From self-sustainable Green Mobile Networks to enhanced interaction with the Smart Grid

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From self-sustainable Green Mobile Networks to enhanced interaction with the Smart Grid

Daniela Renga
Department of Electronics and Telecommunications
Politecnico di Torino
Italy
daniela.renga@polito.it

Michela Meo
Department of Electronics and Telecommunications
Politecnico di Torino
Italy
michela.meo@polito.it

***Abstract*—Due to the staggering increase of mobile traffic, Mobile Network Operators (MNOs) are facing considerable operational cost due to power supply. Renewable Energy (RE) sources to power Base Stations (BSs) represent a promising solution to lower the energy bill, but their intermittent nature may affect the service continuity and the system self-sufficiency. Furthermore, in the new energy market dominated by the Smart Grid, new potentialities arise for MNOs in a Demand Response (DR) framework, since they can dynamically modulate the mobile network energy demand in accordance with SG requests, thus obtaining significant rewards. This work proposes various stochastic models to reliably and accurately characterize the RE production and the operation of a green mobile network, also analyzing the impact of parameter quantization on the model performance. The RE system dimensioning is investigated, trading off cost saving and feasibility constraints, and evaluating the impact of Resource on Demand (RoD) strategies, that allow to achieve more than 40% cost reduction. Finally, by exploiting RoD and WiFi offloading techniques, various energy management policies are designed to enhance the interaction of a green mobile network with the SG in a DR framework, leading to fully erase the energy bill and even gain positive revenues.**

I. Introduction

The staggering increase of the mobile traffic is leading to the deployment of denser and denser cellular access networks. By 2021 the number of networked devices might become as high as more than 12 per capita, with the mobile traffic raising of a factor seven in just a few years [1]. Furthermore, the incoming 5G technology is going to dominate the future scenario in the Smart City context, allowing to support new challenging functionalities, like ubiquitous fast speed Internet access, urban mobility, huge capacity demanding services, just to mention some. Considering that 80% of the total energy consumed in mobile networks is required just to operate the access segment, Mobile Network Operators (MNOs) are facing huge operational cost due to power supply, and this cost is bound to further rise at a fast rate in the next years [2]. Therefore, several research efforts are devoted to make mobile networks more energy efficient, in order to reduce costs and improve sustainability. To this aim, Renewable Energy (RE) sources are widely adopted to power base stations (BSs), making the mobile network more independent from the electric grid [3]. Nevertheless, the intermittent nature of RE generation must be properly addressed in order to guarantee the continuity of service. In particular, some storage must be envisioned to harvest any extra amount of energy that is not immediately used, and make it available during periods of low or null RE generation. Clearly, the RE generation system must be properly dimensioned in order to guarantee the desired level of network self-sustainability, as well as an adequate energy supply to match the network demand, whose profile dynamically varies over time depending on the mobile traffic volume, and that does not necessarily follow the RE generation pattern. Some studies in the literature analyze the behavior of the energy storage under different settings of photovoltaic (PV) panel size [4]–[7]. Nevertheless, they usually do not consider a systematic approach to the dimensioning problem, allowing to trade off all the constraints on cost, service availability, self-sustainability and feasibility in a complex network scenario.

Furthermore, the use of RE sources as power supply for mobile networks requires a proper energy management, capable to balance energy saving, operational cost and network reliability. In addition, the effect on operational cost saving introduced by using RE to power BSs may further benefit from the application of resource management techniques [8]–[11]. However, cost analysis performed in available studies does not usually include the evaluation of capital expenditures due to the installation of PV panels and battery, and the operational cost related to system maintenance and battery replacement.

Finally, the use of RE in mobile networks poses new challenges in view of the brand new scenarios that are taking shape with the widespread Smart Grid (SG) paradigm, envisioning several distributed energy producers. With the new generation electric grid, an active interaction can be enforced between the utility operator and its end users. To this extent, SG Operators (SGOs) commonly deploy Demand Response (DR) policies to address the demand-supply unbalance, providing users monetary incentives to shift their energy demand from high to low peak periods. In this context, MNOs can become prominent stakeholders, since they can dynamically modulate the mobile network energy demand in accordance with the needs of the SG, thus contributing to the SGO objectives and obtaining significant reductions of the energy bill [12]. The potentiality of the interaction between the green mobile network and the SG to decrease the energy bill is not yet well investigated in the literature [13].

