Abstract

The fiber-wireless (FiWi) enhanced LTE-A HetNet, which consists of fiber optic networks as its backhaul and LTE-A HetNets as its wireless front-end, is regarded as a promising technique for a 5G radio access network to host large-scale mobile data transmission. In order to reduce the energy consumption of a FiWi enhanced LTE-A HetNet, we should offload the traffic of lightly loaded BSs to other active BSs and turn them into sleep state, while in order to provide stable service to more user equipments (UEs), we should put as many BSs into active state as possible. Obviously, there is a trade-off between minimizing the energy consumption and maximizing the number of UEs associated with the BSs. However, previous research works either focused on energy consumption minimization or placed emphasis on UE connection maximization, and few of them integrate these two parts together and give an optimal solution. Toward this end, this article studies the issues in energy consumption minimization with the UE connection constraint in FiWi enhanced LTE-A HetNets, and propose a heuristic greedy solution to find an optimal list of active BSs and their associated UEs.

Introduction

To cope with the explosion of mobile data traffic in the future fifth generation (5G), heterogeneous networks (HetNets), which adopt a variety of radio access technologies, such as macrocells, WiFi access points (APs), as well as low-cost low-power small cells, to achieve high data rates are expected to be a paradigm shift from traditional cellular networks [1, 2]. However, the development of HetNets faces new challenges, such as cell association, interference coordination, resource partitioning, and backhaul bottleneck, including the delay and reliability of backhaul links, the importance of which has gradually been recognized over the last few years [3]. By leveraging the complementary advantages of high capacity and reliability of passive optical networks (PONs), and the high mobility and ubiquitous connectivity of wireless networks, fiber-wireless (FiWi) networking is believed to be a promising solution to enhancing Long Term Evolution-Advanced (LTE-A) HetNets, which gives rise to so-called FiWi enhanced LTE-A HetNets [4, 5]. In order to provide support for a large number of connected devices in future 5G applications including the Internet of Things (IoT) and others, FiWi enhanced LTE-A HetNets have been regarded as a compelling solution among various technologies due to their high capacity, reliability, flexibility, and extremely low latency characteristics [5].

High energy efficiency is one of the most important design goals in future 5G networks so as to support various battery hungry services from mobile user equipments (UEs) in different 5G applications. To reduce energy consumption and prolong UE battery life in accessing networks, different kinds of energy saving (ES) schemes have been proposed by means of switching some of the devices into sleep state periodically [6, 7]. Specifically, wireless local area networks (WLANs) mostly adopt the power saving mode (PSM) standardized by IEEE 802.11 as their ES scheme, which powers off UEs’ transmitters periodically according to the data traffic situation. For LTE/LTE-A networks, discontinuous reception (DRX) has been introduced as an effective mechanism to save UE battery, where UEs do not need to monitor the downlink channel in real time, and enter sleep state when there is no data addressed to them. Furthermore, to address the energy consumption problem in PONs, optical network unit (ONU) sleep mode has been specified to switch the ONU transceiver to sleep/active state cyclically, since the ONUs are the major energy consuming units in PONs [8].

Up to now, there have been plenty of research activities focusing on reducing the energy consumption of FiWi networks; some of them have placed emphasis on the wireless end to design device ES schemes, some of them focused on the optical backhaul to design efficient ES mechanisms, and some presented new energy efficiency improving schemes by cooperation between the ES mechanisms of both the optical and wireless ends. Note that when we perform ES schemes in FiWi networks, some quality of service (QoS) requirements should also be satisfied, for example, UE connection (i.e., the number of UEs associated with base stations (BSs)) and delay. Recently some research works have been pre-
sented on reducing energy consumption of FiWi networks while taking packet delay into account. To find the best trade-off between power saving and latency in the DRX mechanism of LTE-A networks, Koc et al. [9] proposed an analytical model and presented a trade-off scheme to maintain a balance between these two performance indicators via DRX configuration. Nishi-yama et al. [10] proposed a cooperative ONU sleep scheme that dynamically controls the ONU sleep period according to mobile UEs’ ES mechanisms, and reduced latency and energy consumption were reported there. To reduce the overall energy consumption in PON LTE-A converged networks supporting machine-to-machine (M2M) communications, Van et al. [11] analyzed the energy consumption and end-to-end delay in M2M scenarios via an M/G/1 queuing model (optical backhaul) and a semi-Markov process (LTE-A front end), and proposed an ES scheme by incorporating the ONU sleep mode with the DRX mechanism. Zhou et al. [12] studied the energy-efficient context-aware resource allocation problem in ultra-dense small cells, and proposed an energy-efficient matching algorithm based on the Gale-Shapley algorithm.

