**Cutting-edge enablers for a sustainable evolution towards 5G and beyond networks**

The transition towards the 5G era is leading to an extensive radio access network (RAN) densification, raising relevant sustainability concerns due to the huge increase of the network energy consumption and to the installation of new infrastructures, that may result underutilized for long periods of time, with a consequent relevant increase of operational cost and capital expenditures for Mobile Operators (MOs). In this context, traditional and consolidated solutions that are typically implemented to promote energy efficiency in communication networks, including the integration of Renewable Energy (RE) sources and the design of Resource on Demand strategies, may not be suitable to effectively address peculiar sustainability concerns and challenges emerging in 5G and beyond scenarios. Indeed, these scenarios feature a high degree of complexity, with new potential vulnerabilities emerging that may impair the provisioning of resilient communication services, jointly with constraints that make the network densification critical, especially in urban environments.
In order to properly tackle specific sustainability challenges arising in 5G and beyond scenarios, two main research paths should be undertaken, that are extensively discussed in this tutorial.

First, traditional sustainability enabler solutions should be revisited and tailored to the novel specific challenges and requirements that characterize 5G ecosystems, also leveraging new functionalities of 5G base stations, like the Advanced Sleep Mode features, and envisioning the integration of Artificial Intelligence algorithms to optimize energy utilization and resource management. Moreover, with the relevant increase of RAN energy demand, MOs become relevant stakeholders for the Smart Grid Operators (SGOs), hence new opportunities arise for a jointed cooperation with the Smart Grid to pursue sustainability and resilience goals, especially in the context of Demand Response programs.

Second, brand-new approaches based on cutting-edge technologies should be devised and integrated in the design of future communication networks to jointly pursue sustainability goals, in terms of greener RAN operation, capital (CAPEX) and operational (OPEX) cost decrease, enhanced feasibility, and to promote resilience to new emerging vulnerabilities.
In particular, the novel paradigm of Vertical Heterogeneous Network can be exploited leveraging the integration of 5G-enabled aerial network nodes in terrestrial radio access networks for sustainability purposes, including both High Altitude Platform Stations (HAPSs) and renewable powered Unmanned Aerial Vehicles (UAVs). Indeed, the integration of aerial nodes in highly populated areas characterized by dense terrestrial networks as a mean to flexibly provide additional capacity and to support joint energy and resource allocation strategies that will be needed in 5G and beyond networks represents an outbreaking approach to enforce sustainability in RANs.
Furthermore, the opportunity of new business models enabled by the flexibility that charachterize 5G and beyond ecosystems should be seized to tackle sustainability and resilience challenges. Specifically, approaches based on sharing the network infrastructure among different mobile operators look promising to enhance the resilience of future mobile networks, and to reduce not only operational costs, but also to limit the CAPEX faced by MOs to install new proprietary network nodes based on 5G technology. In addition, novel multi-level cooperation models between MOs and the Smart Grid -based on inter-technology and inter-service approaches- are explored as effective means to achieve mutual benefits for MOs and the Smart Grid Operators, trading off possibly conflicting goals. Indeed, besides contributing to grant a sustainable RAN operation, these cooperation models enable an effective provisioning of ancillary services, promote a better utilization of distributed renewable energy sources, and enforce resilience in both communication and power systems.