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Energy-efficient resource allocation in future wireless networks by sequential fractional programming

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ABSTRACT

This overview paper discusses the framework of sequential fractional programming for energy efficiency maximization in future 5G networks. One of the main features of future systems will be the presence of severe multi-user interference and the need of improved energy efficiency compared to present systems. However, present approaches to energy efficiency maximization, which are based on the theory of fractional programming, result in an exponential complexity in interference-limited networks. In this context, the work shows how to extend available fractional programming approaches to obtain radio resource allocations enjoying strong optimality properties, while at the same time requiring an affordable complexity to compute. The resulting framework is termed sequential fractional programming, and several examples of its applications to leading 5G candidate technologies are discussed in detail.

1. Introduction

Energy is becoming a primary concern for the information and communication technologies (ICT) community. Nowadays ICT is responsible for 5% of the global footprint (in terms of CO_2-equivalent emissions) [1]. Although this is may seem a small percentage, it is steadily increasing, and the situation might escalate considered the exponential growth of connected devices foreseen for the near future. It is estimated by 2020 there will be more than 50 billions of connected devices [2], with a resulting amount of data traffic which will increase by 1000× [3] compared to today's levels. Trying to cope with such a massive data rate increase by simply scaling up the transmit powers is simply not feasible, due to both sustainable growth and economical reasons. Present technologies and conventional approaches to wireless communications are simply not able to provide 1000 times higher data rates by simply scaling up the transmit powers, and even if they were, the resulting energy consumption would cause unacceptable operating costs and detrimental environmental effects.

All key players (both academic and industrial) in the wireless community agree that the 1000× data-rate increase must be achieved *at a similar or lower power consumption as today's networks* [4,5]. This means that the efficiency with which each Joule of energy is used to transmit information must increase by at least a factor 1000. This fundamental fact leads to the notion of bit-per-Joule energy efficiency, defined precisely as the amount of information which is reliably transmitted per Joule of consumed energy, and which is acknowledged as a key performance indicator for 5G networks. Several approaches have been proposed to improve the energy efficiency of communication systems and to make ICT more environmentally-friendly. We list here some popular trends which are attracting a considerable amount of interest in the wireless community.

- **Resource allocation.** Traditionally, the radio resources of a wireless system are optimized in order to maximize the system throughput or data-rate. Instead, with the rise of energy efficiency as key performance indicator of 5G, we are witnessing a paradigm shift from throughput-optimized to energy-efficiency-optimized wireless networks, where the radio resources, and above all the transmit power, are allocated for energy efficiency maximization. This approach provides huge energy efficiency gains over traditional resource allocation schemes, at the price of a moderate throughput reduction [6].
- **Network planning and deployment** Typical network deployments are designed to maximize coverage and throughput. However, significant energy savings can be obtained by rethinking conventional network paradigms taking into account the energy efficiency in the covered area. The trend in this research area is towards dense networks, and indeed two strong 5G candidate technologies go in this direction, namely heterogeneous networks [7] and massive MIMO [8]. The former densifies the number of infrastructure nodes, whereas

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the latter densifies the number of deployed antennas. Several studies have proved that network densification is a very energy-efficient technique, reducing the (electrical and/or physical) distances among the communicating nodes, thus enabling higher data rates without additional energy consumption [9–11]. On top of these techniques, the use of base stations sleep/wake algorithms and antenna muting techniques to adapt to the traffic conditions, can lead to a further reduction of energy consumptions [12].

- **Energy harvesting and sharing.** Recently, harvesting both solar and wind energy has been shown to be a concrete possibility to operate communication systems [13,14]. It should be emphasized how this approach does not directly increase the system energy efficiency, because it does not reduce the amount of energy required to operate the system. Nevertheless, it is attractive because it allows wireless networks to be powered by renewable and clean energy sources, thereby providing a virtually unlimited energy supply, and reducing CO_2 emissions. Moreover, energy can also be harvested from the radio signals over the air [15]. This enables network nodes to share energy with one another by means of wireless power transfer techniques, with the aim of wirelessly recharging nodes which are low on battery [16–19].

