Green Mobile Networks: from 4G to 5G and Beyond

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Summary

In order to comply with the Paris Agreement and the European Green Deal, the communication community has recognised the network energy efficiency as a fundamental and urgent aspect, to make the communication network sustainable. In line with this, 5G systems aim at consuming a fraction of the energy consumption of 4G mobile networks, even if the amount of traffic which 5G networks are supposed to manage is much larger than in 4G ones. In addition, discussions about 6G networks have identified 1 Tbit/W as the energy efficiency constraint for the next generation of Radio Access Networks (RANs).
For this reason, several research efforts have been put in the transition towards more sustainable and energy efficient RANs. To this aim, energy reducing strategies are often implemented in these networks to reduce the energy consumption, by dynamically adapting the available radio resources to the varying user demand. Besides the reduction of the absolute value of the energy consumption of telecommunication networks through this dynamic resource allocation, a trend in networking considers the Renewable Energy Sources (RES), adopted to power the Base Stations (BSs) of the RANs, reducing the amount of energy that has to be purchased from the power grid, which is the key contributor for the increase of the Operational Cost. Besides the RAN energy efficiency, the next generation of networks is envisioned to expand the existing mobile networks, achieving ultra-low delays, extensive coverage, as well as ultra-high reliability. In order to reply to these requirements, the Multi Access Edge Computing (MEC) paradigm has been introduced: it pushes computing and storage resources in physical

proximity of end users, placing servers on the edges of the network. In RANs, these servers are co-located on BSs, which provide storage and computation services, in addition to access services. At the same time, the aerial network has been identified as the complementary infrastructure to the terrestrial 5G RAN. It relies mainly on Unmanned Aerial Vehicles (UAVs): mounting a BS on UAVs (UAV-BS) has been proposed as a promising solution to dynamically deploy fast and flexible communication facilities, where traditional ground infrastructures are not feasible or cost-effective. Through the additional capacity provided by UAV-BSs, connectivity is brought to the users that are suffering from low-quality service.

The contribution of this thesis consists in designing, analysing and evaluating high energy efficient RANs, in the 4G environment and investigating various critical issues raised by the introduction of the MEC technology and the UAV-BSs, pillar technologies for 5G and beyond RANs.

As mentioned, the RAN management based on the BS switching is one of the most studied approaches to reduce the heterogeneous RAN energy consumption. It is based on the sleep mode of BSs. In particular, when it is used, a BS is switched to sleep mode, in case its traffic demand is low. Alternatively, in case the RAN is supplied by a RES system, the BS switching decisions are based on the amount of available renewable energy, which is locally produced. In particular, a BS is put in sleep mode, when that quantity is not sufficient for the network supply, to minimise the energy which has to be purchased from the grid. The decisions for the BS switching are driven by the future traffic demand and/or the future renewable energy production and assuming them perfectly known is an optimistic and unrealistic assumption. In this thesis, this assumption is overcome, through the employment of Machine Learning (ML) algorithms for their prediction. First, a clear understanding of the effects on the network operation of the introduction of ML algorithms for the forecast of future traffic and/or the PV panel production is provided. Results, obtained through simulations, reveal that they are suitable for this application and allow to achieve significant energy saving. Nevertheless, the achieved energy saving strongly depends on the traffic pattern. For this reason, ML approaches are necessary, since they are a versatile framework, which adapts the network operation to the traffic characteristics typical of each area and to its evolution, which cannot be performed autonomously and that needs continuous updates to follow traffic pattern variations. Nevertheless, QoS may be compromised because of incorrect BS deactivation, with a limited sensitivity to the type of ML algorithm, which is used. This is because critical BS (de)activation decisions are taken in correspondence of specific traffic values, and high accuracy in the estimations is not required in general, but only close to the values which trigger a BS switching. For this reason, traffic predictions performed over a shorter time scale, combined with a careful processing of the predictions are proposed, resulting in very effective improvement in RAN energy saving and QoS. The processing of the predictions aims at detecting the overall trend of the traffic profile and combining predictions at different time lags. They result more impacting on the achieved RAN energy efficiency and QoS than the careful selection of the traffic predictor. Up to 40% energy saving is achieved, while having good Quality of Service (QoS), i.e. no more than 1.5% of lost traffic, with the proposed methodologies, which highlight the fundamental role of the macro cell BSs in hierarchical RANs, in order to provide the adequate QoS, while reducing the network energy consumption. The impact of the BS switching on the BS failure rate is also analysed in this work. To do this a failure rate model is employed, which accounts for the time a BS spends in sleep mode, which saves the BS from deterioration, as well as for the BS switching frequency, which is harmful for its HW components. The actual impact of the combination of these two phenomena depends on the HW components of the BS, as well as on the RAN management strategy. Results reveal that when the BS is sensitive to switching, more conservative resource allocations should be employed to better prevent BSs from HW failure, while less strict switching conditions can be applied, in case the switching of a BS is not costly.

