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Hybrid small cell base station deployment in heterogeneous cellular networks with wireless power transfer

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ABSTRACT

This paper studies a large-scale heterogeneous cellular network (HCN) consisting of ultra-dense small cells and macro cells. Each small cell base station (SBS) serves a dedicated user with a constant distance in a random direction. To reduce electricity consumption without degrading network performance, a hybrid SBS deployment strategy is considered, in which both on-grid and off-grid SBSs are placed in the network for data transmissions. The on-grid SBSs are connected to the electric grid and powered by stable energy, while the off-grid SBSs are powered by harvesting the ambient radio frequency energy broadcasted by the macro base stations (MBSs) and the on-grid SBSs. Using tools from stochastic geometry, the outage probabilities of both cellular network users and dedicated users are analyzed. On this basis, the tradeoff between the energy efficiency and throughput of the HCN is characterized and the optimal ratio of on-grid and off-grid SBSs is also analyzed. These results can provide useful insights and guidelines for the practical design of the next generation energy harvesting-based HCNs.

1. Introduction

With the exponential growth of mobile data traffic, cellular network designers are faced with the challenge of supporting high capacity and providing good quality of service. Heterogeneous cellular networks (HCNs), consisting of macro cells and ultra-dense small cells, are considered as one of the key technologies in the fifth generation (5G) wireless cellular networks to overcome these challenges. Small cell base stations (SBSs) cover much smaller area and need lower transmit power compared to the macro cell base stations (MBSs). In the dense deployment of SBSs (the density of SBSs can be 10–100 times that of MBSs), the distance between a base station (BS) and its users is greatly reduced. Some of the MBSs can be turned off when they have no traffic load [28], which is the case most of the time, to save energy consumption. Moreover, the low transmit power of SBSs also means energy harvesting techniques can be adopted, which further reduces the power consumption of the HCN from the electric grid [6].

However, the ultra-dense deployment of purely on-grid (powered by electric grid) SBSs may not be feasible because of the complexity of network topology and the variety of site locations. As SBSs are densely deployed, some of them may find it hard to access the power grid. In addition, the aggregate power consumption of the HCN will be high due to the

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large number of SBSs in spite of the low power consumption of a single SBS [1]. Therefore, some researchers proposed to introduce radio frequency (RF) energy harvesting to power the SBSs [7]. However, using only off-grid (powered by RF energy harvesting) SBSs is also infeasible as the RF energy harvested from a limited number of sources such as MBSs, and TV transmission and relay towers is inadequate to power the SBSs, resulting in degraded user experience. Therefore, to achieve a balance between energy efficiency and service quality, the dense SBSs should consist of both on-grid SBSs and off-grid SBSs, and the ratio of them should be chosen properly to maximize the energy efficiency of the HCNs [18].

1.1. Related work

Recently, energy harvesting has attracted widespread attention due to rapidly growing energy demands and increasing energy prices [3]. Energy harvesting enables the wireless nodes to collect energy from ambient renewable energy sources (e.g., wind power and solar) to reduce the need for manual battery replacement/recharging, thus cutting down the energy bills and lowering carbon dioxide emissions [17]. Yu et al. in [28] develop a tractable model to analyze the performance of HCNs with energy harvesting (solar, wind) powered small cells. However, for some devices located in harsh environments that are difficult to access, such as military nodes or large-scale wireless sensor nodes, the recharging of the batteries remains difficult, especially when the number of nodes is huge and the nodes are distributed across a wide area [22]. RF energy harvesting has been proposed as a (partial) solution to these problems. For off-grid SBSs, the controllability of RF energy harvesting is much better comparing with energy harvesting from renewable energy sources. The reason is that the traffic pattern and the locations of the SBSs are relatively static over time in a certain region [7].

RF energy harvesting has become a promising solution for generating a small amount of electrical power to replenish the power supply in low transmission power small cell networks (SCNs), wireless sensor networks [2,13,20,30], and wireless body networks [5,25]. A power conversion circuit embedded into the RF harvester of each node can transform the received electromagnetic waves into direct-current (DC) power. Then the devices or the off-grid SBSs can use the energy harvested from RF signals to supplement their batteries. In [15,27], Lee et al. assume that a secondary transmitter can harvest RF energy from its nearest primary transmitter, while the secondary transmitter can transmit when it is far enough from the primary users and collect sufficient energy. In [19], a simultaneous wireless information and power transfer (SWIPT) receiver was deployed in a cooperative network, and the received RF signal was split into two parts, which are used for information transmission and energy harvesting, respectively. However, the energy from the signals of the other transmitters in the network was not considered for harvesting, and network deployment strategy was not analyzed.

Recently, Dhillon et al. in [6] investigated a novel model for multi-tier HCN, in which each BS is powered independently by a self-contained energy harvester. They analyzed the uncertainty of BS availability caused by limited battery capacity and inherent stochasticity of energy harvesting using tools from stochastic geometry [24]. In [11], the network capacity of a large-scale mobile wireless sensor network powered by RF energy is analyzed, and the capacity is maximized by optimizing the transmission power under outage probability constraint. A novel hybrid network, containing both cellular network and randomly located power beacons, is investigated and the deployment of the cellular network under outage probability constraint is characterized [12]. However, most of the existing studies did not consider the effect of energy harvested from multiply transmitters in the network. In a practical network, it is beneficial for a node to harvest energy from all active transmitters as more energy can be accumulated. A fundamental problem is to characterize the performance of large-scale wireless networks with the assumption that a node can harvest energy from multiple sources.

In this paper, we study a two-tier large-scale HCN shown in Fig. 1, which is composed of a tier of MBSs and a hybrid tier of on-grid and off-grid SBSs. The network users (NUs) are randomly distributed in the coverage area. Each SBS has a dedicated user (DU) which is located at a fixed distance from it but in a random direction [28]. To reduce the demand for energy supply from the electric grid, a hybrid small cell base stations deployment (H-SBSD) strategy is considered, in which the on-grid SBSs are connected to the power grid while the off-grid SBSs collect the RF energy broadcasted by the MBSs and on-grid SBSs. The off-grid SBSs become active only when the harvested energy is sufficient for transmission, which is different from [28]. On the user side, two types of users are considered: 1) the DUs associated with active SBSs, 2) the remaining DUs and NUs that require communications. The outage probabilities of each type of user are derived. The network throughput and the energy efficiency are characterized considering the density of the SBSs, the cell association biases and the ratio of on/off-grid SBSs. The results give valuable insights on the influence of various network parameters and useful guidelines for practical system design.

1.2. Contributions of the present work

The main contributions of the paper are summarized as follows:

- We propose a novel hybrid SBS deployment (H-SBSD) strategy, composed of a tier of MBSs, and a hybrid tier type of on-grid SBSs and off-grid SBSs. The on-grid SBSs are connected to the power grid, while the off-grid SBSs are powered by energy harvesting and collect ambient RF energy broadcasted by the MBSs and the on-grid SBSs. We find the optimal on/off-grid ratio that maximizes energy efficiency, which is different from [28], where BS deployment was not considered;
- In a practical scenario, the energy collected by an energy harvesting based SBS is dependent on the aggregated RF energy from all active energy sources. We consider the effects of randomly distributed network nodes and the concurrent