It should be mentioned that besides the heterogeneous networks and massive MIMO technologies described above, other strong candidate technologies have been proposed for the implementation of 5G cellular networks, such as mmWaves, cloud architectures, full-duplex, device-to-device communications.

mmWaves resort to transmissions at much higher carrier frequencies, for which the wavelength is of the order of a few millimeters [20,21]. This of course has the advantage of allowing much higher communication bandwidths, but on the other hand electromagnetic propagation at mmWaves is more subject to path-loss attenuation and obstacle blockage, which might limit the range that can be covered by mmWaves communication links. Thus, as far as energy efficiency is concerned, mmWaves technologies have the potential to dramatically increase the data rate, even though it is not clear how much power would be required to operate a mmWave communication.

Full-duplex systems are based on the ability of network nodes of transmitting and receiving over the same resource block (e.g. same bandwidth, time slot) [22,23]. Full-duplex can be practically accomplished by using a subset of the equipped antennas for transmission and the remaining ones for reception, and clearly has the potential advantage of doubling the amount of transmitted data without using additional transmit power, bandwidth or time. In principle, this might double the energy efficiency of the system, even though a critical issue is the management of the self-interference that transmitting and receiving over the same resource block causes due to the non-ideal directivity of the antenna beams. This issue is typically handled by interference cancellation techniques. However, the cancellation must be performed with much higher precision than for conventional interference cancellation receivers, because the transmitter and receiver are co-located and the residual interference after cancellation might significantly degrade the performance. Moreover, sophisticated interference cancellation schemes result in additional energy consumptions.

Finally, the device-to-device technique allows neighboring devices to establish direct connections, bypassing the base station [24–26]. This reduces the base-station load and provides a significant proximity gain. However, it also creates additional interference because the device-to-device link will reuse a resource block also used by a cellular user. Thus, the advantages of this approach depend on the use of interference management techniques aimed at coordinating the network interference, guaranteeing minimum rates to the cellular users. In this context, both centralized and distributed approaches have been proposed. In a centralized device-to-device system, the system base station coordinates the activation of device-to-device links, dictating the resource blocks to be used. Instead, in a distributed system, the mobiles are allowed to establish device-to-device connections autonomously, provided they can guarantee a minimum quality-of-service to cellular users.

1.1. Contributions

Among the three energy-efficient techniques introduced above, this work focuses on the first one: radio resource allocation for energy efficiency. More in detail, the contributions of this work are as follows.

- An extensive literature overview of energy efficiency optimization in interference-limited wireless networks is provided, covering the most widely used system scenarios and transmission technologies in cellular networks. In addition, a thorough description of the mathematical foundations of bit-per-Joule energy efficiency are discussed.
- The optimization framework of sequential fractional programming is reviewed, showing how it applies to general interference-limited wireless networks with affordable complexity. Thus, sequential fractional programming easily lends itself to being used in conjunction with most 5G candidate technologies.
- Several examples are provided in which energy efficiency maximization is carried out by means of sequential fractional programming in systems employing 5G candidate technologies, such as massive MIMO, heterogeneous networks, device-to-device communications.

The rest of this section provides the literature overview on energy-efficient resource allocation, also developing a general problem formulation for energy efficiency maximization in wireless networks. Next, Section 2 introduces the necessary optimization framework required to tackle energy efficiency maximization problems, whereas Section 3 describes the latest approaches to resource allocation for energy efficiency maximization, along with a comprehensive set of recent applications to networks employing candidate 5G technologies. Finally, concluding remarks are provided in Section 5, together with some perspectives about future research directions which will be important to reach the ultimate goal of 1000× energy efficiency. It should be mentioned that a tutorial/survey related to this work has appeared in the book [6]. There, the full details about fractional programming theory are described, whereas this work focuses on the main fundamental points, providing a more recent literature overview and describing new applications of the sequential fractional programming framework.

1.2. Survey of energy-efficient resource allocation in wireless networks

As it will be described in the rest of this section, energy-efficient metrics are naturally defined by fractional functions. As a consequence, the best tool to tackle energy efficiency maximization problems is unarguably fractional programming theory, i.e. the branch of optimization theory concerned with the optimization and properties of fractional functions. Indeed, over the last years fractional programming has become a well-established tool which has been successfully used for energy-efficient resource allocation in many different wireless communication scenarios [6]. This section provides an overview of recent contributions of fractional programming to the most relevant instances of communi-

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