Computer Networks 78 (2015) 107–118

Contents lists available at ScienceDirect

Computer Networks

journal homepage: www.elsevier.com/locate/comnet

# Optimal power management under delay constraint in cellular networks with hybrid energy sources

J. Peng, P. Hong, K. Xue *

*Information Network Lab, Department of Electronic Engineering and Information Science, University of Science and Technology of China, Hefei 230027, China*

ARTICLE INFO

*Article history:*
Received 25 February 2014
Received in revised form 27 August 2014
Accepted 22 September 2014
Available online 28 November 2014

*Keywords:*
Hybrid energy sources
Battery management
Power allocation
Worst delay constraint
Cellular networks
Lyapunov optimization

ABSTRACT

In cellular networks, energy provision contributes up a significant fraction of the total operational cost. To address this problem, service providers have started considering the deployment of renewable energy sources. Due to the variability of renewable energy source, conventional grid energy sources is still required to provide steady service for users. In this paper, Base Stations (BSs) equipped with hybrid energy sources and limited energy storages are considered. We investigate a joint power allocation and battery management scheme to cut down electricity cost under electricity markets, which is ignored by previous studies. Considering the random data arrival, link quality, renewable energy and electricity price, a stochastic program which minimizes the time-average expected electricity cost while stabilizing the network is formulated. Based on the Lyapunov optimization technique, we design an online algorithm to approximately obtain the optimal solution. Especially, our algorithm can guarantee the worst delay through introducing virtual queues. Furthermore, theoretical analysis shows that our algorithm offers an explicit tradeoff between cost saving and delay performance. Numerical simulation results demonstrate the effectiveness of our algorithm.



## 1. Introduction

The upsurge in mobile data traffic as a result of explosive growth in data demand and the popularity of smart phones, has presented cellular network operators with several challenges. One of the challenges is economic challenge caused by the energy consumption increase, which presents operators with high operational expenditures (OPEX) through increased electricity bills. It is estimated that energy consumption rises at 15–20% per year and double every five years in the field of Information and Communication Technology (ICT). The direct result is a collective cellular network OPEX of $22 billion in 2013 [1]. Thus, reining back the spiraling OPEX is crucial to the continuing success of operators.

One natural solution to cut down OPEX is to improve energy-efficiency in all components of cellular networks, especially Base Stations (BSs) which consume a significant portion of energy, reported to amount to about 60–80% [2]. Power allocation is one traditional way to achieve huge green gain by reducing the transmission power intelligently while maintaining the system performance [3–5]. The authors of [3] try to minimize a weighted sum of the expenditure power and the average delay. Hasan et al. [4] maximizes the energy efficiency for downlink orthogonal frequency division multiple access networks through power allocation. Meshkati et al. [5] studies the Quality of Service (QoS) constrained power and rate control in multiple-access networks using a game theoretic framework. In recent years, the deployment of renewable energy

* Corresponding author.
*E-mail addresses:* pjinlin@mail.ustc.edu.cn (J. Peng), plhong@ustc.edu.cn (P. Hong), kpxue@ustc.edu.cn (K. Xue).

http://dx.doi.org/10.1016/j.comnet.2014.09.016
1389-1286/

sources, such as solar panels and wind turbines, has started being considered as another effective solution [6,7]. Due to the variability of renewable energy sources, conventional energy sources such as power grid is still required to guarantee User Equipments' (UEs') QoS. What's more, energy storages such as battery can be introduced to avoid energy waste when the energy harvested is more than the energy needed. Therefore, BSs equipped with hybrid energy sources (conventional grid and renewable energy sources) and finite energy storages will be common in the near future and have gotten a lot of researchers' attention [8–13]. In this trend, Zheng et al. investigate the OPEX saving problem from the perspective of network planning framework in [8]. Chia et al. [9] and Han and Ansari [10] minimize average grid energy consumption via battery management and BS cell size adaptation, respectively. Gong et al. [11] minimizes average grid energy consumption while satisfying UEs' outage probability requirement through resource allocation. Gong et al. propose a multi-stage water filling policy to achieve the optimal power allocation of a single-link wireless communication in [12]. Xu and Zhang [13] studies the throughput-optimal transmission policies for energy harvesting wireless transmitters with the non-ideal circuit power.

