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Load-adaptive networking for energy-efficient wireless access[☆]

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ABSTRACT

Energy-efficient operation is essential for mobile network operators to meet the growing demand for higher data rates while managing rising operating costs. Here, the main challenge is to guarantee the quality of user experience whilst saving energy. This challenge demands adaptive algorithms that enable a load-aware network operation that dynamically configures different network elements according to user needs. To this end, in this paper, we present an adaptive and context-aware power management framework for networks composed of different radio access technologies. We implement and evaluate our framework in an indoor and outdoor testbed. The experimental results confirm that significant energy can be saved in practice by efficiently adapting resources to the actual traffic demand.

1. Introduction

One of the most urgent challenges in the new century is reducing the high energy consumption. As mobile Internet becomes more prevalent, energy consumption related to communication networks also increases. In 2010, the global electricity and diesel energy consumption by all mobile networks was approximately 120 TWh, resulting in $13 billion energy costs and, is responsible for 70 Mt CO2 emissions [1]. This is not surprising, as, typically, mobile networks are over-provisioned to provide the best connectivity to the users. However, the actual demand varies considerably based on context (e.g., time and location). To save energy in mobile networks, this mismatch in demand and provisioned resources needs to be addressed. An attractive solution proposed in literature is to adaptively re-configure the mobile network elements (e.g., switching base stations to lower energy consumption modes or off) to meet current capacity demands. In this paper, we evaluate the potential of such an approach based on a context-aware energy management framework implemented in an indoor and outdoor testbed.

One of the major challenges in context-aware energy management is to provide timely and accurate network re-configurations as the user demand varies. In this work, we consider a load-aware energy-saving framework, which takes into account that radio access networks are heterogeneous in structure (e.g., cell size) and technology (e.g., using different wireless technology standards [2]). This work builds on our earlier works [2–6] which introduce the conceptual framework of a load-adaptive network. In this paper, we provide further analysis on load-adaptive network design (Section 3), which includes a discussion about the main parameters and costs that influence energy-efficiency of a load-adaptive system. This is essential to ensure that the cost of energy management mechanisms do not negate energy savings.

The proposed framework is made up of several components including an energy optimiser, and a context manager, context collection agents and a controller (see Section 4 for details). We fully integrated our energy optimiser, Morfeo [4] and context manager [3] into this framework along with other components. We ran extensive tests using a testbed with a total of 19 outdoor and indoor wireless access devices (WADs) and 20 users. We also used two types of WADs with different energy consumption, capacity and coverage characteristics to understand their impact on energy savings and load balancing. Our results demonstrate that significant energy savings are possible, but depend on hardware and software characteristics of the WAD as well as the required network coverage and actual traffic load. In summary, we make the following contributions in this work:

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- Design and implementation of a context-aware energy management framework which provides load-aware network operation.
- Design of experiments to measure the system parameters that influence the implementation of the energy saving framework in a real testbed.
- Extensive experiments in indoor and outdoor testbeds to evaluate different traffic conditions (e.g., no traffic, constant traffic, increasing traffic).
- Analysis and discussion of the limitations of energy-savings using a power-off strategy.

The remainder of the paper is structured as follows. We present the state of the art in Section 2, and in Section 3, discuss the design of a load-adaptive network. Sections 4 and 5 present our implementation and experimental evaluation, respectively. Section 6 concludes the paper.

2. Greening ICT networks: state of the art

Greening ICT networks has become a central theme in research and standardisation activities due to expected high increase in energy consumption [7–9]. There is extensive literature on energy saving solutions in mobile networks including 2G, 3G and LTE advanced, and also Wireless LANs (WLANs) and other short-range radio technologies. The standard use-cases consider saving energy (1) at a single Access Point (AP) of a given technology, (2) among APs of a given technology, and (3) across different networks of different technologies [10]. Nevertheless, the majority of the proposed solutions focus on single technology rather than a heterogeneous network. Also, common solutions typically either trigger low-power modes during periods with no network traffic, or use power control for cell zooming and exploit coverage and energy trade-offs. In the following, we present further details on these two approaches.

