Emerging Topics in 5G Networks: Spectral and Energy Efficient Network Architecture, Transceiver and Algorithm Design

Tutorial Speakers: Marco Maso and Muhammad Ali Imran

***Abstract*—The deployment of every new generation of cellular networks is typically preceded by both an analysis of the issues affecting the current generation and the identification of new technological challenges. The importance of this step is evident at the dawn of the development of the fifth generation (5G) network technology. A spectral and energy efficiency aware development of new algorithms, resource management policies, transceivers and in general network technologies is seen as a necessary step to take, to achieve the expected performance increase 5G networks should yield. This will come at a non-negligible cost for operators. In this context, spectral and energy efficiency will both be key metrics to assess the performance of the future network. In this in-depth tutorial, we start from these observations and discuss several candidate solutions and paradigms to achieve the expected increase in terms of future network performance and end-user quality-of-experience. Specifically, we will answer the following questions:**

- **What are the competitive technologies, paradigms and architectures to increase current wireless networks' performance?**
- **What are the contributing factors to the energy consumption of modern heterogeneous networks (an end-to-end power consumption breakdown will be proposed to answer this question)?**
- **What ecological (carbon footprint) and economic (low carbon economy index) impact will future 5G wireless networks have?**

The majority of the presented results are taken from the Authors' most recent research on green heterogeneous networks, wireless energy transfer and uplink fast power control [1]–[17].

I. Motivation and Importance

Fifth generation (5G) networks are expected to yield performance increase as compared to fourth generation (4G) networks at several levels. In this context, one of the biggest concerns for both the telecommunication industry and the operators in view of the definition and deployment of 5G networks is to achieve an overall spectral efficiency enhancement, all the while guaranteeing high levels of energy efficiency of the network. In fact, on the one hand future 5G networks are expected to provide ubiquitous broadband access to a large number of mobile users and satisfy the ever-growing user data demand experienced by 4G networks. On the other hand, they should also allow a significant reduction of both the additional operational/capital expenditure and the carbon footprint of the information and communication technology (ICT) infrastructure. In particular, concerning the latter aspect, it is worth observing that CO_2 emissions are expected to grow at a steady 6% rate per year till 2020, unless paradigm-shifting technological advancements are introduced in the ICT infrastructure [18]. Thus, the ICT sector in general, and mobile communication industry in particular, cannot be exempted from reducing their contribution to the global carbon footprint.

However, assuming that the dichotomy between spectral and energy efficiency may pertain only the ICT infrastructure would be a very inaccurate stance. In fact, this dichotomy is clearly present at the user level as well. In this context, the limited battery lifetime of each device acts as an energy bottleneck which constrains its performance, inducing a detriment in the overall perceived quality of experience/service. As a result, the overall user/device experience is affected by both the spectral efficiency of the network and the energy efficiency of the adopted device/terminal. Thus, the design and development of both spectral and energy efficiency solutions both at the network and at the device level will definitely be a non-negotiable necessity for upcoming 5G networks.

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A. *Heterogeneous Networks*

Long-Term Evolution Advanced (LTE-A) already allows operators to employ innovative spectral and energy efficient technologies to complement the physical layer (PHY) of 4G networks. Many PHY solutions currently adopted in LTE-A networks are expected to be part of future 5G networks as well, even though not necessarily in the same form/implementation. Notable examples of such approaches are bandwidth extension through spectrum aggregation, improved multiple-input multiple-output (MIMO) schemes, coordinated multi point (CoMP) transmission and reception, and hybrid usage of multiple radio access technologies (RATs), to name a few.

In this context, the recently observed proliferation of ad-hoc low-power small-cell base-stations (SBS), with the aim to serve areas with high traffic density and improve the coverage, is expected to characterize 5G cellular networks as well. In fact, it is a common belief that multiple RATs based approaches to network planning are going to play an extremely important role to cope with the high spectral and energy efficiency demands of future 5G mobile communications network. The resulting networks will certainly be very heterogeneous and have a hierarchical structure, where the legacy tier of macro-cell base-stations (MBSs) will be underlaid with one or more tiers of SBSs operating according to different duplexing schemes, frequency/time division or full-duplex (TDD/FDD/FD).

This tutorial starts from these observations to illustrate and compare the requirements for an alternative need-oriented deployment model or topology using femto-cells, relays and distributed antennas (DAs) in the so-obtained heterogeneous networks (HetNets). Additionally, it discusses the spectral and energy aware deployment of advanced HetNets, where a plethora of low-power and low-cost user/operator deployed base stations complement the existing macro-cell network. The performance of such networks will be discussed in terms of area green efficiency, area spectral efficiency, energy consumption and savings, carbon dioxide (CO_2) emissions and economics. Parts of the tutorial are planned to cover recent advances in the HetNets area, including emerging technologies and ideas such as Device-to-Device communications, energy efficient communications and cost-effective backhauling solutions.