Moreover, there are also some research activities focusing on improving UE connection in HetNets. To achieve load balancing among multi-tier LTE-A HetNets and improve UE connection, Liu et al. [13] proposed a load balancing algorithm by adopting device-to-device (D2D) communications to offload the associated UEs of congested BSs to adjacent uncongested BSs. Xu et al. [14] proposed a novel D2D local area network architecture by introducing device freedom to improve network capacity as well as energy efficiency.

Obviously, there is a trade-off between energy consumption minimization and UE connection maximization in FiWi enhanced LTE-A HetNets, where UE connection maximization is considered to maximize the number of UEs associated with the BSs in the network. On one hand, to minimize the overall energy consumption, we close the ONUs, BSs, and UEs as long as possible, and thus few UEs can access the Internet. On the other hand, to maximize the UE connection, we turn on all equipment as long as possible, which results in very high energy consumption. Note that previous works mostly focused on reducing energy consumption in FiWi networks or improving UE connection in LTE-A HetNets. Little work can be found on minimizing the energy consumption of FiWi enhanced LTE-A HetNets, especially with the UE connection constraint being considered, where the UE connection constraint denotes the predefined ratio of the UEs that associate with the BSs vs. all the UEs in the network. Toward this end, we provide this article to discuss the challenging issues in minimizing energy consumption with the UE connection constraint in FiWi enhanced LTE-A HetNets. Two algorithms are presented as our solutions: a brute force algorithm, which adopts an enumeration strategy to find an optimal solution for an active BS list and their associated UEs, and a heuristic greedy algorithm, which attaches the UEs to each BS greedily in the order of WiFi APs, pico evolved NodeBs (eNBs), and macro eNBs.

The remainder of this article is organized as follows. An overview of FiWi enhanced LTE-A HetNets and some traditional ES schemes are illustrated. We define the problem of energy consumption minimization with the UE connection constraint, and present two solutions, a brute force algorithm and a heuristic greedy algorithm. Some numerical results are given to validate our algorithms, and we conclude the whole article.

**OVERVIEW OF FiWi ENHANCED LTE-A HETNETS AND ENERGY SAVING SCHEMES**

In this section, we present an architecture of FiWi enhanced LTE-A HetNets and review some classical ES schemes utilized in PONs, WLANs, and LTE-A networks: ONU sleep mode, PSM, and DRX.

**FiWi Enhanced LTE-A HetNets**

As depicted in Fig. 1, a FiWi enhanced LTE-A HetNet comprises two parts, the optical backhaul and the wireless front-end. In this article, we utilize cost-effective Ethernet PON (EPON), which has been widely deployed in lots of countries and areas for fiber optic access networks as the backhaul of the converged network. EPON can cover a range from 20 to 100 km and adopts a tree-based topology, where the optical line terminal (OLT) located at the central office (CO) forms the root, and a number of ONUs connected to the OLT via a 1:N splitter form the leaf nodes. In a FiWi enhanced LTE-A HetNet, an ONU can host an eNB or a WiFi AP to provide 4G LTE-A services or wireless access to UEs. WiFi APs and eNBs are distributed randomly with overlapping coverage in the wireless front-end. Nevertheless, it is noted that when a UE visits the network at any time, it can only utilize either an LTE-A network or a WiFi network.

**Energy Saving Schemes**

**ONU Sleep Mode in PONs:** In ONU sleep mode, depending on whether the ONU has any data to transfer (send/receive), it switches to active state or sleep state periodically. During
active state, the ONU can receive and transmit data immediately, but consumes more energy. While in sleep state, it consumes little energy, but cannot send or receive data, and thus if there is incoming data from the OLT at this time, packet delay is unavoidable.

Figure 2 presents an example of the process of ONU sleep mode in PONs. When there is no incoming data at the OLT, it sends a sleep request (SR) message to the ONU, and then the ONU returns an acknowledge (ACK) message and enters sleep state for a sleep interval. During the sleep interval, no matter whether there is incoming data at the OLT, the ONU will not wake up unless the sleep period ends. After that, the ONU enters the active state and wakes up to check whether there is incoming data for it. If there is no arriving data, the OLT will send an SR message to the ONU with the predefined sleep interval, and the ONU switches to sleep state again. Otherwise, the OLT sends an SR message to the ONU with a sleep period of 0 ms, and then the data frames are transmitted to the ONU immediately. After that, the OLT resends an SR message to the ONU with the predefined sleep interval, and the ONU switches to the sleep state. From the analysis above, we can see that the additional packet delay caused by ONU sleep mode only appears when there is incoming data at the OLT and the ONU is in sleep state, where the data has to be buffered until the sleep period ends.