II. Contribution

The research at the basis of this study is focused on investigating some critical issues affecting mobile networks powered by solar energy. Another relevant objective is to deploy and analyze the effects of various energy management techniques on improving the energy self-sufficiency of green mobile networks and their interaction with the SG, in order to cut down the high operational cost of MNOs.
When PV panels are employed to power mobile networks, simple and reliable RE production models are needed to facilitate the system design and dimensioning. After a description of the RE generation system in Sec. IV-A, a simple stochastic model of the daily RE production is proposed and validated in Sec. IV-B. In addition, properly designed models are required to accurately represent the complex operation of a renewable powered mobile access network, where electric loads vary with traffic demand, and some interaction with the Smart Grid can be envisioned. To this purpose, various stochastic models based on discrete time Markov chains are designed and presented in Sec. IV-C. The effects of parameter quantization are also analyzed in Sec. IV-D, deriving proper settings to build an accurate model. Clearly, the introduction of RE to power mobile networks entails a proper system dimensioning, in order to balance the solar energy intermittent production, the traffic demand variability and the need for service continuity. Whereas several studies focus on the use of RE to power BSs, and real installations are extensively deployed worldwide [3], the system dimensioning issue does not result well investigated. This study analyzes via simulation the RE system dimensioning in a mobile access network, trading off energy self-sufficiency targets and cost and feasibility constraints (Sec. V). Furthermore, in a green mobile network scenario, MNOs are encouraged to deploy strategies allowing to further increase the energy efficiency and reduce costs. This study aims at analyzing via simulation the impact of Resource on Demand (RoD) strategies on system dimensioning, energy saving and cost reduction in green mobile networks (Sec. VI). Finally, the use of RE contributes to give MNOs the opportunity of becoming active players in the Smart Grid environment. By enrolling for a DR program, MNOs can accomplish requests from the SG, that periodically asks its users either to increase or decrease their consumption, thus providing ancillary services to the SGO. In return, MNOs receive monetary rewards for doing so, hence decreasing the related energy bill. This study proposes different energy management policies aiming at enhancing the interaction of the mobile network with the SG, both in terms of energy bill reduction and increased capability of providing ancillary services. Besides combining the possible presence of a local RE system with the application of RoD policies, the proposed energy management strategies envision the implementation of WiFi offloading (WO) techniques in order to better react to the SG requests. Indeed, some of the mobile traffic can be migrated to nearby Access Points to accomplish the requests of decreasing the consumption from the grid. The interaction with the SG is investigated through a Markovian model and via simulation. The performance analysis is presented in Sec. VII. Only some results obtained from this work are described in this paper for sake of brevity. The extended results can be retrieved in publications that are cited throughout the paper and can be found in the References [10], [12]–[20].

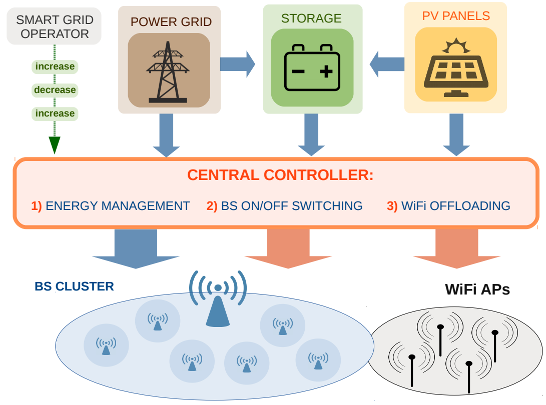


Fig. 1: The green mobile access network structure.

III. Renewable-powered mobile network scenario

The scenario considered in this work, shown in Fig. 1, consists of a small geographical area where the Internet mobile access is provided by a macro Long Term Evolution (LTE) BS, providing baseline coverage, whereas m additional micro BSs allow to locally increase the capacity in case of peak demand. Blue arrows represent energy flows. The cluster of BSs is connected to the electric grid for power supply; in addition, it can be powered by locally installed PV panels. To face the RE production intermittence, the system is equipped with some storage units, where the extra amounts of produced RE can be harvested and used when solar energy is not available. In some cases, the storage may be used to harvest energy drawn from the grid. An active interaction with the SG in a Demand Response framework may be envisioned. Hence, the mobile access network can exploit various techniques to adapt its energy demand from the grid to the SG requests of increasing or decreasing its consumption (green arrow), in order to reduce its cost, thanks to the rewards provided by the SGO for satisfying its requests. For energy saving purposes, or in order to enhance the capability of responding to the SG requests, a RoD can be applied, by dynamically switching off unneeded micro BSs when the traffic demand is low. This approach allows to adapt the overall energy consumption to the actual traffic load, making it more load proportional. Furthermore, nearby WiFi Access Points may be exploited to transfer some of the traffic from the micro BSs, in order to reduce the load of the mobile access network and better answering the requests from the SG. A central controller is in charge of handling the communication and power exchanges between all the system components and managing the RoD and WiFi offloading techniques (orange arrows), when they are applied.

