Cost saving and ancillary service provisioning in green Mobile Networks

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Muhammad Ali, Michela Meo and Daniela Renga

Abstract Mobile Network Operators (MNOs) are facing huge operational costs, due to the staggering increase in mobile traffic and to substantial bandwidth reliability requirements to enable demanding services in Smart Urban Ecosystems. With the purpose of reducing the cost due to power supply, dynamic load adaptation techniques are often implemented in Mobile Networks, in order to save energy when the traffic demand is low. Moreover, renewable energy (RE) sources are commonly introduced to power base stations, further contributing to decrease the operational expenditures. Finally, in a Demand Response context, the Smart Grid (SG) may actively ask its customers to dynamically adapt their consumption, by means of monetary incentives. The MNO is interested in improving the interaction with the SG, since mutual benefits can be obtained: cost reduction for the MNO and ancillary service provisioning from the SG side.

We investigate via simulation a mobile access network where WiFi offloading techniques are combined with a properly designed energy management strategy, in order to reduce the load and better satisfy the SG requests. The impact of WiFi offloading is analyzed in different scenarios, including those envisioning the use of RE to power base stations (BSs) and/or the application of Resource on Demand (RoD) strategies, that activate or deactivate BSs based on traffic demand. Real data about traffic, RE production and SG requests are adopted.

WiFi offloading results effective both in improving the probability of providing ancillary services and in reducing operational costs in any scenario, even when no

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RE is available. Furthermore, its impact is even more significant than the application of RoD strategies. Positive revenues are also possible for the MNO when RE are used, even when photovoltaic panels with relatively small capacity are installed.

1 Introduction

The staggering increase of the mobile traffic is currently leading Mobile Operators to deploy denser mobile access networks, especially in urban environments, thus entailing a considerable rise in their operational costs. Furthermore, with the extensive penetration of the Smart City paradigm, cellular networks are going to play a fundamental role in urban environments. Indeed, mobile networks will be essential in enabling several of the countless services deployed in Smart Urban Ecosystems, including smart mobility, safety and environmental protection, smart building, and enforcement of energy efficiency and awareness. In this context, mobile networks should provide high bandwidth capacity, fast speed Internet access for the services that are becoming the more and more demanding, and high reliability in terms of service continuity. Considering that mobile traffic is growing twice as fast as fixed IP and that 27 billion of networked devices and connections are expected by 2021, leading to an annual mobile traffic exceeding half a zettabyte, the energy consumed by mobile access networks is bound to incredibly rise, and so is the energy bill for Mobile Operators [5]. At the same time, within the Smart City ecosystem, the Smart Grid represents a new paradigm replacing the traditional electric grid, by envisioning several distributed energy producers, possibly from renewable energy sources, rather than a single energy supplier, and enabling bidirectional flows both of information and energy. One of the challenges of new electricity generation and distribution networks is coping with the mismatches between electricity demand and supply, mismatches that are more difficult to predict due to the presence of renewable sources. However, by making the grid "smart" and capable of interacting with the customers, it is possible to introduce new paradigms of electricity supply and consumption in which the customers take actively part in the process. With the electric power grid becoming a *Smart Grid* (SG), the Demand Response (DR) policies applied by the SG operator (SGO) may highly affect the energy costs, by introducing huge variability in the energy prices over time. The DR approaches aim at maintaining the demand-supply balance by adapting demand to the production curve. Production excesses are coped with by setting low energy prices that incentivize end users to increase their demand; conversely, users are induced to reduce their consumption when the production is low, by letting energy prices rise. By dynamically modulating their power consumption in accordance with the SG requests, users can contribute to provide the so-called *ancillary services* (ASs).

In this context, big consumers can have a central role. While they can significantly contribute to DR objectives by adapting their (huge) demand, their convenience consists in the possibility to obtain important electricity cost reductions. Telecommunication mobile operators are an example of such big consumers. Today, operators are experiencing huge costs to power their devices and this is expected to get even worse in the future. At the same time, they have some possibility to act on their network to adapt consumption to the SG requests.

