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Power management in heterogeneous networks with energy harvesting base stations

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ABSTRACT

In this paper, heterogeneous cellular networks (HCNs) with base stations (BSs) powered from both renewable energy sources and the grid power are considered. Based on a techno-economic analysis, we demonstrate that by controlling both transmit power and stored energy usage of BSs, energy costs can be effectively reduced. Specifically, we propose a two-stage BS operation scheme where an optimization and control subproblem is solved at each stage, respectively. For the first subproblem, transmit power of BSs is adjusted while quality of service (QoS) experienced by users is preserved. In the second subproblem, we consider the strategic scheduling of renewable energy used to power the BSs. That is, harvested energy may be reserved in the battery for future use to minimize the cost of on-grid power that varies in real-time. We propose: (1) an optimization approach built on a lattice model with a method to process outage rate constraint, and (2) a control algorithm based on nonlinear model predictive control (NMPC) theory to solve the two subproblems, respectively. Simulation results include a collection of case studies that demonstrate as to how operators may manage energy harvesting BSs to reduce their electricity costs.

1. Introduction

A heterogeneous cellular network (HCN) [1] is defined as a mixture of macrocells and small cells including microcells, picocells and femtocells. In cellular networks, approximately 60–80 percent of power of a cellular network is consumed by base stations (BSs) [2]. With increasing numbers of BSs, reducing power consumption of BSs is critical in our quest for a green cellular network. Hence, most efforts to save energy in cellular networks focus on BSs. Energy harvesting [3] refers to the aggregation of renewable energy (e.g., solar and wind) from the operational environment. Therefore, utilizing harvested energy to supplement conventional on-grid power in powering base stations can serve as a candidate solution for power savings. However, how to best operate BSs with energy harvesting is not trivial due to limited availability of harvested energy, as well as uncertainty about timing and quantity of energy collected. This paper provides some key insight on managing BSs powered by both renewable energy and grid power.

1.1. Related work

As one of most effective approaches for energy savings in HCNs, energy harvesting BSs have been extensively studied recently [4–9]. Ericsson [4] has developed a wind-powered tower for cellular network BSs. Nokia Siemens Networks [5] has also developed a green BS which relies on a combination of solar and wind power to avoid using any grid electricity. Authors in [6] study structure, design, and control system of 3 KW wind and solar hybrid power systems for 3G BS. [7] proposes a feasible configuration of

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a stand-alone PV/Wind Hybrid Energy system with diesel generator as a backup for cellular mobile telephony BS site in isolated areas of central India. [8,9] describe a wind turbine generator system for supplying power to a small-scale BS on an island. It is expected that new energy harvesting systems will be integrated into mobile telephony BSs in near future, providing opportunities to reduce energy costs for operators.

There have been many efforts related to resource allocation in energy harvesting networks [10–14]. Authors in [10] consider delay minimization for interference networks with renewable energy source, where the transmission power of a node comes from both the conventional AC power and the renewable energy source. [11] considers energy allocation problem for point-to-point wireless communications with energy harvesters to maximize the throughput. [12,13] maximize the short-term throughput of an energy harvesting node under a deadline constraint. In [14] an online algorithm jointly manages the energy and makes power allocation decisions for packet transmissions to achieve close-to-optimal utility performance in energy-harvesting networks with finite capacity energy storage devices.

Besides, intelligently operating energy harvesting BSs in HCNs related to power saving has also received considerable interest [15–24]. A new tractable model for K-tier HCNs is developed in [15], where each BS is powered solely by a self-contained energy harvesting module. [16] proposes a hand over parameter tuning algorithm and a power control algorithm to guide mobile users to access BSs with green energy supply, thus reducing grid electricity expense and CO_2 emission. [17] deals with several aspects including lower power consumption that must be considered when a radio BS site is driven from a solar power source. Results in [15–17] are only valid for systems with a single energy source and not applicable to cellular networks employing hybrid energy BSs. However, as discussed in [18], a BS powered solely by an energy harvester may not be able to maintain stable operation and guarantee quality of service (QoS). Therefore, a hybrid energy harvesting system design is preferable in practice for providing uninterrupted service.

There have been some recent efforts that consider BSs with mixed power supply from both renewable energy sources and power grid. The reliable grid power guarantees that the service requirement is satisfied, while effective renewable energy allocation policy reduces grid power consumption. Authors in [19] propose a two-stage dynamic programming (DP) algorithm to optimize on-grid power consumption over BSs' on–off states and allocation of BS's resource blocks. [20] optimizes energy utilization in such networks by maximizing utilization of green energy, and thus saving on-grid energy. An energy aware cell size adaptation algorithm named ICE is proposed in [21,22], which balances the energy consumption among BSs, and enables more users to be served with green energy. Authors in [23] study resource allocation algorithm design for energy-efficient communication in an orthogonal frequency division multiple access (OFDMA) downlink network with hybrid energy harvesting BS. A power optimization problem with average delay constraint on the downlink of a Green Base station is considered in [24]. This Green BS is powered by both renewable energy as well as conventional sources like diesel generators or the power grid. The authors try to minimize energy drawn from conventional energy sources and utilize harvested energy to the maximum extent. The optimal action consists of scheduling the users and allocating the optimal transmission rate for the chosen user.

Alternately, cost reduction for energy harvesting cellular networks has also been investigated [25,26]. [25] poses a novel cellular network planning problem to reduce capital and operational expenditure (CAPEX and OPEX, respectively), considering the use of renewable energy sources. A fundamentally new concept of energy balancing, and a novel algorithm to accomplish it is proposed. Authors in [26] present a novel optimization framework enabling cellular network planning to reduce deployment cost that takes into consideration two state-of-the-art technologies: (i) Dynamic Spectrum Access, and (ii) energy harvesting.

In summary, prior efforts on energy harvesting cellular network while extensive, either focus on technical issues or economic issues. It is not only prudent but in fact critical to take a techno-economic perspective of energy harvesting BS management. For example, how should an operator minimize on-grid power expenditure by management of BSs while considering varying real-time electricity price? To the best of our knowledge, this is an open question that requires a more holistic view of both technical and economic aspects of HCNs.

1.2. Contributions

In this work, we aim to minimize on-grid power cost of HCNs with energy harvesting BSs by managing both transmit power and stored energy. Taking QoS into account, a lattice model is considered to obtain coverage probability in region of interest (ROI). We formulate an optimization problem to find optimal transmit power and stored energy under a coverage probability constraint. Then, we propose a two-stage BS operation scheme which first optimizes transmit power and then manages stored energy usage.

Unique aspects of our work can be summarized as follows:

- With the introduction of a lattice model, we provide a structured method to obtain coverage probability of HCNs with an irregular deployment of BSs in ROI.
- We conduct a techno-economic analysis of on-grid power consumption in HCNs with hybrid energy supply.
- Including a coverage probability constraint, we provide an approach to minimize energy consumption of a HCN with hybrid energy supply via controlling transmit power of each BS.
- A novel treatment of stored energy management problem is proposed in the context of nonlinear model predictive control (NMPC) theory.

This paper includes several distinct sections. Section 2 presents the system model. Section 3 first describes the problem formulation, then decomposes the problem into 2 subproblems. Transmit power optimization is discussed