IV. Modeling the green mobile network

The proposed modeling of the RE generation and of the operation of the green mobile network are here described.

A. Renewable energy generation system

The cluster of BSs is equipped with a set of PV panels, made up by modules built with crystalline silicon technology and showing a maximum efficiency of 20% [21]. A nominal capacity of 0.2 kWp per m^2 of PV panel surface is assumed [5]. The characterization of the RE production has been performed by using real RE generation profiles obtained from PVWatts [22]. The tool provides, on an hourly basis and for a given location, the average levels of RE power production obtained from a standard PV panel with capacity of 1 kWp during the typical meteorological year (TMY). To derive the results reported in Sec. IV-D, irradiation data have been obtained from traces available in the Solar Radiation Data (SoDa) web service [23]. The mobile network is equipped with a variable number of lead-acid batteries, that are commonly adopted in PV systems for harvesting purposes. Storage elements with capacity 200 Ah and voltage 12 V are assumed, with estimated charging/discharging efficiency of 75% [24]. A tight constraint of maximum Depth of Discharge (DOD) $\leq$50-70 is recommended in RE systems, due to the possibly very slow and irregular recharge, in order to prolong the battery lifetime [24].

B. Modeling the solar energy production

The variability of the RE generation over time, which is location dependent, highly affects the system performance in terms of energy self-sufficiency of the network and resiliency to power outages. Furthermore, a proper system dimensioning should be based on a reliable characterization of the RE production profile. In this study, the renewable energy production has been modeled in different ways, depending on the aspects of the green mobile network system that had to be investigated. In some cases real traces about RE production have been employed as input data for simulations. This Section, focusing on the PV powering system of a BS that is part of a mobile network, proposes a simple stochastic model of the energy produced by PV panels of relatively small size in the city of Turin, investigating the impact of the energy generation variability on the power supply system performance. Only two parameters are sufficient to characterize the renewable energy generation in any location, by means of a random variable with a mean value and a variance, denoted RE_p and representing the local daily peak production. The daily RE production is derived as $RE_p \cdot f_N(t)$, where $f_N(t)$ is the shape function representing the normalized typical production profile of a day, that is scaled by RE_p to obtain the RE generation daily variability. This model is representative of the RE generation at latitudes showing low intra-day weather variability, and it can be applied at different time scales (daily or hourly production). Results obtained under several settings of RE system demonstrate that the mean and variance of the random variable representing the daily RE production per kWp of PV panel capacity, denoted as RE_d, allow to accurately predict the system performance in terms of probability of battery depletion and energy demand from the grid. Here we report some highlights about the proposed model. Further details end results can be found in [14].

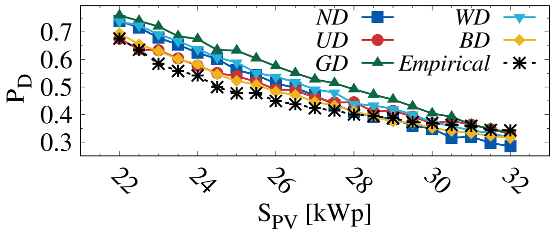


Fig. 2: Depletion probability, P_D, under various types of distribution for RE_d.

The RE model has been validated by considering different distribution functions to characterize the random variable representing the RE daily generation per kWp of PV panel capacity, RE_d. Normal (ND), uniform (UD), Gamma (GD), Weibull (WD), and Beta (BD) distributions, that are commonly used in the literature to represent the RE production [14], have been tested via simulation under multiple combinations of RE_d mean value and variance. The depletion probability of the battery, denoted as P_D, is reported in Fig. 2 for increasing PV panel capacity, denoted S_{PV}, under various distributions of RE_d, and it is compared against the values obtained under the Empirical distribution (EM), derived from real traces of sun radiation in Turin. The results obtained under UD and BD result close to those obtained under ED, and outperform ND, WD and GD, unless extremely large S_{PV} are considered. The UD can hence be adopted to reliably represent solar energy generation, avoiding the computational complexity that other distributions, like GD, may entail.