Power Saving Mode in WLANs: A UE in PSM has two states: active state, where the UE can send and receive data but consumes more energy, and sleep state, where the UE cannot receive/transmit any data but has lower energy consumption. A UE switches between these two states to reduce energy consumption in WLANs depending on whether there is any data to transfer.

Specifically, in the beginning of every beacon interval of PSM, the WiFi AP sends a beacon frame to the UE with a traffic indicator map (TIM). If the TIM indicates that there is no data to transmit/receive, the UE enters sleep state until the beacon interval ends. Otherwise, the UE sends back a power save poll frame to request data from the AP, and then the AP transmits the buffered data to it. After that, the UE switches to sleep state until next beacon interval. It is noted that, during the whole process, if the data arrives at the AP when the UE is in sleep state, the incoming data has to first be buffered at the AP until the current beacon interval ends, and additional packet delay unavoidably occurs.

Discontinuous Reception in LTE-A Networks: A DRX mechanism configured by radio resource control (RRC) in LTE-A networks has two modes, RRC_CONNECTED and RRC_IDLE. In particular, if there is no data to transfer for a long period, the UE adopts the RRC_IDLE mode. Otherwise, it stays in the RRC_CONNECTED mode, where the UE is still hosted by an eNB during its sleep state.

Figure 3 illustrates a process of the DRX mechanism in LTE-A networks. Note that only a long DRX cycle is considered here since it represents most traffic scenarios. Generally, a UE using a DRX mechanism has four states: active state, listen state, sleep state, and sleep-to-active (S2A) state. The UE can send and receive data during the active state, which lasts for a predefined period. When the active state ends, if previous data transmission has not finished, the UE reenters the active state. Otherwise, it switches to the listen state to monitor the incoming data traffic. During the listen period, if there is any incoming data, the UE enters the active state immediately to perform data transmission. Otherwise, it goes to the sleep state to save energy after a configured period. Then the UE wakes up and proceeds to the S2A state, during which network synchronization is performed. After that the UE enters the active state and proceeds to another cycle. Depending on whether or not there is any incoming data, the UE switches to active or listen state accordingly.

ENERGY CONSUMPTION MINIMIZATION IN FIWi ENHANCED LTE-A HETNETS WITH THE UE CONNECTION CONSTRAINT

ENERGY CONSUMPTION MINIMIZATION WITH THE UE CONNECTION CONSTRAINT

The overall energy consumption in FiWi enhanced LTE-A HetNets mainly contains the energy consumed by ONUs in the optical backhaul, and the energy consumed by BSs and UEs in the wireless front-end. The ES schemes discussed can be adopted to reduce the energy consumption of ONUs and UEs. However, it is noted that among the equipment in the wireless front-end, BSs consume most of the energy [15]. Therefore, we present some analysis on energy consumption minimization in LTE-A HetNets in this section, where minimizing the energy consumption of BSs is our main focus. For LTE-A HetNets, due to a common assumption, the energy consumption of macro BSs and APs during downlink transmission includes the consumed transmit power and the non-transmit power consumption (the energy consumed in signal processing, equipment cooling, battery backup, etc.).
which is independent of data transmission. In this article, we only focus on the transmit powers related to data transmission, and non-transmit powers are outside the scope of this research.

Without loss of generality, we adopt a three-tier LTE-A HetNet as the wireless front-end of a FiWi enhanced LTE-A HetNet. In particular, the three-tier LTE-A HetNet consists of several macro eNBs and a number of pico eNBs, WiFi APs, and UEs randomly distributed in the coverage of these macro eNBs. Unless otherwise indicated, we use the general term BS to represent macro eNB, pico eNB, and WiFi AP in this article. Every WiFi AP is assumed to be open access. Moreover, each BS has a certain number of independent orthogonal channels to host a fixed amount of UEs, and the UEs within the BS coverage area can access the Internet by associating with any but one of them. For the case of multi-tier LTE-A HetNets including other types of small cells, the following algorithms can be followed similarly.

Assume that the backhaul of FiWi enhanced LTE-A HetNets is capable of handling the traffic demands in the wireless front-end. In order to reduce the overall energy consumption, we adopt cell load adaption in the wireless front-end, where lightly loaded BSs can be switched into sleep state via offloading their UE traffic to other active BSs. Besides, when we perform energy consumption reduction, a predefined UE connection ratio, which represents the ratio of UEs associated with the BSs vs. all UEs, should also be satisfied. Overall, the goal is to find an optimal solution that minimizes the overall energy consumption while satisfying a predefined UE connection constraint. Specifically, this problem can be defined as follows.

