Energy-Neutral System-Level Analysis and Optimization of 5G Networks

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I. Summary

The tutorial titled *Energy-Neutral System-Level Analysis and Optimization of 5G Networks* is intended to provide the audience with background on energy-neutral system design, as well as on the mathematical tools for modeling, analyzing, and optimizing the energy-neutral operation of future wireless networks.

II. Abstract

The Internet of Things (IoT) will connect billions of devices by 2020. Such systems suppose batteries and/or energy harvesting from the environment, which also bets for very low energy devices. In order to enable IoT service capabilities, 5G wireless networks will need to bring a drastic energy efficiency improvement and will need to develop energy harvesting capabilities. This energy chase will cover low-energy devices and network elements, and will rely on the availability of renewable energy sources, dedicated power sources, as well as the possibility of harvesting energy directly from the radio waves that are primarily used for data transmission. This leads to a new design space, where the availability of energy is not deterministic anymore but may depend on environmental factors, the interference may not necessarily be harmful as it may be a natural source electromagnetic-based power to be used for replenishing the batteries of low-energy devices, and the intended signals may be exploited for both data transmission and energy harvesting. This paradigm-shift introduces a new concept in the design of 5G wireless networks: energy-neutrality. Energy-neutral networks are systems that not only make an efficient use of the available energy, but, more importantly, that operate in a complete self-powered fashion.

The present tutorial provides the audience with a complete survey of the potential benefits, research challenges, implementation efforts and application of technologies and protocols for achieving energy-neutrality, as well as the mathematical tools for their modeling, analysis and optimization. This tutorial is unique of its kind, as it tackles both system-level modeling and optimization aspects, which are usually treated independently. Special focus will be put on two methodologies for enabling the system-level modeling and the system-level and distributed optimization of energy-neutral 5G wireless networks: stochastic geometry and fractional programming. In the proposed tutorial, we illustrate how several candidate transmission technologies, communication protocols, and network architectures for 5G can be modeled, studied and optimized for their energy-neutral operation.

III. Outline

The tutorial is organized in three main parts that are described as follows.

Introduction. The tutorial starts by introducing the problem of energy efficiency and by motivating its importance in current and future wireless networks. Different metrics that have been proposed in the literature to quantify the energy efficiency of communication systems are introduced and discussed. Several communication networks are described, starting from point-to-point systems to more general interference networks that use various technologies for interference management. The concept of energy-neutrality operation as a challenging but mandatory generalization of the concept of energy efficiency is introduced. We define a energy-neutral network as a system that operates in a complete self-powered fashion and show that this challenging goal can be achieved only when the network is capable of performing the following tasks simultaneously:

(1) All network elements and devices are capable of harvesting energy from the environment (e.g., solar, wind, or radio frequency energy) to replenish their batteries and to sustain their operation.
(2) All network elements and devices make an efficient use of the available energy, by maximizing the amount of data per unit energy that is reliably transmitted through suitable allocation strategies of the radio resources.

We illustrate the most promising application scenarios, where the concept of energy-neutrality can be successfully applied (i.e., the Internet of Things - IoT) and show that the analysis and the design of energy-neutral wireless networks require new mathematical tools and approaches. Despite futuristic, examples of commercial devices that rely solely on the energy that is harvested from electromagnetic waves exist in the market already, e.g., the Freevolt and CleanTag technologies introduced by Drayson Technologies Limited (http://www.draysontechnologies.com/technologies.html). Also, they constitute an integral and important part of the new service capabilities that 5G networks need to guarantee (http://5g-ppp.eu/wpcontent/uploads/2015/02/5G-Vision-Brochure-v1.pdf).