B. *Energy Efficiency Oriented Solutions*

According to a recent mid-range estimate, the annual electricity consumption of the world's ICT ecosystem (as a whole) is around 1500 TWh. ICT approaches 10% of the current world electricity consumption, or in other terms 150% of what is generated for global aviation. Alternatively, this quantity is equal to all the electric generation of Japan and Germany combined, or again to the consumption of the global illumination system in 1985

[19]. Several state-of-the-art solutions and paradigms have been proposed to achieve the expected future decrease of these figures, all the while guaranteeing the desired spectral efficiency and end-user quality-of-experience increase. In particular, examples of considered candidate remedies are: (i) enhanced BS energy efficiency by improving power amplifier technology; (ii) power saving protocols, e.g., BS sleeping, which enables inactive operation mode for BSs under low load conditions; (iii) schemes such as cell-breathing and cell-zooming, where different cells adapt their size depending on the received interference or traffic load conditions; (iv) renewable energy sources exploitation (especially in the off-grid sites).

Switching the focus to the end device/user, a very promising approach to address the energy scarcity problem has been gaining momentum lately, i.e., the design and implementation of energy harvesting devices, to scavenge energy from ambient heat, light, vibrations and so on. In the context of wireless communications, energy harvesting techniques have grown from long-established concepts into devices for powering ubiquitously deployed sensor networks and mobile electronics [20]. In this regard, a recent research front [21] envisions the idea of harvesting energy from the radio frequency (RF) signals typically used to transmit information and energy simultaneously in a wireless communication. Interestingly, the massive deployment of radio transmitters, which broadcast a significant and controllable amount of RF energy to remote devices, intrinsically provides an abundance of energy sources for harvesting purposes. This could lead to the design of self-sustainable transmissions in which the mobile users would receive both energy and information from the MBSs/SBSs, i.e., by means of the so-called simultaneous information and power transfer (SWIPT), increasing their battery lifetime.

This tutorial illustrates and discusses all the aforementioned aspects both from the network and an end-user perspective. Specific focus is devoted to the design of novel energy-harvesting oriented transceivers and algorithms, and to the introduction of the so-called wireless powered networks (WPN).

II. Objectives and Timeliness

This in-depth tutorial is built upon the expertise of the Authors in advanced strategies for green networks deployment, and focuses on a series of emerging state-of-the-art topics in 5G networks. In particular, it gives comprehensive and balanced coverage of novel technologies that will drive the future network architecture, transceiver and algorithm design. Specific attention will be devoted to the potential application of such tools to achieve the spectral and energy efficiency improvement that is expected from 5G wireless networks. At the dawn of 5G standardization, this is certainly a timely tutorial that aims at further steering the directions of research in view of 5G networks and assist both the academic and industrial community in setting up their future goals and objectives.

This tutorial is suitable for people with a general background on wireless communication technologies. The mathematical content is kept to a level at the reach of graduate level students, researchers and experts from academia and industry. The technical part follows the same logic. In fact, this tutorial is designed to offer a wide range of benefits to a larger set of potential attendees: for instance, beginners can learn about new technologies such as wireless power transfer and full-duplex transceiver design; researchers can understand the extensive theoretical developments in the design of green heterogeneous networks; industrial and academic experts can learn about the energy economics and ecological impacts of the discussed technologies for a sustainable development of telecommunications industry. Thus, we expect that this tutorial will attract both graduate level students, researchers and leading experts from academia and industry as well as anyone who is interested in learning about 5G networks, their deployment issues and current research trends. This has been confirmed by the response during our recently well attended tutorials in IEEE ICC 2014, EUCNC 2015 and IEEE CAMAD 2015.

General features of this tutorial are the following:

- It presents a thorough review of the motivation and the taxonomy of spectral and energy efficient 5G wireless networks;
- It introduces many state-of-the-art techniques, e.g. energy efficiency based on power control, cognitive interference reduction, resource allocation, wireless-powered network architecture and transceiver design, all framed in the context of future 5G networks;
- It presents a comprehensive and detailed comparative study, supported by simulations and illustrative examples of several network deployment configurations;
- It is supported by list of strong references in the relevant areas;
- The slides present a contemporary tutorial type presentation in order to make it understandable to most of the audience;
- The slides include excellent graphical illustrations to highlight the technical description of the system, when necessary, and its implementation;
- Interestingly, the content of the tutorial and its maturity, is such that the tutorial itself can occupy either a half-day (2h 30 minutes) or a full-day (5 hours) slot, depending on both the available slots and the decisions of the organizing committee. In this sense, our proposal is flexible and provides details about both possibilities.