We consider in this study the use of WiFi offloading (WO) technique. WiFi offloading consists in transferring a portion of the mobile traffic from the BSs to some nearby WiFi Access Points (APs). This technique is commonly adopted to relieve mobile access networks from a part of their traffic load during peak hours in heterogeneous networks. In our case, WiFi offloading is introduced as a way to decrease the traffic load whenever the SG requests a reduction of the consumption. WiFi offloading alone may not lead to remarkable reduction in the consumption, due to the limited load proportionality of energy consumption. However, when applied in a scenario where the base stations (BSs) can also be switched on and off, WiFi offloading allows to further decrease the number of active BSs, hence to further reduce the system consumption. Hence, we investigate the effect of WiFi offloading in improving the interaction of the mobile network with the SG, both in the case of the normal network operation as well as in the case in which Resource on Demand (RoD) strategies are used to reduce the overall consumption of the network. RoD techniques reduce the consumption by dynamically switching on and off the base stations based on the traffic load. Furthermore, we investigate whether the WiFi offloading approach may further benefit from the introduction of a local renewable energy (RE) generator in the mobile access network. Several examples of mobile networks powered by RE can already be found in the literature [12]. The irregular and unpredictable nature of RE production is addressed by the installation of an energy storage device, where extra amounts of produced RE can be harvested for future usage, for example during the night. The expected impact of local RE generation results from two reasons. On the one hand, the RE production allows the BSs to become more independent from the grid, hence decreasing the demand from the SG, with consequent lowering of the cost. On the other hand, the presence of batteries allows also to store energy, when it is convenient, for future usage.

RoD approaches implying BS sleep modes are commonly adopted to make mobile networks more energy efficient and the use of RE to power the BSs is emerging as a technique to make mobile networks more independent from the grid [27, 12, 4]. Studies start to be available related to the application of BS sleep mode based RoD strategies to RE powered BSs [6, 7, 28, 10]. Finally, WO represents a widely adopted technique allowing to migrate traffic from cellular networks to WiFi networks to tackle the recent explosion of mobile data traffic [13, 22]. However, the interaction between a renewable powered mobile access network and the SG in a DR framework and with usage of BS sleep mode RoD techniques is not well investigated in literature and only few recent studies focus on this issue [11, 23]. In addition, the impact of WO on improving the energy efficiency and reducing operational costs in a renewable powered mobile access network interacting with the SG, with possible application of BS sleep mode RoD strategies, is an aspect that still remains to be investigated.

The study presented hereafter investigates a portion of a RE powered mobile access network interacting with the Smart Grid in a Demand Response framework.

WiFi offloading techniques are introduced to enhance the response of the cellular network to the SG requests. The role of WiFi offloading in reducing the energy bill is analyzed via simulation and its impact on improving the capability of providing ancillary services is examined as well. Results show that the introduction of WiFi offloading provides mutual benefits for the Mobile Network Operator (MNO) and the SG. Indeed, the application of WiFi offloading techniques combined with a properly designed energy management strategy allows to save up to 100% of the energy bill in our scenario, when WiFi offloading is applied jointly with RE powering. Furthermore, the introduction of WiFi offloading is effective in increasing the capability of providing ancillary services, in particular by raising the probability of satisfying the SG requests of decreasing the grid consumption by up to almost 75% in the scenario investigated in our study. Finally, under the application of WiFi offloading, an increase in the RE generation system size contributes to significantly increase the network performance in terms of both raising the probability of providing ancillary services and reducing operational costs, even achieving positive revenues.

2 Mobile networks in a Demand Response framework

The increasing penetration of distributed renewable energy generators in the SG, integrated alongside traditional synchronous centralized generators, has been responsible of the huge diffusion of the Demand Response paradigm in recent years. On the one hand, the presence of several additional distributed power generators may more frequently lead to overrun the absorptive capacity of the traditional power grid, causing system instability or failure [19]. On the other hand, the erratic nature of renewable energy production increases the risk of requiring the activation of additional high inertia generators, in case of peak power demand and low renewable energy production, and this is neither desirable nor effective in providing the needed energy supply in a short time. In particular, *Price Based Programs* are often adopted as effective methods to flatten the pattern of energy demand, by adjusting the energy prices over time, depending on the varying energy load. Users are incentivized to shift their demand from high peak to low peak periods, by receiving a monetary reward or penalty, depending on whether they are able or not to accomplish the request from the SG of increasing or decreasing their consumption [19]. By satisfying the SG requests, users therefore contribute to provide ancillary services.

The mobile operator (MO) may play a relevant role in the DR framework, by making the mobile access network actively interact with the SG and dynamically modulate its energy consumption in accordance with SGO requests. The DR policy adopted in our work envisions that every day the MO forecasts its energy consumption for the following day depending on the expected traffic, which is estimated based on historical data. The information is hence provided to the SGO, with a granularity of half an hour. During the next day, every half an hour the SG announces to the end users its current request, that may be of type *increase* (U), *decrease* (D) or *nothing-to-do* (N). In case of U request, the SG is asking its users to increase the

Table 1: Energy prices, rewards and penalties in [€/MWh].

