energy arrival rates. The first-level energy rate is 100, and each energy arrival is $1\,\mathrm{J}$ during $T = 30\,\mathrm{s}$. The second-level energy rate is 20, and each energy arrival is $0.2\,\mathrm{J}$ during $T = 3\,\mathrm{s}$. Additionally, it is assumed that the initially stored energy of SBS j^x is different. The first-level SBS j^1 is set to $\mathcal{E}_{j^1} = 100\,\mathrm{J}$, and SBS j^2 is set to $\mathcal{E}_{j^2} = 20\,\mathrm{J}$. We use $\mathcal{K} = 10^5$
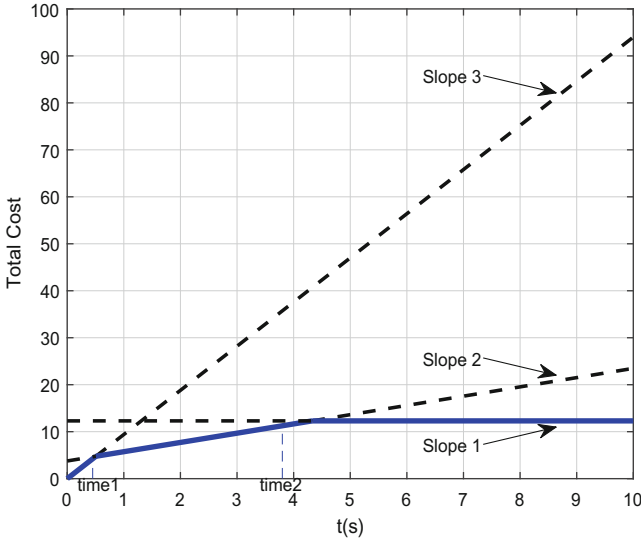

Fig. 1. The total cost of 3-tier heterogeneous cellular network: The thick line indicates the optimal cost as a function of the networks duration time.

bits and $\tau = 10^5$. Moreover, the maximum number of UE connections of the MBS is $M = 50$, and we use $q = 0.88$. If there are no special instructions, we often choose $c = 1.52$ as a suitable optimal ratio value. The statistical results are averaged over a large number of independent simulation runs during period T. We compare our multislope ON/OFF scheduling algorithm MTOA to the approach that schedules in a fixed time. We use FT1 (fixed transfer time for UEs, second-level SBS turn OFF in $t = 1$ s, first-level SBS turn OFF in $t = 8$ s) and FT2 (fixed transfer time for UEs, second-level SBS turn OFF in $t = 2$ s, first-level SBS turn OFF in $t = 9$ s) as the two fixed-time approaches. Each level SBS has different maximum ESM capacity. The maximum capacity of the first-level ESM is $\mathcal{E}_{\max}^1 = 500$ J, and the maximum capacity of the second-level ESM is $\mathcal{E}_{\max}^2 = 100$ J.

Figure 1 shows the algorithm strategy for 3-tier HetNets. Slope 1 represents the total cost of the UEs connected to SBS j^2, slope 2 represents the total cost of the UEs connected to SBS j^1, and slope 3 represents the total cost of the UEs connected to the MBS. Initially, the UEs connect to SBS j^2. When $t =$ time1, due to MTOA, SBS j^2 turns OFF, and the UEs connect to SBS j^1. When t reaches time2, due to MTOA, SBS j^1 turns OFF, and the UEs connect to the MBS. When time period T ends, the UEs reconnect to the BS.

Figure 2 shows the total costs for the proposed algorithm and the fixed-time approach for the 6 first-level SBSs, 50 UEs distributed within the MBS area, and various UEs distributed within $\mathcal{I}_{j^2}$. From Fig. 2, we can see that for each algorithm, as the number of second-level SBSs increases, the total cost of MTOA and FT also increase. This is mainly due to the fact that increasing the number
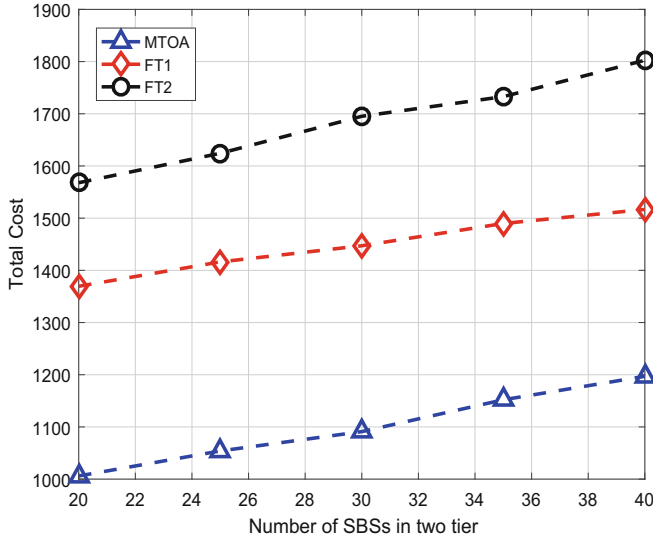

Fig. 2. Total cost of 3-tier heterogeneous cellular network during period T for the proposed and fixed-time approach.

of second-level SBSs increases the overall power consumption of the network. From Fig. 2, we can clearly see that the proposed algorithm significantly reduces the total cost compared to the FT. This performance advantage reaches a 23.5% reduction in the total cost relative to FT1 at 30 second-level SBSs and a 35.6% reduction in the total cost relative to FT2 at 30 second-level SBSs.

5   Conclusion

In this paper, we derive a novel approach to optimize the user association and switch SBSs in HetNets. We have construct a multislope online problem under the uncertainty of renewable energy harvesting and meanwhile considers the QoS when changing the connection state. The simulation results show that the proposed approach can reduce the total energy consumption and ensure the QoS. ON/OFF scheduling can effectively reduce energy consumption and better satisfy the psychological needs of the UEs.

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