We start by describing the outline of the half-day version.

III. Half-day Format

In this case, the tutorial is organized in 6 parts. Part 1 presents a typical tutorial style coverage on current profile of mobile networks, and significance of energy efficiency in view of the deployment of 5G networks. Part 2 is more focused on the design of energy efficient advanced HetNets; relevant design aspects such as future network architectures and resource allocation algorithms are discussed for different types of HetNets configurations. Part 3 provides an in-depth investigation on the performance analysis of HetNets in terms of area spectral and area green efficiency; the study is supported by detailed comparative results and discussions, with illustrative examples and simulations. Backhaul capacity requirements and energy efficiency of backhaul are also covered. Part 4 discusses the economics and ecology of several configurations of advanced HetNets by presenting some case studies based on regional and national statistics, with special focus on cost savings associated with energy and CO_2 production savings. Part 5 of the tutorial presents a historical and technical introduction of a recent and promising solution to energy-constrained wireless networks, i.e., energy harvesting and the exploitation of the so-called wireless energy transfer. In this context, the concept of wireless powered network is introduced, and its architectures and main paradigms are discussed. Finally, Part 6 introduces the notion of self-sustainable systems and provides relevant case studies, with specific focus on energy-recycling oriented transceiver design for 5G networks, corroborating them with state-of-the-art results on the subject.

A. Schedule

The proposed content of the tutorial in this case is the following:

1) Moving toward spectral and energy efficient 5G Networks (20 minutes)
   - (1.1) Relevance of Energy efficiency in 5G networks
   - (1.2) Cellular traffic classification and profiling and associated carbon footprint of 5G networks
   - (1.3) Taxonomy of main approaches for building Green 5G networks

2) HetNets: From Theory to Practice (20 minutes)
   - (2.1) Introduction to HetNets and types of multi-radios access technologies (femtos, DAs, Relays)
   - (2.2) Benefits and challenges of HetNets (coverage, capacity, offloading, mobility etc.)
   - (2.3) Network deployment strategies (interference, bandwidth partition, user distribution and propagation models)
3) Spectral and Energy Performance Analysis (20 minutes)
   - (3.1) Performance analysis based on area green efficiency (AGE) and area spectral efficiency (ASE) for HetNets
   - (3.2) End-to-end breakdown of total power consumption including uplink and downlink
   - (3.3) Backhaul capacity requirements and backhaul energy efficiency (BEE)
4) Economics and Ecology of HetNets (20 minutes)
   - (4.1) Reduction in CO_2 emissions (CO_2 emissions forecast till 2020)
   - (4.2) Low Carbon Economy Index Evaluation for several cellular topologies
   - (4.3) Cost Savings associated with energy and CO_2 emissions savings
   - (4.4) Overview of Capital and Operational Expenditure (CAPEX and OPEX)
5) Wireless Energy transfer (WET): introduction (20 minutes)
   - (5.1) Energy harvesting for 5G networks
   - (5.2) Historical introduction to WET
   - (5.3) Technical introduction and circuit design for WET
   - (5.4) Practical challenges for WET
   - (5.5) Architectures and Paradigms for wireless powered networks (WPN)
6) Self-sustainable systems and energy recycling strategies (50 minutes)
   - (6.1) Self-sustainable transmissions: the case of orthogonal frequency division multiplexing (OFDM)
   - (6.2) Energy recycling strategies: case studies (single- and multi-antenna settings)
7) Conclusions

Alternatively, if the format of the tutorial will be full-day, the structure would be the one detailed in the following section.

IV. Full-day Format

In this case, the tutorial is organized in 8 parts. Part 1, Part 2 and Part 3 are a broader version of their half-day counterparts. Part 4 covers emerging device-centric architectures and techniques for 5G, including device-to-device D2D communications, caching and its impact on the energy consumption/efficiency of future 5G networks. Part 5 presents a broader version of Part 4 of the half-day tutorial. In particular, it discusses the economics and ecology of several configurations of advanced HetNets by presenting some case studies based on regional and national statistics, with special focus on cost savings associated with energy and CO_2 savings. Part 6 of the tutorial presents a historical and technical introduction of a recent and promising solution to energy-constrained wireless networks, i.e., energy harvesting and the exploitation of the so-called WET. Part 7 is entirely devoted to the detailed introduction of WPN, encompassing aspects such as possible WPN architectures, design paradigms, resource allocation and scheduling algorithms, MAC and routing protocols. Finally, Part 8 presents a broader version of its half-day counterpart, i.e., Part 6 of the half-day tutorial. Specifically, it introduces the notion of self-sustainable systems and provides relevant case studies, with specific focus on two different applications: self-sustainable OFDM communications and energy-recycling oriented transceiver design for 5G networks. State-of-the-art results on the subject are presented to corroborate the theoretical definitions and notions.