Obviously, all the above works [3–5,8–13] have not considered the influence of electricity markets. A grid operator may charge different prices for conventional grid energy at different times of a day, especially when the smart grid is applied. One typical example is the widely used peak-valley electricity price. The data set obtained from the publicly available government sources [14] also shows that electricity price may change every several minutes unpredictably. If the real-time electricity market is considered, the traditional minimization of electricity consumption may not be equivalent to that of the electricity cost. Based on the above analysis, Guo and Fang [15] and Guo et al. [16] adopt energy storages to overcome the variability of real-time electricity price under electricity markets and minimize the average electricity cost at data centers and in the smart grid, respectively.

Motivated by Guo and Fang [15] and Guo et al. [16], in this paper, we discuss the problem of minimizing the electricity cost of BSs, equipped with hybrid energy sources and finite battery energy storages, under electricity markets. Different from [15,16] which just consider energy supplement control through battery management, we additionally control the energy requirement through power allocation in cellular networks. On the one hand, we can allocate less power and delay some data to be transmitted when the electricity price is low or the available harvested energy is much enough. On the other hand, due to the time-varying link quality, we can reduce the power consumption through delaying data to be transmitted when link quality is good enough. Therefore, with joint battery management and power allocation, we can further achieve OPEX saving gain by sacrificing delay performance. However, it is challenging to stabilize the system and ensure the delay performance, especially when we consider the variability and unpredictability of renewable energy, electricity price, business data and link quality. Facing such random processes with possibly unknown statistics, we formulate the problem as a stochastic program. Based on the Lyapunov optimization technique which is extremely useful in the development of stable queue control algorithms [17–19], we design an online algorithm to approximately obtain the optimal solution. Our contributions are summarized as follows:

- From the perspective of service provider, we take the first step to investigate the problem of minimizing the electricity cost under electricity markets by joint power allocation and battery management for BS equipped with hybrid energy sources and finite energy storages. When electricity price is constant, our problem can be degenerated into the conventional grid energy minimization problem.
- We formulate the problem as a stochastic program which minimizes the time-average expected electricity cost while stabilizing the system. Besides, we propose an online algorithm based on the Lyapunov optimization technique to approximately obtain the optimal solution without the knowledge of future information. Especially, our algorithm can guarantee the worst delay experienced by UEs through introducing virtual queues.
- Through theoretical analysis, we show that our algorithm can offer an explicit tradeoff between the cost saving and worst delay performance. Besides, numerical simulation results demonstrate the effectiveness of our proposed algorithm.

The rest of the paper is organized as follows: We present the system model and formulate our problem in Section 2. In Section 3, we propose an online algorithm to approximately solve our problem. Theoretical analysis and discussions on the performance of our algorithm are given in Section 4. Numerical simulation results are presented and discussed in Section 5. Finally, we conclude our work in Section 6.

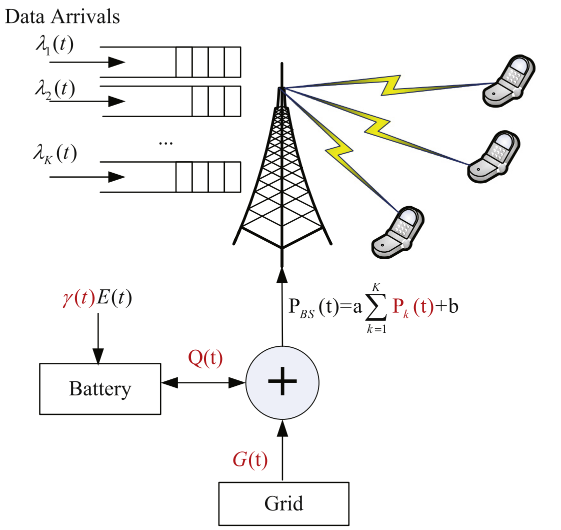


**Fig. 1.** System model.