Energy OPtimal ALgorithms for mobile Internet: stochastic modeling, performance analysis and optimal control

Georgios S. Paschos*◇, Petteri Mannersalo†, Slawomir Stanczak+, Eitan Altman‡and Leandros Tassiulas*◇
* CERTH-ITI, Volos, Greece, † VTT, Oulu, Finland, + HHI-Fraunchofer, Berlin, Germany, ‡ INRIA, Sophia-Antipolis, France, ◇ ECE @ University of Thessaly, Volos, Greece
gpasxos@uth.gr, petteri.mannersalo@vtt.fi, stanczak@hhi.fhg.de, eitan.altman@sophia.inria.fr, leandros@uth.gr

***Abstract*—EnergyOPAL research focused on algorithms which can enable an energy friendly future mobile Internet. Turning off the electronics of a wireless device is understood to be crucial for saving energy over idle periods. On the other hand, the responsiveness of the wireless network should not be compromised. Each node should try to adapt its power consumption profile to the traffic running through it. If each node is seen as an entity, cooperation among nodes is needed in order to achieve an efficient performance in terms of energy. Scheduling and power control plays a big role in this context. We identify important tradeoffs and provide optimal control as a proposed solution to this problem.**

I. Introduction

A wireless terminal is meant to be mobile and thus relying exclusively in battery supply. Therefore one can quickly conclude that energy efficiency can be directly translated to extension of battery lifetime and thus an increase in autonomy. Particularly in multihop networks, the energy performance of each node has a direct impact on the performance of the entire network. For example, in wireless sensor networks the interest is on maximizing the lifetime of the weakest node and thus the lifetime of the network. On the other hand, due to the widespread of mobile handhelds, wasting energy on wireless access sums up to an important figure towards having an effect on the consumed power on a national level (the current trend is of the order of 1% of total electricity consumption). For these reasons, economy of energy resources is a very important topic in wireless communications. During EnergyOPAL effort, we aimed at examining algorithms able to provide power savings for communicating nodes as well as to solve the extended problem of considering power consumption in the whole network.

The first step towards solving the energy efficiency problem is to consider the single link case. One of the most expensive (in terms of energy) components of a mobile device is the wireless transceiver, the electrical circuit that makes signal transmission and reception possible. Although transmitting a particular message is inevitable (and therefore this particular energy part cannot be saved), having the transmitter *on* in order to listen to the channel is indeed amenable. It is well known that a considerable amount of energy is wasted by listening only to the channel (and not receiving any messages). The solution in this case is to turn off the transceiver (in other words to put the transceiver to sleeping mode) in order to save power. If we assume that the activation of the link in question is independent from the rest implying that we are agnostic to scheduling decisions, then the problem of designing an efficient sleepmode algorithm is reduced to designing an algorithm that adapts to incoming traffic in such way that QoS requirements for delay are fulfilled while minimum energy is spent. In the general case, however, the link activation is not independent but it is a well thought coordinated action called scheduling. This determines when the mobiles should transmit and when they should listen to the channel. One can then improve the energy efficiency of the system simply by developing an algorithm that orchestrates the activity of the whole network.

EnergyOPAL was a Specific Joint Research Project, part of the EuroNF Network of Excellence. Four institutes participated in EnergyOPAL, CERTH-ITI (Greece), VTT (Finland), HHI-Fraunchofer (Germany) and INRIA (France). The goal was to cooperate on energy optimal algorithms for the future mobile Internet.

II. Sleep mode algorithms

EnergyOPAL research results comprise theoretical findings and proposed algorithms that enhance wireless networks making them more efficient in terms of energy used. In [1], [2], [3], [4], the focus is on WiMAX networks but the proposed techniques can also be applied directly to cellular technology as well as other wireless access technologies. The performance of the network (captured as energy consumption and response delay) is optimized over a space of policies for turning on/off the devices; see [1] for the policies inspected. Since the problem of deciding when to turn off is theoretically proven to be an adaptation to traffic arrival process problem, the results hold even for more general theoretical scenarios.

On the same topic, [2] attacks the problem by means of dynamic programming, a tool used to solve control problems in dynamical systems. Important properties of the system are unveiled, and deep understanding is provided. For example it is shown that for Poisson traffic (common with aggregation points inside a network), the optimal sleep pattern needs only to be periodic with fixed length. More complex traffic patterns are studied and optimality results are given. EnergyOPAL studied the same problem in case of multiclass modes, see [4]. For mobile networks or VoIP applications, the WiMAX protocol defines simultaneously operating classes of sleep mode. In [4], QoS provisioning under this scheme is studied, leading to the conclusion that important energy savings can be extracted even when an ongoing VoIP call is combined with data transfer.

III. Energy saving techniques for sensor networks

On a different track, EnergyOPAL studied energy minimization in multihop wireless networks. In [5], optimal network control is studied for the cases where the devices operate on batteries with the ability to recharge them. In [6], the problem of minimizing energy is studied when a wireless sensor network is making measurements and delivering them to the data sink. The problem is solved via advanced optimization techniques and the solution is given, which provides intuition on how the measurements are gathered in an energy efficient way; spatial correlation of measurements is exploited to provide an edge in performance.

IV. Competition and cooperation for energy efficiency in random access

The majority of modern wireless devices rely on random access for communications. Popular protocols, like IEEE 802.11, promote the competition among the wireless nodes as the solution to distributizing the access and simplifying the link scheduling. In this context, wireless nodes contend for access in the medium, for example by means of deciding on an access probability (in IEEE 802.11 this is accomplished by means of the contention window and the backoff counter). The question then is *what is the impact of such competition on the energy efficiency*? In [7] we attempt to answer this question. It turns out that devices with tight energy budget suffer more than other devices with less stringent constraints. Also the global welfare depends on these constraints. A device connected to the plug can cause a whole wireless network to suffer by increasing the level of competition. Thus, clever mechanisms for cooperation are proposed.

V. A new approach to Green networking

Green networks are entwined with the notion of energy minimization. The intuition is that by reducing the consumed energy per transmission, the whole system consumes less electrical power which maps back to less CO_2 emmissions for the environment. On the other hand, [8] studies the problem of jointly minimizing energy as well as the effect of radio transmissions to human beings, making the network green for the human also from the health aspects as well. It is shown that such a problem might have quite different solutions leading for example to the usage of relays instead of femtocells that turn on and off.

VI. Impact of EnergyOPAL research - Conclusion

An important aspect of our work is the aspiration to affect the standards of current mobile networks as well as the future ones. The algorithms proposed by the standards are in a sense *open* since there exists a number of customizable parameters which are left to the network operator to define. In our work we give explicit solutions (some in closed form and some algorithmic) how to optimally control these parameters. Also, we prove that the standards are suboptimal in the sense that even if the parameters are optimally controlled, there exist other sleep policies which perform strictly better. In this sense, we provide intuition for future standards designers of how to setup better performing customizable policies for the future access networks.

Our work can serve as a substratum for green networking research at the access layer. Currently we are experiencing a growing interest and focus of the networking society on methods for energy saving and efficiency. As reported by the vision of Euro-NF [9], this is one of the major concerns of research community towards the Future Internet; making the 202020 goal a reality. We hope that our work provides an important basis and critical intuition as regards energy saving in mobile terminals or in general saving power in the access layer of wireless networks.

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