A. Schedule

The proposed content of the tutorial in this case is the following:

1) Moving toward spectral and energy efficient 5G Networks (30 minutes)
   - (1.1) Relevance of Energy efficiency in 5G networks
   - (1.2) Cellular traffic classification and profiling and associated carbon footprint of 5G networks
   - (1.3) Taxonomy of main approaches for building Green 5G networks
   - (1.4) Competition and demand (present green profiles, future trends and challenges)
2) HetNets: From Theory to Practice (30 minutes)
   - (2.1) Introduction to HetNets and types of multi-radios access technologies (femtos, DAs, Relays)
   - (2.2) Benefits and challenges of HetNets (coverage, capacity, offloading, mobility etc.)
   - (2.3) Network deployment strategies (interference, bandwidth partition, user distribution and propagation models)
   - (2.4) Uplink and downlink power control schemes and their usage
3) Spectral and Energy Performance Analysis (30 minutes)
   - (3.1) Performance analysis based on area green efficiency (AGE) and area spectral efficiency (ASE) for HetNets
   - (3.2) End-to-end breakdown of total power consumption including uplink and downlink
   - (3.3) Backhaul capacity requirements and backhaul energy efficiency (BEE)
   - (3.4) Interference management analysis and comparisons for several configurations
4) Green Device-Centric Architectures and Techniques (30 minutes)
   - (4.1) Device Centric communication
   - (4.2) Options to extend the battery life-time of a mobile device in a wireless network
   - (4.3) Cognitive small-cells: Interference reduction and adaptive beamforming
   - (4.4) Caching in D2D communications
5) Economics and Ecology of HetNets (30 minutes)
   - (5.1) Reduction in CO_2 emissions (CO_2 emissions forecast till 2020)
   - (5.2) Low Carbon Economy Index Evaluation for several cellular topologies
   - (5.3) Cost Savings associated with energy and CO_2 emissions savings
   - (5.4) Overview of Capital and Operational Expenditure (CAPEX)
6) Wireless Energy transfer (WET): introduction (30 minutes)
   - (6.1) Energy harvesting for 5G networks
   - (6.2) Historical introduction to WET
   - (6.3) Technical introduction and circuit design for WET
   - (6.4) Practical challenges for WET
7) Wireless powered networks (WPN) (20 min)
   - (7.1) Architectures and Paradigms for WPN
   - (7.2) Design of WPN (Resource allocation, scheduling, cognitive radio networks)
   - (7.3) Protocols for WPN (MAC, Routing)
8) Self-sustainable systems and energy recycling strategies (1 h and 40 minutes)
   - (8.1) Battery-less devices: myth or reality?

(8.2) Self-sustainable transmissions: the case of OFDM
(8.3) Energy recycling strategies: case studies (single- and multi-antenna transceiver design)

9) Conclusions

V. PREVIOUS EXPERIENCE

A. Tutorials

2015 M. Maso and M. A. Imran, *Advanced Green Networks: New paradigms for energy and spectral efficient network design*, invited tutorial at IEEE CAMAD 2015, Guildford, UK, Sep. 2015

2015 M. Maso and K. Tourki, *Energy management for 5G Networks: Self-sustainability and Energy Recycling*, EUCNC 2015, Issy les Moulineaux, France, Jun. 2015

2014 M. Z. Shakir, D. L.-Perez, M. A. Imran, and K. A. Qaraqe, *Small Cells: Capacity, mobility and energy efficiency perspectives*, in IEEE Intl. Conf. Communs., ICC 2014, Sydney, Australia, Jun. 2014, Technically sponsored tutorial by IEEE ComSoc TCGCC.

2014 M. A. Imran and A. Imran, *Self-Organization: An enabler for Energy Efficient operation of 5G Cellular Systems and Beyond*, WCNC 2014, Istanbul, Turkey, Apr. 2014.

2013 M. Z. Shakir, M. A. Imran, and K. A. Qaraqe, *Green Heterogeneous Small-cell Networks*, (IEEE PIMRC '2013), London, United Kingdom, 8-11 Sep. 2013, Technically sponsored by IEEE ComSoc TCGCC.

2013 M. Z. Shakir, and M. A. Imran, *Energy and Spectral Efficient Design for HetNets*, 1st International Conference on Communications and Signal Processing, (ICCSPA 2013), Sharjha, UAE, 11-13 Feb. 2013.

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