Our results also show the relevance of the variability of RE generation. The average daily grid demand obtained considering a UD of RE_d and varying PV panel sizes, results often negligible for low variance values of RE_d, whereas it becomes larger as the variance increases, with sharper ascent for smaller RE_d. Nevertheless, for low RE_d of about 1 kWh, the produced RE is never enough, under any variance, to make the BS energy self-sufficient, unless by increasing the PV size: in fact, even with very low variance, some amount of energy must be required from the grid.

C. Stochastic models for the mobile access network operation

Stochastic models allowing to analyze the operation of a green mobile access network typically represent the state of the battery charge over time, that changes depending on the RE production, on the varying network energy demand, and varies according to the RE availability, based on the dynamic variations of the mobile network energy demand and the application of energy management. Results presented in this work about the mobile network performance have been obtained by using simulation tools and different Markovian models, that have been designed featuring different connotative characteristics depending on the aspects they are focused on and on the main investigation objectives they aim to achieve. The Markovian model proposed in [17] represents the operation of a RE powered BS, taking into account the variability of weather conditions from day to day. Each state is represented by three state variables: battery charge level, daytime, day type (based on weather conditions). It is employed to study the effects of parameter quantization on the design of RE power systems for cellular BSs (Sec. IV-D). A simple 3-state Markov chain model (each state representing the battery charge at the beginning of the day) has been deployed to analytically study the RE dimensioning problem (results not reported) for a single BS. Finally, a more complex Markovian model, described in [13], is deployed to represent the operation of a green mobile network to study the application of RoD strategies to modulate the consumption and it is suitable to investigate the interaction of the cellular network with the Smart Grid in a Demand Response framework (Sec. VII). Each state is defined by the battery charge level, the period of the day (night, morning, RE peak production period, afternoon, evening) and the type of SG request. Real data from the tool PVWatts are used to specifically derive the probability density functions of RE production per each day type [17] or per day period [13]. Real traffic traces provided by an Italian mobile operator are considered, both from Residential (RA) and Business (BA) areas [15]. The BS energy consumption, that depends on the dynamically varying traffic load, is derived according to the EARTH model proposed in [2].

D. Quantization issue

The configuration of quantization settings for the parameters defined in the models presented earlier may affect the outcome of the system performance investigation, although the effects of discretization are not well investigated in the literature. In our work, the quantization issue was investigated for various parameters, i.e. time, weather, and energy storage, by means of a Markovian model representing the operation of the green mobile system. According to our findings, a time granularity of 1 hour is sufficiently accurate in catching the intra-day variations of energy production and consumption in a green mobile network. Each day can be classified based on weather conditions considering 5 to 7 equi-probable levels of average daily solar irradiance. The energy and storage quantization step should be 1/5 of the minimum amount of energy consumed in a time slot. The complete results, not reported for the sake of brevity, can be found in [17].

V. System dimensioning

The RE generation model described in Sec. IV-B has been applied to study the relationship between the RE generator sizing and a green mobile system performance in terms of battery depletion probability. Fig. 3 reports the battery depletion probability, P_D, versus the value of M, denoting the daily peak renewable power production, under a normal distribution of RE_d, with coefficient of variation 16%. Let us denote B the storage capacity of the set of battery units. For $B \geq 18kWh$,

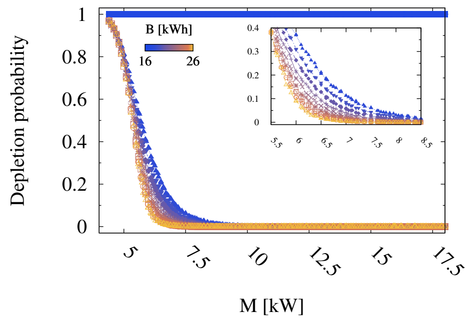


Fig. 3: Battery depletion probability versus RE production level for different battery capacity values.