Low-power modes: Using low-power modes to save energy is well-investigated [11–14]. Here, with low-power mode, we mean both a sleep mode, which deactivates different parts of a WAD, as well as an off mode, which shuts down the entire device. The main goal of using a low-power mode is to reduce the number of active base stations or sectors under low traffic conditions. If the overhead of off/sleep and on transitions are acceptable, significant energy savings become possible [15]. The OPERA-Net (Optimising Power Efficiency in mobile Radio Networks) project [16] shows that 30% energy saving is achievable without affecting user satisfaction when a sleep mode is used to turn off sectors in a 3G network. Similarly, the E3 (End-to-End Efficiency) project [17] has quantified the gains from switching off sectors as 20–40%, while maintaining an acceptable grade of service for different traffic types. The TREND (Towards Real Energy-efficient Network Design) project [18] proposes using sleep modes in home femtocell networks, where long under-utilised periods are the norm, and hence, high energy savings can be obtained without affecting service quality. The EARTH (Energy-Aware Radio and network Technologies) project [19] proposes several deployment and network management strategies, and sophisticated hardware and software techniques to achieve overall energy savings of 70%. Among these, the cell DTX (discontinuous transmission), which allows putting a transceiver to a low-power mode, is shown to be the most efficient approach when combined with bandwidth adaptation (e.g., adapting the resource blocks in an LTE subframe according to the traffic demand).

In addition, it may also be possible to turn off entire networks [20,21]. In [20], using heterogeneous 2G/3G networks of the same operator, an optimal strategy powers on/off an entire system (2G or 3G) for high or low traffic scenarios, respectively. In [21], significant savings are achieved if operators enable cooperative roaming and switch off networks under low load. The main challenge, as these studies confirm, is to offload the current traffic to active cells and avoid coverage holes. In [22], re–arranging the user–cell association is shown to achieve 50% energy savings. However, this result serves as an upper bound, as complete knowledge of user locations is assumed. In [23], the temporal-spatial user traffic diversity is exploited to turn off 3G base stations. A network trace-based evaluation shows gains up to 52.7% savings in a dense area, and up to 23.4% in a sparse area. Savings are also more significant during night time, e.g., up to 70%. However, even during daytime, 20–40% savings are possible by exploiting temporal-spatial traffic diversity. Similar strategies also exist for WLANs [24–27].

Cell zooming: Cell zooming via transmit power control requires determining the optimal transmission power for each base station while maintaining good QoS. Here, we consider two approaches: (i) adjusting the transmission power to obtain the Signal to Interference plus Noise Ratio (SINR) that achieves the desired network capacity with the current modulation coding scheme, and (ii) adjusting the transmission power accepting a degradation in SINR, which may be salvaged by more robust modulation coding schemes. In [28], the optimum cell size based on different base station technologies, data rates, and traffic demands is investigated and a two-level scheme is shown to achieve up to 40% energy savings. The EARTH project also considers power control as an attractive solution for high load scenarios and in combination with cell DTX. Cell zooming is proposed to be used in combination with sleep modes to alleviate coverage holes resulting from switching off base stations, and to extend coverage. However, in [29], it is shown that this may be insufficient compared to deploying smaller but more cells. Similarly, [30,31] propose a heuristic approach to adopt the on/off activity of APs and corresponding transmit power in accordance with number and location of active users. The main goal is to strike a balance between computational complexity and accuracy to enable energy savings. Power-bandwidth optimisation techniques are investigated in [32], where authors also discuss practical trade-offs associated with the implementation of the energy efficient schemes. The paper concludes that energy efficient techniques provide considerable power savings even accounting for realistic system parameters and channel environments.

3. Designing a load-adaptive network

The main goal of a load-adaptive network is to configure itself to satisfy the actual capacity demand and also to reduce the energy consumption of the network. To this end, we first identify the main system and design parameters, and next, discuss network configuration decisions that affect the capacity and energy consumption of a network. Finally, we propose a functional architecture that takes into account these parameters and decision making procedures to achieve a load-adaptive operation.

3.1. Design parameters and decision mechanisms

The context and deployment-based parameters that we take into account are summarised in Table 1. In our design, we include the delay and energy cost of network re-configuration (i.e., τ and E_{rec}), and context collection delay (i.e., ϵ). These costs are zero only in the ideal case and, it is not possible to re-configure the network continuously and in real-time, but at specific points in time and with a configuration that needs to be valid for a minimum time period (i.e., δ in Table 1). This also requires mechanisms that can predict the capacity demand during δ. In addition, some over-provisioning is required to be able to handle traffic bursts. In the case that the actual demand significantly differs from the predicted demand, additional mechanisms are required to detect and correct those situations. It is clear that a re-configuration only makes sense if the saved energy is greater than zero ($E_s > 0$).