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Energy-efficient design of heterogeneous cellular networks from deployment to operation

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ABSTRACT

The ever-increasing traffic demand has motivated mobile operators to explore how they can boost their network capacity with a minimal increase in their capital and operating expenditures. In order to tackle this problem, we investigate the energy-efficient design of heterogeneous cellular network (or simply HetNet), especially with a focus on deployment and operation strategies. We first formulate a general problem pertaining to minimizing the total energy consumption cost while satisfying the requirement of area spectral efficiency (ASE). We decompose this problem into a deployment problem at peak time and an operation problem at off-peak time. Under practical assumptions made from an observation on various topologies including an acquired real base-station deployment dataset, we demonstrate the submodularity of ASE function with respect to micro base-station deployment. Subsequently, we propose a greedy algorithm that is shown to be a constant-factor approximation to the optimal deployment. Although the greedy algorithm can be applied as an offline centralized solution for the operation problem, we further propose two online distributed algorithms with low complexity and signaling overhead using Lagrangian relaxation technique. Extensive simulations show that the proposed algorithms can significantly reduce the energy consumption with minimal deployment of micro base-stations.

1. Introduction

Motivated by the explosive traffic demand from bandwidth-hungry multimedia and Internet-related services in broadband cellular networks, communication network engineers seek to maximally exploit the spectral resources in all available dimensions. Heterogeneous cellular network (HetNet) [1–3] where small cells such as micro, pico and femto are used as a way of additionally increasing capacity and coverage beyond the initial deployment of macro cells, has emerged as a promising solution. Many wireless standards such as 802.16 m/WiMax2, 3GPP-LTE and LTE Advanced are also designed to support the heterogeneous cellular system. Incrementally deploying micro base stations (BSs) is much simpler than building out complex cell towers and macro BSs. Besides, it can also reduce both capital (e.g., hardware) and operating (e.g., electricity, backhaul and site lease) expenditures, which is especially attractive to mobile operators [4].

Meanwhile, *green networks* have recently received significant attention due to the depletion of non-renewable energy resources and a limit on CO_2 emissions. From the perspective of mobile operators, developing more energy-efficient networks is not only a matter of being green and

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responsible, but also an economically important issue. In particular, it is well known that BSs are one of the most energy-hungry segments in the cellular networks, which contributes to about 60–80% of the total energy consumption [5,6]. However, they are often under-utilized such as at nighttime because being deployed by the operator targeting peak traffic usage. Even when a BS is experiencing little or no activity, it consumes the majority of its peak energy. For instance, a typical UMTS BS consumes between 800–1500 W and has a transmission power of 20–40 W for RF output. Therefore, beyond turning off only radio transceivers, dynamic approaches [6,7] that allow the system to entirely switch off some under-utilized BSs and transfer the corresponding load to neighboring cells during low traffic period can substantially reduce the amount of wasted energy in the network.

1.1. Our objective and contributions

Although recent papers have made several steps towards green cellular networks [5–12], most studies have focused only on the network operation aspect. However, this paper considers both deployment and operation aspects in order to unburden the mobile operators from huge capital and operating expenditures (CAPEX and OPEX). To this end, our objective is to provide both theoretical framework and practical solutions for the following two key questions:

- *Deployment:* where and how many micro BSs need to be additionally deployed considering the traffic at peak time?
- *Operation:* how to operate (i.e., load-aware dynamic switching on–off) macro and micro BSs for energy conservation during off-peak times?

First, in the deployment problem, we try to find a minimal deployment of micro BSs while satisfying the requirement of area spectral efficiency (ASE), i.e., minimizing CAPEX. We make an observation from various topologies that there is a monotone relationship between coverage and ASE increment. Under such an assumption, we are able to prove the submodularity of the ASE function with respect to micro BS deployment and allows us to propose a greedy algorithm that can be shown to be a constant-factor approximation of optimal deployment. We also show through simulations that deploying micro BSs is much energy is inherently more energy-efficient than the conventional macro BSs.

Second, in the operation problem, our objective is to minimize energy consumption through dynamic BS operation, i.e., minimizing unnecessary OPEX. Even though the above greedy deployment algorithm can be also applied as a centralized offline solution for this problem, we further propose two distributed online algorithms using Lagrangian relaxation to have more practical solutions. Extensive simulations based on real cellular traffic traces and information regarding BS location that the proposed distributed algorithms not only can achieve the near performance of the centralized algorithm but also can significantly reduce the energy consumption by about 60–80% compared to the conventional static operation (i.e., always-ON strategy).

We would like to mention that this paper is in fact an extended version of our own prior work [1] that focused on the development of algorithms. In this paper, we strengthen our contributions by (i) further presenting technical analysis that make the proposed algorithms applicable to more general cases, (ii) justifying the effectiveness of two-step approach to tackle the original problem, and (iii) providing new theoretical results and proofs.

1.2. Related work

A large body of research in HetNet has focused on resource allocation, e.g., spectrum allocation [13,14], power control [15–17]; however, there has been relatively little work dealing with BS deployment. The studies in [18,19] showed the energy consumption benefit of heterogeneous deployment only by simulations. In homogeneous setting (i.e., only one type of BSs), several BS deployment problems [20,21] have been theoretically investigated. Stamatelos and Ephremides [20] showed that an algorithm minimizing the overlapped coverage (i.e., the co-channel interference area) can maximize spectral efficiency in omni-antenna case. Srinivas and Modiano [21] proposed an algorithm which jointly considers both BS deployment and user assignment in backbone base mobile ad hoc networks for throughput optimization. In [22–24], the authors studied the energy efficiency and its relationship with the transmit powers and densities of macro/micro BSs in two-tier HetNet. In particular, [22,23] used a stochastic geometric based model to derive energy efficiency and area power consumption, respectively. Shin et al. [25] proposed an iterative BS planning algorithm under simplified network models.

Our work differs from the previous works in that: (i) we present an analytical framework for optimal BS deployment in HetNet with the different types of BSs, and (ii) run extensive simulations based on BS topologies and traffic profiles acquired from real cellular networks.

Despite the fact that communication network engineers have been concerned with energy issues for decades, their main focus was to prolong battery life-time of mobile terminals or sensor nodes. Recently, there has been a shift of emphasis to the network-side as well but an amount of literature on green cellular networks is relatively scant compared to the mobile-side. Dynamic BS operation (i.e., switching-on/off BSs depending on the traffic profile) for energy saving has been investigated in [1,5–9]. In [26], the authors considered to dynamically adapt the speed of computing system inside BSs for energy conservation. In addition, the concept of BS sharing, where different operators pool their BSs together to further conserve energy, was introduced in [5,10]. However, most of the previous works [5,6,10] attempted to see how much energy saving can be possibly achieved under the deterministic traffic variation over time rather than developing algorithms that can be implemented in practice.

In several preliminary BS switching algorithms [7,8], the authors do not capture the effect of the signal strength degradation when traffic loads are transferred from the