Scientific Report

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Period of the fellowship	02/04/2012 to 01/04/2013

I – SCIENTIFIC ACTIVITY DURING YOUR FELLOWSHIP

The rising costs of electricity price and the issues related to climate change are now calling for new solutions to reduce the electricity consumption in all sectors, and to adopt green attitudes in deploying new infrastructures. The ICT (Information and Communications Technology) sector is nowadays one of the main energy consumer worldwide, with an electricity consumption ranging between 2% and 10%, and this figure is expected to grow even further in the near future.

Among the most promising approaches that have been recently pursed to reduce energy consumption in the ICT sector, we highlight: 1) the reduction of energy waste, for example enabling sleep modes on network devices during low traffic periods; 2) the use of renewable sources. Of course the two approaches can be combined together thus allowing to minimize the energy consumption from national power grids.

Recently, several initiatives have been undertaken to promote the use of solar panels and/or wind turbines to power the Base Stations (BSs), especially in remote areas or in developing countries, where there is no power grid or it is not reliable, or simply for sustainability reasons in developed countries, as an alternative to the power grid.
According to the GSMA, up to now around 35,000 BSs powered by renewable energies have been installed worldwide. Just to give an idea on the environmental impact, replacing 100,000 diesel powered base stations with renewable energy sites, can reduce CO_2 emissions by up to five million tons annually. Furthermore, it is estimated that annual operating expenses could be cut from approximately 40,000 USD with a diesel powered BS, to 7,000 USD with renewable site solutions, with a payback period (due to capital expenses increment) of only two years.

During my stay at INRIA, in MAESTRO team, I have mainly worked with Sara Alouf on the problem of renewable energy optimization in cellular networks. In particular we assumed that BSs are powered by renewable sources (e.g., sun, wind) and/or by the grid. Our aim was to optimize the usage of renewable sources. Specifically, we considered a cellular network in a urban area composed of one or a few macro-cells (referred to as macros for short) and several micro-cells (a.k.a. micros) that provide additional capacity. This scenario is typical of urban networks, in which the macros act as umbrella cells and the micros are particularly used during peak hours. Due to the capillary presence of micros in a nationwide network, the total power consumption of all the micros can be significantly high. Thus, even if micros are less power-consuming than macros, the savings achievable in each of them, through the use of renewable energy, can be huge considering their number.
We mainly focused on a novel scenario in which the macros are powered by the grid, while the micro-cells are powered either by renewable sources or by the grid if the energy from renewable sources is not enough. Obviously, renewable equipments (e.g., solar panels, wind turbines, batteries) require space (several squared meters). Thus, deploying renewable-powered base stations in urban environments is challenging for operators. However, first we noted that micros consume much less power than macros (about 200-300 W), thus requiring small-size renewable equipments. For example, a micro that consumes 200 W needs a solar panel of about 15-20 m^2. Second, we can envision that operators might rent solar panels above roofs, for example because they are already

deployed for domestic usage.
In this context, a telecom operator may want to reduce as much as possible the power consumption from the grid by using the power from renewable sources. In our problem, this means optimally exploiting the renewable energy from the micros, while minimizing the probability of depleting their energy batteries.
We thus defined the Energy Depletion Probability for each single micro BS, namely EDP, as the probability of depleting the energy in the battery, thus resorting to the power grid.
Essentially, our idea was to associate users preferentially to BSs with lower EDP through the cell-breathing technique: BSs can adjust their transmission power on the pilot channel in order to cover a larger or a smaller area (and this is strongly related to the number of served users), depending on their current EDP. Indeed, different BSs can experience different renewable energy arrival patterns, essentially based on their positions and, possibly, time of the day.
We proposed a markovian model that is equivalent to a token bucket filter in order to model a single micro BS as a server and compute the relative EDP over time. Then, we proposed a simple procedure that each micro BS can locally adopt in order to dynamically adjust the arrival rate of users based on its renewable energy availability. Essentially, this can be done by dynamically changing the micro BS power on the pilot channel, thus changing the number of users associated to the BS.