Price, reward or penalty	p_G	r_U	r_D	p_U	p_D
Value [€/MWh]	37	24	60	12	30

energy consumption from the grid with respect to the forecast energy; in case of D, the request is for decreasing the consumption with respect to the reference amount that had been foreseen the day ahead; in case of N, no specific behavior is required. Whenever the MO is able to satisfy the SG request of U or D, it receives a reward, proportional to the increase or reduction in the consumption, respectively; in case it does not accomplish and even opposes the request, a penalty is computed, proportional to the gap with respect to the expected demand. Tab. 1 reports the values of energy prices, rewards and penalties adopted in this study [24]. p_G is the cost for unit of energy bought from the grid. r_U and r_D are the rewards per unit of energy traded to provide ancillary services in case of U and D, respectively. p_U and p_D are the penalties paid for each unit of energy opposing the SG request with respect to the predicted consumption, in case of U and D, respectively. Let us denote with C_f the forecast network consumption in a given timeslot, and with C_a the actual consumption in the same timeslot. When a request of type U is issued, if $C_a > C_f$ a reward is provided to the Mobile Operator, corresponding to $r_U \cdot (C_a - C_f)$. Conversely, if $C_a < C_f$ a penalty is due, resulting in an additional cost of $p_U \cdot |C_a - C_f|$. Similarly, when a request of type D occurs, a reward is provided to the MO if $C_a < C_f$, corresponding to $r_D \cdot |C_a - C_f|$, whereas if $C_a > C_f$ an additional cost of $p_D \cdot (C_a - C_f)$ must be paid by the MO.

In this work, we investigate the potential of improving the interaction with the Smart Grid of a mobile access network, by designing energy management strategies aiming to better react to the requests from the SG. These strategies improve the interaction with the Smart Grid by exploiting RE sources to power the BSs and the implementation of RoD and WO techniques, with the purpose of reducing the electric cost for the MO and enhancing the ancillary service provisioning. The considered scenario is depicted in Fig. 1. It consists of a green mobile access network where a macro BS and multiple micro BSs provide coverage over a given area. As it will be further detailed later on, the cluster of BSs can be powered by the traditional electric grid, by the renewable energy that is locally produced by PV panels, and by the energy previously harvested in some local storage. A central controller takes care of energy management and it is in charge of applying the RoD and WO techniques to the network system.

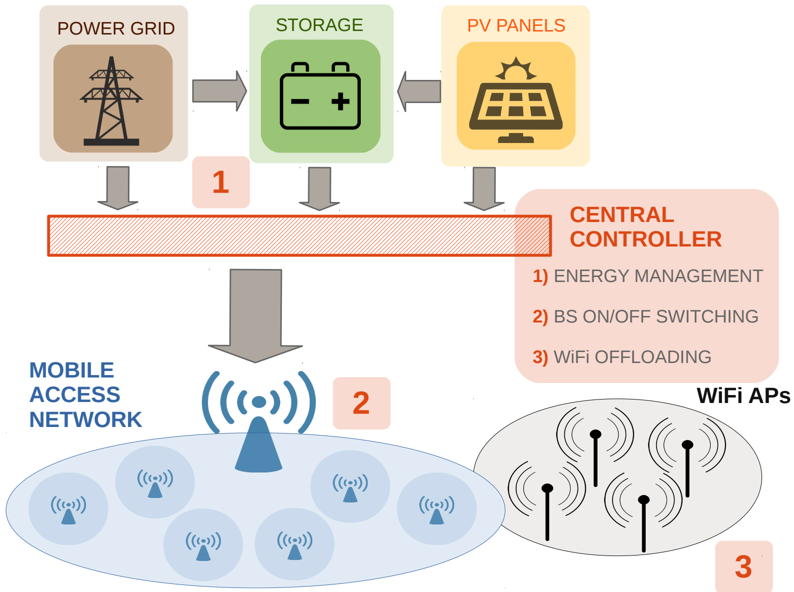


Fig. 1: The green mobile access network scenario.

3 Mobile network response to the SG

To respond to the SG requests, the mobile operator uses WiFi Offloading. Currently, WiFi APs are increasingly deployed by more and more operators and private users, making the WiFi technology become available almost everywhere. Therefore, WO looks a very promising solution to increase the capacity of cellular networks[13]. In our case, WO is exploited to increase the chance of satisfying the requests from the grid of decreasing the consumption, by reducing the traffic load right when the reward for providing ancillary service is higher. This technique can also be combined with RoD to further increase its effectiveness. Indeed, the impact of WiFi offloading in improving the interaction with the SG is evaluated in two different scenarios. In the first scenario, all the BSs are always kept active, even during off-peak periods. In the latter, a RoD strategy is applied in order to adapt over time the network power consumption to the actual traffic demand when the SG requires to reduce the energy amount drawn from the grid, hence saving energy and receiving rewards. The proposed strategy exploits the possibility of putting the BSs into deep sleep mode, in which negligible consumption can be assumed. We consider a cluster composed of one macro BS and a few micro BS that can increase the capacity of the cluster. When a request of type D is issued, the RoD scheme operates by switching off one or more micro BSs, depending on the current traffic that has to be handled by each of them. If the traffic load decreases below a given threshold, denoted as ρ_{min}, the micro BS can be switched off and its traffic moved to the macro BS, as long as there is still enough capacity on the macro BS to handle the additional load [6].