**Energy Consumption Minimization with UE Connection Constraint (ECMCC):** Given initial information, such as the topology of BSs and UEs, including their numbers, locations, channel numbers, and coverage radii, the numbers of OLTs and ONUs in the optical backhaul, the transmit powers of OLTs, ONUs, BSs, and UEs, and the UE connection constraint, find an optimal list of active BSs and their associated UEs that minimize the overall energy consumption in a FiWi enhanced LTE-A HetNet while satisfying a given UE connection constraint.

### Solutions to ECMCC in FiWi Enhanced LTE-A HetNets

In the following, we present two schemes to solve the ECMCC problem in FiWi enhanced LTE-A HetNets. To simplify our algorithm presentation, some notations are predefined as follows. Let $U$, $M$, $P$, and $A$ denote the sets of UEs, macro eNBs, pico eNBs, and WiFi APs, respectively, and $G_U$, $G_M$, $G_P$, and $G_A$ separately denote their logical topology. $S$ is the set of obtained active BSs, and $U_i$ is the set of UEs associated with each active BS $i \in S$.

**A Brute Force Algorithm:** A brute force solution to ECMCC mainly contains three steps. First, we enumerate all possible combinations of active BSs; second, the UE connection ratios of all enumerated combinations are calculated; and finally, we can easily find an optimal combination.

Algorithm 1: A brute force algorithm for ECMCC.

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**Figure 3.** Illustration of the DRX process in LTE-A networks.
For future 5G applications with a large number of connected devices, BFA and HGA provide energy-efficient solutions for network operators to obtain the optimal/near-optimal BS configurations with given UE connection constraints, i.e., a list of active BSs and their associated UEs with the highest overall energy efficiency.

Algorithm 2. A heuristic greedy algorithm for ECMCC.

ECMCC, BFA may have to run for a very long time due to its exponential computational complexity, so that it can only be implemented with small number of BSs in practice. Therefore, BFA is just presented as a baseline for our following heuristic greedy solution.

A Heuristic Greedy Algorithm: It is noted that macro eNBs have the highest power consumption and the largest coverage in LTE-A HetNets so as to conserve as many UEs as possible, while both pico eNBs and WiFi APs have lower power consumption and smaller coverage. In order to minimize the overall energy consumption, we should turn on as few macro eNBs as possible. On the other side, to fulfill the UE connection constraint, more macro eNBs might have to be active. Therefore, in order to minimize the overall energy consumption with a given UE connection constraint, we introduce a variable $V$ to denote the energy consumption/UE connection ratio of each BS, which can be computed via dividing the transmit power of a BS by its maximum associated UE number. After that a heuristic greedy solution to the ECMCC problem is proposed in the following. Note that if there are three kinds of BSs that host the same number of UEs (i.e., the same $V$s), it is better to adopt WiFi APs or pico eNBs due to their lower capital and operational expenditures (CAPEX and OPEX) than macro eNBs. Furthermore, WiFi APs have higher priority over pico eNBs since they transmit data traffic by adopting unlicensed spectrum. The details of our heuristic greedy algorithm (HGA) are shown in Algorithm 2.

Compared to BFA, HGA is a little more complex, but it can achieve better computational complexity (i.e., $O(n^2)$). In particular, the for all loop of steps 2–4 runs $n$ times, and the computational complexity of steps 5–15 is $O(n^2)$, where the outer for all loop runs $n$ times, and the running time of steps 4–12 is $O(n)$. Therefore, the overall computational complexity of HGA can easily be computed by adding them up (i.e., $O(n^2)$). Although HGA can only obtain a near-optimal solution, it is more practical and can solve many scenarios with large numbers of BSs, which cannot be solved by BFA due to its high computational efficiency.

As discussed above, HGA is regarded as a workable solution to the ECMCC problem in the scenario of a FiWi enhanced LTE-A HetNet connecting to one OLT. For a large-scale FiWi enhanced HetNet, which consists of multiple zones connecting to different OLTs in the CO, our schemes can also be adopted. However, considering that the running time of solving the ECMCC problem in a large-scale network will be too long to be implemented, we can first divide the network into small independent zones according to the OLT to which they connect, and then execute HGA to optimize them separately.