To the best of our knowledge, the problem of renewable-powered BSs management has been considered only very recently in the literature, and there are no analytical models that capture the main feature of renewable energy availability over time in a cellular network.
We are currently working on the markovian model of the evolution of BS battery level over time. Moreover, we aim at proposing a simple decentralized algorithm that dynamically adjusts the BSs coverage based on energy and users traffic patterns. Finally, we plan to evaluate the trade-off between operators' costs and QoS performances obtained by either adopting ON-GRID solutions (as the one considered in this work, where power from the grid is available to feed the BSs) or OFF-GRID solutions (where BSs can solely rely on renewable energy).

II – PUBLICATION(S) DURING YOUR FELLOWSHIP

- D. Ciullo, V. Martina, M. Garetto, E. Leonardi, *How much can large-scale Video-On-Demand benefit from users' cooperation*?, **accepted at** IEEE INFOCOM , Turin, Italy, April 14-19, 2013.

- L. Chiaraviglio, D. Ciullo, M. Mellia, M. Meo, *Modeling Sleep Mode Gains in Energy-Aware Networks*, **submitted to** Computer Networks, October 2012.

- M. Ajmone Marsan, L. Chiaraviglio, D. Ciullo, M. Meo, *On the Effectiveness of Single and Multiple Base Station Sleep Modes in Cellular Networks*, **submitted to** Computer Networks, November 2012.

- D. Ciullo, V. Martina, M. Garetto, E. Leonardi, G. L. Torrisi, *Peer-assisted VoD Systems: an Efficient Modeling Framework*, **submitted to** IEEE Transactions on

Parallel and Distributed Systems (TPDS), September 2012.

- D. Ciullo, V. Martina, M. Garetto, E. Leonardi, G. L. Torrisi, *Asymptotic properties of sequential streaming leveraging users' cooperation*, **submitted to** IEEE Transactions on Information Theory, October 2012.

III – ATTENDED SEMINARS, WORKHOPS, CONFERENCES

- CCNx Community Meeting 2012, 12-13 September 2012, Sophia Antipolis, France.

Seminars:

- Uri Yechiali (Tel Aviv University), *The Asymmetric Inclusion Process: Tandem-Queue Networks with Unlimited Batch Service*, April 18, 2012, INRIA Sophia Antipolis, France.

- Evsey Morozov (Petrozavodsk State University), *Gaussian Queues*, September 20, 2012, INRIA Sophia Antipolis, France.

- Balakrishna Prabhu (LAAS-CNRS), *Steady-state approximations of dynamic speed-scaling in data centers*, November 22, 2012, INRIA Sophia Antipolis, France.

IV – RESEARCH EXCHANGE PROGRAMME (REP)

Between November 5th, 2012 and November 9th, 2012, I visited the group of LCA2 of Professor Jean-Yves Le Boudec at EPFL, Lausanne, Switzerland.
I gave a talk on my research activities on energy efficiency in cellular networks, and we exchanged some ideas about possible joint research activities.
Indeed, the main goal of this REP was to cooperate with EPFL on the energy-efficient management of sustainable wireless networks. Specifically, we focused on cellular networks where base stations (BSs) are powered by renewable sources, and we aimed at optimizing the usage of renewable energy, while minimizing the grid energy consumption. To this purpose, we studied some network policies that control BSs power consumption based on renewable energy availability: for example by adjusting the BSs coverage (i.e., through cell breathing) or the quality of service level offered to users (i.e., service degradation) over time.
We mainly focused on remote areas in which the power grid is often unreliable. Our aim was to optimize the usage of renewable energy while minimizing BSs service interruption probability due to battery depletion, through the adoption of smart policies that manage the renewable energy storage over time. We supposed that BSs know the weather forecast for each day and the statistics on average users' traffic. Specifically, a BS may degrade the quality of service level offered to users during the day, thus consuming less energy and storing the saved energy for the night (or next days). For example, in case of

forecasts of some consecutive unlucky days, the BS should store energy when abundant, and use it gradually when needed. In this work, we have sought to propose a simple policy that optimizes the service level over time. For example, a waterfilling-based technique can equalize the service level over time by adapting the quality based on the actual power gap (i.e., the difference between the power demand and generation). We plan to continue this research activity and to propose a stochastic dynamic optimization algorithm that optimizes the service level based on actual forecast of the demanded and generated power, taking into account of the prediction error in weather and traffic forecasting.