Stochastic geometry. To quantify the potential gains of energy harvesting and to optimize network operation based on the stochastic availability of the harvested energy (see Requirement (1) in the introduction part), a critical role is played by the spatial distribution of energy sources and energy-neutral devices. This originates from the ultra-dense and largescale nature of emerging wireless networks and because the harvested power is a function of the transmission distance and, thus, of the locations of all network elements. As a consequence, system-level analysis and optimization (either distributed or centralized) need to account for the spatial characteristics of the network being considered. In this context, the theory of point processes and stochastic geometry constitute essential mathematical tools, as they provide us with general and accurate methods for modeling random spatial patterns.

Thus, motivated by the introductory part, the second part of the tutorial provides the audience with a solid background and comprehensive description of stochastic geometry modeling, by introducing key theorems, by explaining how to formulate problems from the standpoint of system-level analysis and optimization, as well as by illustrating how to use stochastic geometry for modeling and analyzing energy-neutral wireless networks. In addition to the basic theory, several new methodologies for system-level modeling and for computing various performance metrics are illustrated, which include the equivalent-in-distribution approach for computing the error probability, the moment-generating function for computing the area spectral efficiency, and the intensity-matching approach for quantifying the trade-offs in terms of achievable rate and harvested energy. As far as system-level optimization is concerned, the concept of spatially-average proportionally fair criterion is introduced and shown to constitute a tractable approach for optimizing energy-neutral large-scale wireless networks relying on stochastic geometry modeling. Finally, the suitability of stochastic geometry for modeling and analyzing wireless networks is substantiated with the aid of experimental data for the locations of cellular base station and for the footprints of buildings, which are taken from two publicly available databases from the UK (OFCOM and Ordnance Survey).

Fractional programming. In order to achieve Requirement (2) mentioned in the introduction part, energy efficiency maximization is a critical challenge to be faced. We show that network's energy efficiency is naturally defined by fractional functions that measure the benefit-cost ratio of data transmission, in terms of data rate, reliability, and consumed energy. As a result, optimizing a wireless network for energy-neutral operation naturally leads to the need of efficiently solving a fractional program. In general, fractional programs are non-convex and therefore conventional convex optimization tools are not applicable. Instead, the theories of generalized concavity and fractional programming are the most suited tools to tackle fractional optimization problems.

Motivated by the introductory part, thus, the third part of the tutorial provides the audience with a solid background on fractional programming theory, by explaining the concepts and key-tools to understand, to formulate, and to solve practical optimization problems for achieving an energy-neutral operation. With the aid of several examples, we show how different energy-neutral problems that originate from real-world systems can be formulated in terms of a fractional theory framework. The essential notion of generalized concavity is formally introduced, and the main tools to manage fractional optimization problems are described. All relevant cases that are encountered in practice are covered, by beginning with the simple case study of a single-ratio problem and then gradually moving towards more advanced scenarios that encompass multi-ratio problems, where the sum, product, or the minimum of a family of ratios are to be maximized. For each case study, the most widely used algorithms for system optimization are explained and compared. We also explain how the Requirements (1) and (2) described in the introductory part are intertwined, as the optimization of communication protocols naturally depend on the underlying network spatial models and harvested energy. Thus, we also show how fractional programming and stochastic geometry can be merged together to provide a holistic framework towards the design of energy-neutral wireless networks.

Applications. The fourth part of the tutorial is focused on the application of the methodologies for system-level analysis and optimization introduced in parts two and three of the tutorial for designing and optimizing 5G wireless networks. More specifically, several examples are provided in order to show that stochastic geometry and fractional programming are extremely valuable tools for modeling and solving practical resource management problems towards the energy-neutral design of 5G wireless networks. We introduce a general system model for large-scale interference networks, which allow us to model several candidate transmission technologies for 5G: heterogeneous networks, multi-hop networks, small-cell networks, LTE-A multi-cell and CoMP systems, device-to-device communication, massive MIMO systems, full-duplex transmission, millimeter-wave communication, wearable networks, IoT in general, self-powered communication (based on radio signals and renewable energy sources), simultaneous wireless information and power transfer, interference alignment, as well as network architectures based on the emerging concepts of cell-less design and resource sharing. We show that all these problems can be handled, in a unified fashion, by the methodologies proposed in parts two and three, in terms of system-level analysis and optimization, respectively. From the optimization standpoint, in particular, we show that, on the one hand, the mean spatially-average proportionally fair criterion can be used for tractable system-level optimization that is independent of the specific network realization, hence providing simple yet sub-optimal solutions. We show, on the other hand, that fractional programming constitutes a tractable approach for dynamic and real-time optimization of interference networks and, more specifically, for solving challenging non-convex optimization problems that involve vectors or matrices that need to be optimized. Also, we show how stochastic geometry and fractional programming can be synergically used with other mathematical tools, such as sequential optimization, queuing theory, random matrix theory.

