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Optimization design and economic analysis of energy management strategy based on photovoltaic/energy storage for heterogeneous cellular networks using the HOMER model

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ABSTRACT

The present study aims to address the sustainability of power resources and environmental conditions for heterogeneous cellular networks. To this end, this study examined an autonomous solar power system to supply heterogeneous cellular networks with their required energy sources. Optimal criteria, system architecture, energy production, and cost analysis are discussed based on the characteristics of solar radiation exposure in South Korea. However, the analysis can be generalized to other cases with a slight difference in daily peak solar hours per case. Additionally, this study compares the feasibility of using an autonomous solar power system to feed heterogeneous cellular networks versus a conventional energy source—i.e., the public electric grid. This study shows that the deployment of the solar power system can satisfactorily meet the energy needs of the base stations (BSs) in heterogeneous cellular networks cost effectively, efficiently, sustainably, and reliably and can improve planning by providing cleaner energy.

1. Introduction

A heterogeneous cellular network (HCN) is a layered structure network that consists of various types of base stations (macro, micro, and pico) with different transmission powers and coverage areas (Fig. 1). The HCN architecture is characterized by high-density deployment of low-power small BSs (micro and pico) within a large macro cell. The deployed small BSs are closer to end users; thus, they require less transmission power for advantageous path loss conditions. These small BSs meet the needs of mobile subscribers for a high data rate with prolonged mobile battery life (Alsharif et al., 2013). However, sometimes, the different BSs are located on the same tower, which is called a centralized HCN.

All BS types in an HCN are powered by the electric grid, and the BSs are considered as the primary source of energy consumption in an HCN (Hasan et al., 2011). Accordingly, improving the electrical energy consumption in an HCN is an economically important issue for Korean cellular network operators because a significant portion of the operational expenditure (OPEX) comprises electricity costs. Additionally, energy efficiency in an HCN is a growing concern for cellular network operators, not only to maintain profitability but also to reduce overall environment effects. A consensus has emerged that the cellular network sector is one of the main contributors to greenhouse gas emissions (Suarez et al., 2012). Accordingly, improving the energy efficiency of wireless networks has become a compelling challenge for researchers, vendors, and mobile operators. Thus, the main goal of this study is energy cost minimization, OPEX minimization, and elimination of greenhouse gasses to promote a green HCN while guaranteeing service and coverage for users and ensuring the evolution capability of the BSs in an HCN.

One of the popular techniques for improving the energy efficiency of an HCN is to design and optimize the power-saving communication protocols that adjust the transmission power of the transceivers according to the HCN data traffic intensity. Radio access networks are dimensioned for peak hour data traffic; therefore, the utilization of the BSs can be very inefficient during off-peak hours. The most intuitive idea is to switch off the BSs when the data traffic load is below a certain threshold for a certain time period (Wu et al., 2015). When some BSs are switched off, radio coverage and service provisioning are covered by the devices that remain active (Alsharif et al., 2013). The BS switching problem can be formulated as an optimization problem that minimizes the number of active BSs while meeting the data traffic load in the access network. In (Di Piazza et al., 2011), the authors developed a capacity extension policy for a two-tier HCN and determined which type of BSs should be added or switched off to

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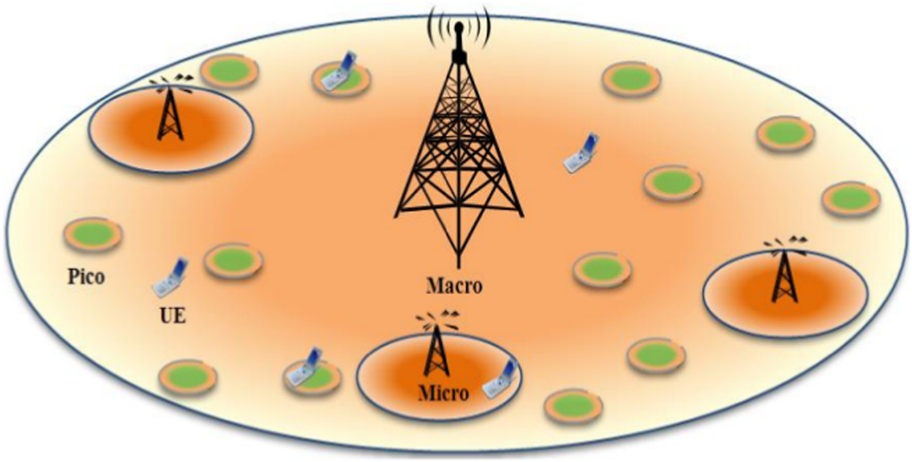