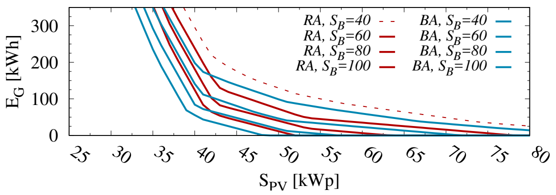
P_D tends to be very high for low M. As M increases, P_D decreases in a sharp way, although the growth is more gradual in case of higher coefficient ov variation (data not reported). At some point, for sufficiently high values of M, P_D becomes very close to 0. The battery size shows a relevant impact on P_D only in case of mid to low RE production. Higher coefficient of variations generally requires larger PV panels to reduce P_D. Additional results and extended discussion related to this topic can be retrieved in [14], [15].

VI. Resource on Demand for cost reduction

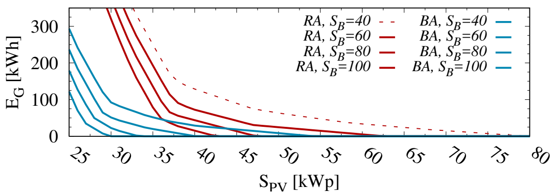
The impact on RE system dimensioning and cost of energy saving techniques applied to green mobile networks is here investigated. A renewable powered mobile access network consisting of a macro BS and 6 micro BSs is considered. The effect of a Resource on Demand strategy based on BS on/off switching during periods of low traffic is analyzed, under several different settings of system dimensioning and traffic distribution. The details of this strategy and the complete description of the experimental setting and simulations can be found in [15]. Fig. 4 shows the total energy yearly drawn from the grid, E_G, for increasing PV panel size, S_{PV}, either without any RoD strategy (Fig. 4a) and under RoD (Fig. 4b). Each curve represents a different battery capacity in terms of number of storage units, denoted S_B, both in RA and BA. In general, for the case without RoD, E_G decreases with the panel size, especially for lower S_{PV}, and larger batteries allow to reduce E_G. E_G can be decreased below 50 kWh only for $S_{PV} > 40kW_p$, Under RoD E_G is considerably reduced for any PV size. Noticeably in RA, $E_G < 50$ kWh can be provided with much lower S_{PV} than in BA.

A. Renewable system cost and feasibility

Fig. 5 reports the yearly cost, denoted as c, versus some target values of the percentage of time slots (0.5 hours) in which energy is requested to the grid, indicated as $f_{G_{Max}}$, in the baseline scenario (all BSs are kept active) in the RA. The required capacity of the PV panel, S_{PV}, is reported on the secondary y-axis. The cost c includes capital expenditures (for the PV panel and battery installation) and operational cost for electricity bill and the RE system management cost. In



(a) No RoD



(b) Under RoD

Fig. 4: Yearly grid energy, E_G, versus S_{PV} in Residential and Business area (RA and BA), for different storage sizes.

case $f_{G_{Max}} = 0$, no energy is bought from the grid; in case $f_{G_{Max}} = 1\%$, up to 1% of the times energy can be purchased from the grid. The most relevant contribution in reducing the PV panel capacity, hence improving the system feasibility in terms of area occupancy, and in terms of c reduction is achieved by slightly relaxing the constraint on f_G from a completely self-sustainable system to $f_G < 1\%$, with up to 41.3% reduction in S_{PV} and in the physical area occupancy, and a corresponding decrease in cost. Conversely, further lessening the constraint on f_G does not provide significant additional benefits. The introduction of a RoD strategy reduces the energy consumption by up to 26% and c by up to 39%, resulting more effective in the BA rather than in the RE. This is due to the coupling between the BA traffic patterns and the RE generation profiles, that show their peaks in the central hours of the day.

VII. Enhancing the Interaction with the SG

The interaction of a renewable powered mobile access network with the Smart Grid is now investigated. We assume that the MNO participates in the Demand Response program deployed by the SG, with the twofold objective of obtaining a reduction of the energy bill and contributing in providing ancillary services. In order to accomplish the requests coming from the SG to adapt the user load to the actual energy supply, the MNO may operate in different ways. In case the SG is asking to decrease the consumption (DOWN request - D), the MNO can exploit the presence of a local RE generator to power the BSs, either using the solar energy currently produced by PV panels or drawing from the storage the previously harvested energy. In addition, it can exploit the application of energy saving techniques, like RoD or WiFi offloading, to reduce the energy network demand. Conversely, if an increased energy consumption is required by the SG (UP request - U), the MNO can positively react only if a storage is locally present, allowing to draw from the grid an extra amount of energy to be stored in the battery for future usage.

