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Fast track article

Analysis of power saving and its impact on web traffic in cellular networks with continuous connectivity[☆]

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ABSTRACT

In this work, we analyze the power saving and its impact on web traffic performance when customers adopt the continuous connectivity paradigm. To this end, we provide a model for packet transmission and cost. We model each mobile user's traffic with a realistic web traffic profile, and study the aggregate behavior of the users attached to a base station by means of a processor-shared queueing system. In particular, we evaluate user access delay, download time and expected economy of energy in the cell. Our study shows that dramatic energy saving can be achieved by mobile devices and base stations, e.g., as much as 70%–90% of the energy cost in cells with realistic traffic load and the considered parameter settings.

1. Introduction

The total operating cost for a cellular network is of the order of tens of millions of dollars for a medium–small network with twenty thousand base stations [1]. A relevant portion of this cost is due to power consumption, which can be dramatically reduced by using efficient power saving strategies. Power saving can be achieved in cellular networks operating WiMAX, HSPA, or LTE protocols by optimizing the hardware, the coverage and the distribution of the signal, or also by implementing energy-aware radio resource management mechanisms. In particular, we focus on power saving in wireless transmissions, which would enable the deployment of compact (e.g., air conditioning free) and green (e.g., solar power operated) base stations, thus requiring less operational and management costs.

An interesting case study is offered by the behavioral analysis of users that remain online for long periods. These users request a continuous availability of a dedicated wideband data channel, in order to shorten the delay to access the network as soon as new packets have to be exchanged. This *continuous connectivity* requires frequent exchange of control packets, even when no data are awaiting for transmission. Therefore, in the case of continuous connectivity, a huge amount of energy might be spent just to control the high-speed connection, unless power saving is enforced. However, since power saving mode affects packet delay, some constraints have to be considered when turning to the power saving operational mode.

Power saving and sleep mode in cellular networks have been analytically and experimentally investigated in the literature, mainly from the user equipment (UE) viewpoint. E.g., power saving in the UMTS UE has been evaluated in [2,3] by means of a semi-Markov chain model. The authors of [4] propose an embedded Markov chain to model the system

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vacations in IEEE 802.16e, where the base station queue is seen as an $M/GI/1/N$ system. The authors of [5] use an $M/G/1$ queue with repeated vacations to model an 802.16e-like sleep mode and to compute the service cost for a single user download. Using Laplace–Stieltjes Transform and Probability Generating Functions, [6] derives closed form expressions for the average power consumption (objective) and the average packet delay (constraint) for an UE. The authors of [6] also design a sleep mode mechanism based on traffic estimation and a solution of the optimization problem. Analytical models, supported by simulations, were proposed by Xiao for evaluating the performance of the UE in terms of energy consumption and access delay in both downlink and uplink [7]. Almhana et al. provide an adaptive algorithm that minimizes energy subject to QoS requirements for delay [8]. The works [9,10] closely relate to our proposal and mainly focus on the analysis of the discontinuous reception mode in 3GPP LTE and IEEE 802.16m respectively. The authors consider both the uplink and downlink packets for the UE and show that uplink packets increase the power consumption and decrease the delay.

The existing work does not tackle the base station (or evolved node B, namely eNB) viewpoint nor analytically captures the relation between cell load and service rate statistics. Furthermore, for sake of tractability, many of those studies assume that packet arrivals follow a Poisson model. Instead, in real networks, the user traffic can be very bursty and follow long tail distributions [11]. In contrast, we use a $G/G/1$ queue with vacations to model the behavior of each UE, and we compose the behavior of multiple users into a single $G/G/1$ *PS* queue that models the eNB traffic. We analytically compute the cost reduction achievable thanks to power saving mode operations, and show how to minimize the system cost under QoS constraints. In particular we refer to the mechanisms made available by 3GPP for *Continuous Packet Connectivity* (CPC), i.e., the discontinuous transmission (DTX) and discontinuous reception (DRX) [12].

The importance of DRX has been addressed in [13], where the authors model a procedure for adapting the DRX parameters based on the traffic demand, in LTE and UMTS, via a semi-Markov model for bursty packet data traffic. A description of DRX advantages in LTE from the user viewpoint is given in [14] by means of a simple cost model. In [15], the authors use heuristics and simulation to show the importance of DRX for the UE.

The contributions of our work are as follows: (i) we are the first to provide a complete model for the behavior of users (UEs) and base stations (eNBs) in continuous connectivity and with non-Poisson traffic (namely web traffic), (ii) we provide a cost model that incorporates the different causes of operational costs, (iii) we validate our model using packet-level simulations, (iv) we study the importance of a variety of model parameters by means of a *sensitivity analysis*, and (v) we show how to use the model to minimize operational costs under QoS constraints. Our results confirm that a tremendous cost reduction can be attained by correctly tuning the power saving parameters. In particular, transmission costs can be lowered by more than 90% with realistic traffic loads.

This article extends our work published in the proceedings of IEEE WoWMoM 2011 [16]. Compared with the conference paper, we implemented the following modifications and additions: (i) We have done a research review of recent works and have amended the related work section by adding three new references. (ii) The presentation of the analytical model has been improved as some equations/derivations have been explicitly written. The cost model has also been refined impacting all the numerical results which rely on it. (iii) We have performed simulations in which each user has p parallel browsing sessions; the aim is to evaluate whether our study can be used when each user's traffic consists of superposed arrival processes. (iv) A sensitivity analysis has been performed. We provide both first order and total sensitivity indices and comment on the implications and the interpretations of these indices. (v) The numerical analysis has been revisited and expanded with new numerical results. (vi) A "lessons learned" section has been added, summarizing our recommendations and suggesting a setup which achieves a good tradeoff between energy savings and QoS performance.

The rest of the manuscript is organized as follows: Section 2 presents power saving operations in continuous connectivity mode. Section 3 describes a model for cellular users generating web traffic. Section 4 illustrates a model for downlink transmissions, and Section 5 describes how to evaluate flow performance and transmission costs. In Section 6 we validate the model through simulation. A sensitivity analysis is performed in Section 7, and a performance analysis and optimization is done in Section 8 showing the achievable power saving. Section 9 concludes the article.

2. Continuous connectivity

Cellular packet networks, in which the base station schedules the user activity, require the online UEs to check a control channel continuously, namely for T_{ln} s per system slot (i.e., per subframe T_{sub}). For instance, CPC has been defined by 3GPP for the next generation of high-speed mobile users, in which users register to the data packet service of their wireless operator and then remain online even when they do not transmit or receive any data for long periods [17]. A highly efficient power saving mode operation is then strongly required, which would allow disabling both transmission and reception of frames during the idle periods. The UE, however, has to transmit and receive control frames at regular rhythm, every few tens of milliseconds, so that synchronization with the base station and power control loop can be maintained. Therefore, idle periods are limited by the mandatory control activity that involves the UE. To save energy, when there is no traffic for the user, the UE can enter a power saving mode in which it checks and reports on the control channels according to a fixed pattern, i.e., only once every m time slots. Relevant energy economy can be achieved. In change, the queued packets have to wait for the mth subframe before being served.

Discontinuous transmission. DTX has been first defined by 3GPP release 7. It is a UE operational mode for discontinuous uplink transmission over the Dedicated Physical Control Channel (DPCCH). With DTX, UEs transmit control information according