Fig. 1. Heterogeneous cellular network topology.

achieve the optimal BS density. In (Bhaumik et al., 2010), the authors proposed a multi-layer cellular architecture that adjusts cell sizes between two fixed values according to the data traffic demand. In (Samdanis et al., 2010), the authors examined the energy efficiency of HCN with joint macro and pico coverage. In (Liu et al., 2011), the authors proposed an energy-saving strategy for HCN with overlapping pico BSs, which uses the remaining resources of neighboring picocells and macrocell to accept the users of picocell to be switched off. (Oh et al., 2011) discussed the dynamic operation of cellular base stations. They showed that during periods of low data traffic, some redundant BSs can be switched off to provide significant energy savings. (Zhou et al., 2009) proposed a centralized greedy algorithm and a decentralized algorithm to solve the problem and illustrated the relationship between the energy saving and the outage probabilities. (Oh and Krishnamachari, 2010) proposed the threshold-based method to switch the BSs on/off and showed that the energy saving ratio is related to the data traffic characteristics and the number of neighboring BSs.

These methods are effective when an HCN experiences low data traffic demand. However, when the data traffic demand is intense, few BSs can be switched off; therefore, these "sleep mode"-based algorithms may not be effective. This study focuses on the energy issue in HCNs during high data traffic demand, which is usually during daytime (Oh et al., 2013). The key characteristics of a power source, such as economic, environmental, and sustainable, can be met by utilizing technological advances in solar energy. Numerous drivers and motivators of the deployment of solar energy technologies and the transition toward green energy are identified. Solar energy is free, clean, and abundant in most locations throughout the year. Solar energy is free, clean, and abundant in most locations throughout the year. Solar energy generation depends on many factors, such as solar radiation, sunlight intensity, and the geolocation of the solar panel. In this study, South Korea is considered as a case study; it is located at a latitude between 34°N and 38°N and has excellent potential to use solar energy, where the average daily solar radiation ranges from 2.474 kWh/m^2 in December to 5.622 kWh/m^2 in May (NASA Web Site, 2013). However, the analysis can be generalized to other cases with a slight difference in daily peak solar hours and solar radiation per case. The key contributions of this study are summarized as follows:

(i) To determine the optimal size and technical criteria of an autonomous solar system that ensures 100% energy autonomy and long-term energy balance for BSs in an HCN under various cases of daily solar radiation exposure in South Korea;

(ii) To analyze and evaluate the feasibility of using an autonomous solar system in an HCN in terms of the energy and economic yields to ensure both sustainability and cost effectiveness; and

(iii) To analyze and compare the implications of a choice between an autonomous solar power system and conventional sources in terms of OPEX savings.

The analysis of solar power systems can be challenging because of the large number of design options and uncertainty of key parameters. Moreover, solar radiation adds further complexity because it may be intermittent, seasonal, and uncertain. The Hybrid Optimization Model for Electric Renewables (HOMER) was designed to overcome these challenges (Lambert et al., 2006). HOMER models the operation of a system by generating energy balance calculations for each of the 8760 h in a year. For every hour, HOMER compares the electric demand in one hour to the energy that the system can supply in that hour, calculates the energy flows to and from each component of the system, and determines whether to charge or discharge the batteries. The model then decides whether or not a configuration is feasible, i.e., whether it can meet the electric demand under the specified conditions, and estimates the cost of installing and operating the system throughout the lifetime of the project. Therefore, HOMER is utilized in this present study to perform a techno-economic feasibility analysis of the solar-powered HCN.

The rest of this paper is organized as follows. Section 2 describes the system architecture for an autonomous solar power system to supply HCN BSs. Section 3 presents the mathematical model based on net present cost (NPC). Section 4 introduces the layout of a solar power system and the simulation modeling tools that are used in this study. Section 5 presents methodology of HOMER simulation. Section 6 presents the HOMER simulation configuration. Section 7 provides the optimization results. Finally, Section 8 concludes this paper.

2. System model

The architecture of a system, as illustrated in Fig. 2, combines two subsystems: (i) the solar power system architecture and (ii) the cellular BS architecture, which is discussed in detail in the following subsections.

The BS is typically a DC load (Imran et al., 2011); thus, the PV array directly feeds the required energy to the BS and stores the excess electricity in the battery bank. In case of malfunction of the PV array, which may result in its inability to provide the energy