4 RE to improve the interaction with the SG

The application of WiFi offloading techniques in mobile access networks can help to better answer to the requests form the SG, in particular in those periods in which the SG asks for a reduction of the consumption. However, their impact may be constrained on the one hand by the minimum capacity to be guaranteed even during off-peak periods for an acceptable QoS and, on the other hand, by the maximum amount of traffic load that can be offloaded to the WiFi APs. Furthermore, this approach does not provide huge margine to satisfy the requests to increase consumption from the grid, since the cluster load cannot be forced to grow.

The introduction of photovoltaic (PV) panels to power the BSs cluster makes it more energy self-sufficient and further increases the probability of satisfying the SG when a reduction of the consumption is required. In addition, batteries are needed to address the typical intermittent and unpredictable nature of renewable energy production, since extra amounts of produced RE can be harvested into storage for future usage, when the RE is not available. At the same time, storage is useful not only for powering the BSs when the request from the SG is to decrease the consumption, but also for storing some extra energy drawn from the grid when the request is to increase consumption.

5 Energy management policy

The energy management strategy applied to respond to the SG requests is now presented. A general description is provided assuming the presence of a RE generator, with a set of PV panels whose capacity is S_{PV} and a set of batteries whose size is expressed in terms of the number of storage units, denoted as B. The same operation holds in case no RE generator is envisioned. In this case, S_{PV} and B are simply equal to 0. C_f denotes the network consumption for each half an hour forecast the day ahead, while C_a is the actual network consumption. In our simulations we assume that the predicted consumption C_f is computed assuming that no RoD strategy and no WiFi offloading are applied and all the energy required for the network operation is drawn from the grid. Every half an hour, different actions can be taken, based on the type of grid request and the amount of produced RE. The BSs need C_a may be derived from the produced RE, from the storage (always respecting the maximum discharging rate) or from the grid. RE may be used to power BSs, harvested into battery or wasted in some cases. The RE management is based on a *first use - then harvest* principle, meaning that the produced RE can be directly used to power the BSs and only the extra amounts are possibly harvested afterwards. In

Algorithm 1 Energy management algorithm

1: $E_r = 0$; $E_g = 0$;
2: **switch** $grid\ request$ **do**
3: **case** U:
4: **if** $(R_p < C_a)$ **then**
5: power BSs from the grid;
6: harvest extra energy, E_b, from grid into the battery;
7: waste R_p;
8: $E_g = C_a + E_b$;
9: **else**
10: use R_p to power BSs;
11: store $(R_p - C_a)$ into the battery, waste the extra amount;
12: **end if**
13: **if** $(E_g > C_f)$ **then**: a reward is received;
14: **else if** $(E_g < C_f)$ **then**: a penalty is paid;
15: **end if**
16: **case** D:
17: **if** WO is active **then**: offload some traffic;
18: **end if**
19: **if** RoD is active **then**: switch off some micro BSs;
20: **end if**
21: use R_p to power BSs;
22: compute residual need $E_r = max(0, C_a - R_p)$;
23: **if** $(E_r = 0)$ **then**
24: store $(R_p - C_a)$ into the battery, waste the extra amount;
25: **else**
26: draw E_r from the battery and, if needed, from grid;
27: $E_g = max(0, E_r - Battery\ Level)$;
28: **end if**
29: **if** $(E_g > C_f)$ **then**: a penalty is paid;
30: **else if** $(E_g < C_f)$ **then**: a reward is received;
31: **end if**
32: **case** N:
33: code from line 19 to 26;

order to better answer U requests, an additional amount of energy, denoted as E_b, can be drawn from the grid and harvested into battery for future usage. E_b is the maximum amount that can be injected into the battery in half an hour, constrained by the maximum charging rate and the maximum available battery capacity, denoted as C_B. The RE produced every half an hour is denoted as R_p, while E_g represents the energy drawn from the grid for each half an hour. E_r denotes the residual energy need of the access network after R_p has been used to power the BSs. Every half an hour, energy management decisions are taken according to Alg. 1. Note that, when the WO is active and a D request occurs, part of the traffic load is transferred from some micro BSs to neighboring APs. Afterwards, in case RoD is active and if a D request is issued by the SG, the energy management system checks the load: if it is sufficiently low and there is enough capacity in the macro BS, some of the micro BSs can be switched off and their traffic is moved to the macro BS, as long as there is still enough residual capacity. Afterwards, C_a is updated accordingly. WO and