Our proposed algorithms are mainly used to reduce the energy consumption of BSs in wireless front-ends. They not only hold for the ONU sleep mode, PSM, and DRX discussed earlier, but can also cooperate with other ES schemes for ONUs in PONs and those for UEs in wireless front-ends. For future 5G applications with a large number of connected devices, BFA and HGA provide energy-efficient solutions for network operators to obtain the optimal/near-optimal BS configurations with given UE connection constraints, that is, a list of active BSs and their associated UEs with the highest overall energy efficiency.

Numerical Results and Discussions

In this section, we present some comparison results in terms of overall energy consumption and running time between HGA and BFA, where BFA is adopted as our baseline.

Experimental Settings

Without loss of generality, we adopt a FiWi enhanced LTE-A HetNet scenario in our experiments, where an EPON with 1 OLT and 64 ONUs is adopted as the optical backhaul, and a three-tier HetNet consisting of 1 macro eNB, 10 pico eNBs, and 10 WiFi APs is adopted as the wireless front-end. The transmit powers of OLT, ONU, macro eNB, pico eNB, and WiFi AP are set as 25 mW, 10 mW, 20 W, 200 mW, and 60 mW, respectively. The covering radii of macro eNB, pico eNB, and WiFi AP are set as 400 m, 100 m, and 50 m, respectively. Moreover, we use an Ubuntu 14 64-bit operating system in an Intel i5 core and 4 GB RAM computer, and a macro BS is assumed to have a frequency resource of 200 orthogonal channels, which means that it can provide services for at most 200 UEs at a time. Similarly, the maximum associated UE numbers of a pico eNB and a WiFi AP are assumed to be 60 and 20, respectively.

Numerical Results

Figure 4a illustrates the comparisons of energy consumption in 100 ms between BFA and HGA with different UE connection constraints, where the UE number is set as 2000. From the figure, one can easily see that HGA can find a near-optimal solution to the ECMCC problem compared to BFA. Moreover, with increasing UE connection constraints, the overall energy consumption increases accordingly, because more BSs have to be in active state to host more UEs.

Figure 4b illustrates the comparisons of running time between HGA and BFA with different UE connection constraints. A smaller running time indicates a faster solution, and a smaller energy consumption indicates a more energy-efficient solution. After a comparison, we can see that HGA consumes a little more running time than BFA, but HGA achieves better energy efficiency.
Figure 4b shows the comparisons of running time between BFA and HGA with different number of BSs, where the UE number and UE connection constraint are set to 500 and 0.4, respectively. From the figure, we can observe that BFA has a much longer runtime than HGA, due to its exponential computational complexity. Furthermore, if the number of BSs continues to increase, the runtime of BFA will be so long that it cannot be adopted. Thus, BFA can only be implemented with a small number of BSs in practice.

Moreover, we further perform an evaluation on the energy consumption of HGA with different combinations of pico eNBs and WiFi APs. As illustrated in Fig. 4c, the UE number is set to 2000, and the total number of WiFi APs and pico eNBs is fixed as 50. It can easily be found that with the increase of WiFi APs, the overall energy consumption decreases, which corroborates the fact that WiFi APs have a greater advantage in power consumption than pico eNBs.

**Discussions**

With a given topology of a FiWi enhanced LTE-A HetNet and the information of both BSs and UEs, the list of active BSs and their associated UEs should be provided as soon as possible, since the UE locations might change over time in practice. Doing so in real time is preferred, but it is challenging since a period of time is needed not only to obtain the topology of the whole network and the information of both BSs and UEs, but also to find an optimal solution to ECMCC. As our first step to study the ECMCC problem in FiWi enhanced LTE-A HetNets, we assume that the locations of both BSs and UEs are fixed. For more complex scenarios with moving UEs, our schemes could also work with slow moving devices by introducing continuous optimization and load-balancing techniques. However, for fast moving devices, the ECMCC problem should be redefined by taking multiple connectivity of UEs to different BSs into account, and new optimal solutions should be explored in future works.

**Conclusion**

To minimize the energy consumption in FiWi enhanced LTE-A HetNets with a given UE connection constraint, we study the issues in energy saving of LTE-A HetNets and define the ECMCC problem in this article. After that we present two solutions, that is, BFA, which adopts an enumeration strategy to find an optimal list of active BSs and their associated UEs, and HGA, which associates the UEs to the BSs greedily according to their energy consumption/UE connection ratios. Numerical results on the comparisons of energy consumption and running time between BFA and HGA are provided to show the promise of our proposed scheme. For future work, it should be meaningful to study the tradeoff between energy consumption minimization and UE connection maximization, and take more QoS requirements into account while designing energy saving schemes for the overall network.

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