The study investigates via simulation the effect of the introduction of the MEC paradigm in the RAN, focusing on its simultaneous employment with BSs switching for the RAN energy efficiency. The MEC servers need energy for their supply, while BS switching deactivates RAN resources and, as a consequence, also these MEC platforms. The impact of the MEC server capacity, as well as of the traffic characteristics, on the RAN performances is analysed. Results show that caching at the edge and the dynamic activation of the BSs is promising in reducing latency and the network energy consumption, respectively, without deteriorating their performances because of their coexistence, achieving up to 60% of delay drop, without generating significant growth of the network energy consumption, limited to 7%. In addition, the issue related to the spread of the cache capacity among the BSs in heterogeneous RAN is addressed. Caching on the macro BSs is always needed to significantly reduce delays, while caching also on the micro cells relieves the effort on the macro cell. Moreover, in order to maximise the benefits provided by the MEC technology usage, ensuring also the achievement of the network energy efficiency, different association policies are proposed, which minimise the RAN energy consumption and/or the experienced delay, further reducing the RAN energy consumption and the experienced delay by 27% and 10%, respectively. Because of the high complexity of the problem, we propose a greedy approach for its resolution. This is strictly necessary, since the association procedure is performed while the system is operating, which means that a solution is needed on the fly.

Finally, UAVs equipped with BSs (UAV-BSs) are considered in this thesis, to dynamically provide additional capacity, in case of terrestrial RAN unavailability. In this scenario, UAV-BSs adapt their aerial position where needed, based on position and traffic requirements of users, who are connected to the UAV-BSs through access links, while UAV-BSs are connected to the Core Network, establishing BH links between them and an Access Point. The evaluation of this scenario reveals that UAV-BSs need frequent replacement because of the scarce on-board energy availability on UAV-BSs, provided by on-board batteries. In addition, simulations show that the BH network often saturates, due to its low available bandwidth, which limits its capacity and significantly deteriorates the network QoS. To cope with the latter, we use the MEC paradigm, to cache popular contents on each UAV-BS and decrease the occupancy of the BH network. It results effectively, reducing the lost traffic by 33%. In order to address the former issue, we consider a solar-powered UAV-BSs. The model of a Long Term Evolution (LTE) Multi User (MU)-Multiple Input Multiple Output (MIMO) UAV-BS, powered by an on-board PV panel, is formalised, using the queuing theory, to derive the energy production levels that are needed to satisfy the traffic demand, the probability to waste energy and the proper PV panel capacity. This work investigates the energy efficiency in RANs, addressing various critical issues raised in the 4G and 5G and beyond eco-system. The BS switching and the RES power supply, supported by ML algorithms and properly designed in order to prevent BSs from HW failure, has emerged as an effective and feasible solution, to improve the energy efficiency of the RANs and UAV-BS networks, resulting also suitable to coexist with the MEC paradigm.