Finally, we illustrate some recent experimental results about the implementation of resource management algorithms for achieving energy-neutrality for application to MIMO-aided wireless communication systems operating in the 60 GHz (millimeter wave) frequency band. These experimental trials have been obtained with the aid of the HAEC box, a demonstrator based on software-defined radio, currently in use and under development at the 5G Lab Germany (http://5glab.de/).

The tutorial ends with an open discussion of the latest research directions and open issues that in our opinion represent the most important challenges that need to be addressed and solved, aiming towards the successful design of energy-neutral 5G wireless networks.

Primary Audience. Students, academic researchers, industry affiliates and individuals working for government, military, science and technology institutions who are interested in studying emerging large-scale and distributed 5G communication networks and in understanding how to model and optimize candidate network architectures, transmission technologies and communication protocols towards their self-sustained and energy-neutral operation. The present tutorial is intended to provide the audience with a complete overview of the potential benefits, research challenges, implementation efforts and applications of technologies and protocols for achieving energy-neutrality, as well as the mathematical tools for their modeling, analysis and optimization. This tutorial is unique of its kind, as it tackles both system-level modeling and optimization aspects, which are usually treated independently. Therefore, the audience will receive a unique training experience.

IV. Detailed Outline

1) Introduction
   - Why do we need energy efficiency?
   - Energy efficiency of a communication link
   - Energy efficiency of a communication network
   - The paradigm shift: From energy-efficient to energy-neutral communication networks
   - Fundamentals of energy harvesting based on electromagnetic waves and renewable energy sources

2) Stochastic geometry for energy-neutral modeling and analysis
   - Why stochastic geometry modeling?
   - Enabling mathematical tools and fundamental results
   - Applications to wireless networks (ad hoc, cellular, HetNets)
   - Methodologies for system-level analysis (coverage, area spectral efficiency, potential throughput, harvested energy, etc.)
   - From system-level analysis to system-level optimization: Spatially-average utility function maximization (mean proportionally fair utility, etc.)
   - The "Intensity Matching" approach as a universal method for system-level analysis and optimization
   - Feasibility regions: How to quantify energy-neutrality trade-offs • Experimental validation of stochastic geometry modeling of energy-neutral wireless networks with real base station locations, building footprints, and channel models

3) Fractional programming for energy-neutral optimization
   - Problem formulation as a fractional program
   - Generalized concavity and fractional programming
   - Single-ratio problems
   - Max-Min fractional programming
   - Sum and product of ratios
   - Quantitative analysis for energy neutrality
   - Centralized vs. distributed resource management
   - Computational complexity vs. hardware power consumption 4) Application to the energy-neutral design of 5G wireless networks

4) Application scenarios: Heterogeneous cellular networks, sensors networks, IoT, connected objects, wearables, etc.
   - Multi-carrier CoMP heterogeneous networks
   - Massive MIMO heterogeneous networks
   - Multi-hop, relay-aided, and device-to-device HetNets
   - Millimeter-wave heterogeneous networks
   - Cell-less network design and resources sharing
   - Self-powered (renewable energy sources and RF energy harvesting) heterogeneous networks

5) Conclusion and future challenges
   - Take-home messages
   - Open challenges and research issues