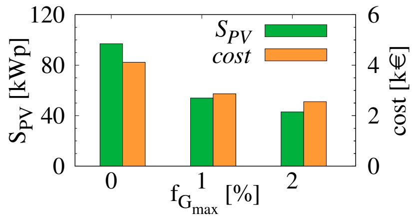


Fig. 5: S_{PV} and c without RoD for various constraints on f_G.

Various energy management strategies have been designed, that variously combine the different proposed approaches to respond to the SG requests. Their effectiveness in providing ancillary services to the SGO and in reducing MNO cost has been evaluated via simulation and by means of the Markovian models proposed in Sec. IV-C. Real data have been used for energy pricing and Smart Grid requests [13], [20]. The corresponding algorithms and the complete performance analysis are extensively detailed in [12], [13], [19], [20].

A. Ancillary service provisioning

The use of RE, RoD and WO contribute to enhance the capability of providing ancillary services. The probability of responding to requests of type D, denoted P_D, increases as the PV panel size grows larger, whereas the probability of responding to requests of type U, denoted P_U, decreases. P_D is favored by the application of RoD, raising up to 95%, whereas P_U shows an opposite behavior. Under WO, up to almost 75% of D requests can be satisfied in our scenario even when no RE is locally produced. The introduction of a small RE generator equipped with some storage remarkably improves P_D, the probability of positively reacting to any SG requests, that becomes close to 1 under larger RE generators. An extended dissertation about this topic and the volumes of traded energy are exposed in [12], [13], [19], [20].

B. Cost saving

The cost for system operation, normalized with respect to the baseline cost that should be paid in case all the cluster energy demand were bought from the grid, has been evaluated under different PV panel sizes (1-5 kWp), without and under RoD. In case of no RoD, the normalized cost is lowered by almost 90% even with the smallest S_{PV}. A further reduction of up to 20% is observed as S_{PV} increases, with the largest gain when shifting from 1 kWp to 3 kWp. The introduction of the RoD leads to a dramatic cost drop, that is more evident for small panels. Under RoD, cost becomes negative for any S_{PV}, meaning that the energy bill is erased and additional revenues of up to more than 20% the baseline cost are gained by the MNO. WO alone results beneficial in reducing operational cost even when no RE is available, with cost savings that are twofold those obtained under RoD only. When RE is locally produced, substantially higher cost saving can be obtained, that are affected by the PV panel and battery sizing. Complete results are not reported for the sake of brevity, but can be found in [12], [13], [19], [20]. Interestingly, a grid energy reduction lower than 50% may correspond to cost saving higher than 100%, resulting in positive revenues. This confirms that a good energy management does not rely on reducing the total grid demand, but on timely raising or lowering the grid consumption exactly when requested by the SG.

VIII. Conclusion

This work shows that RE is an effective and feasible solution to power mobile networks. Our results demonstrate that the accurate design of a green mobile network requires a reliable modeling of the RE generation dynamics, taking into account the location dependent variability that may affect the renewable system dimensioning and the mobile service continuity. The introduction of RoD strategies allows to trade off the feasibility of renewable systems and cost saving, decreasing capital and operational expenditures by up to more than 40%. This study opens the way to new interesting scenarios, where MNOs can profitably interact with the Smart Grid to obtain mutual benefits, fully erasing the energy bill and even gaining positive revenues, although this definitely requires the integration of suitable energy management strategies into the communication infrastructure management.

The potentiality of RE powered mobile networks interacting with the SG will steer further research efforts in the years to come, not only considering the future deployment of more efficient PV modules and the consolidation of new energy storage technologies, but especially in view of the shift towards 5G mobile networks. New challenges will be posed by Cloud Radio Access Networks, entailing few centralized processing units that manage several distributed physical radio access points, entailing the need for dynamic mapping between them. RoD strategies should be adapted to new constraints arising due to BSs providing also caching/computing service. Furthermore, they should integrate online learning techniques that operate in real-time to allow a more accurate prediction of RE generation, mobile traffic and energy price variability. Finally, MNOs could further enhance their interaction with the SG by combining the use of RE with energy saving approaches based on new multi-sleep-mode power models of the BSs and on Device-to-Device communication. Moreover, in a Smart City environment, MNOs could exploit the cooperation with household users providing WO capabilities, and with electrical vehicles, that could operate both as moving mobile antennas and backup batteries for the mobile network.

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