RoD are hence exploited to timely respond to the SG requests when needed, i.e. when the SG asks to decrease the consumption from the grid. The behavior of this energy management algorithm in terms of RoD application is different with respect to the algorithm proposed in [1]. In that paper, when the RoD strategy is active, it was always applied, if possible, regardless the type of SG requests, with the main purpose of decreasing the overall energy consumption. Hence, when the traffic is low, some micro BSs are turned off even in case of U or N requests. Hence, in case of RoD strategy application, the network demand forecast the day ahead, C_f, was computed assuming the application of RoD.
In case of U request, a reward is obtained if the total energy taken from the grid, E_g, is larger than the predicted consumption C_f. The reward is proportional to the extra amount of energy taken from the grid. By converse, in case it is lower, a penalty is paid proportional to the energy gap with respect to the reference level C_f predicted the day ahead. Similarly, in case of D, a reward is obtained if $E_g < C_f$, and vice versa for the penalty.

6 Simulating the mobile network-Smart Grid interaction

As depicted in Fig. 1, we consider a portion of a mobile access network is studied, consisting of a macro BS, providing coverage over a given area, and 6 micro BSs, providing additional capacity for peak periods. Real traffic traces from a residential area, provided by an Italian mobile operator [6], are used to simulate the traffic variation over time in the system. The macro and micro BS consumptions are derived by applying the EARTH model [15], which takes into account the partial load proportionality. The BS cluster draws its energy demand from the traditional electric grid, but it may also be powered by RE. The BS cluster interacts with the SG and answers to its requests according to the energy management policy described above. Unlike our previous work [1], where SG requests (U, D, N) were randomly generated according to a uniform distribution, so that each type of request had the same occurrence probability, in our simulations realistic traces of SG requests are considered. These traces are obtained by considering real energy prices, derived from the Australian energy market [2], that dynamically vary over time, either within a single day, from day to day or over seasons. The pricing data from the Australian energy market have been considered instead of the Italian energy prices in order to study a scenario where the SG request dynamics are highly affected by the extensive penetration of RE sources. The energy prices adopted for this study are those registered in the Australian State of New South Wales during the year 2016. These prices are set by the SG operator and they are provided with a timestep granularity of 30 minutes. Their values are mapped into three price ranges, corresponding to the three types of SG requests. Low range values are mapped as requests of type U, whereas high prices are mapped as requests of type D. Intermediate prices correspond to N requests. Thresholds to define the three ranges are set so that the U and D requests are equiprobable (40% each), whereas N represents 20% of the total SG istances.

By mapping the actual sequence of energy prices into SG requests, a more realistic performance analysis can hence be conducted with respect to [1]. The energy prices defined by the Smart Grid Operator may be highly affected, among several factors, by the dynamic variations of the local RE production. Hence, the study should consider the typical solar radiation profiles observed in a city located in this state. In particular, the city of Sydney has been selected to derive, by means of PV Watts, real profiles of solar energy production, as it will be described later on.
Neighbor WiFi Access Points (APs) may be exploited to transfer and handle 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. Typically, up to 20% of the maximum mobile traffic load can be trasferred to neighbor APs by means of WO [18]. Two different scenarios are considered. In the first one, the macro and micro BSs are always active, providing full capacity even during off-peak periods. In the latter, the RoD strategy described in Sec. 2 is introduced to accomplish requests of type D, by adapting the consumption to the actual traffic load; the threshold ρ_{min} has been set equal to 0.37, since this value optimizes the energy saving [6]. A centralized controller is in charge of energy management (which is performed according to the proposed policy), decisions about when each micro BS should be switched off (based on the RoD strategy) and traffic transferred to the APs, and about when the WiFi offloading approach is applied.

The system performance in both scenarios has been tested by simulation over an entire year in baseline conditions, i.e., without any RE generator. The performance has been evaluated in terms of yearly energy consumption, probability of providing ancillary services, and costs, including cost for energy, rewards for providing ancillary services and penalties for opposing the SG requests. In addition, the WiFi offloading has been applied in both scenarios to study its impact. When the WiFi offloading is introduced, the energy management policy envisions that, in case of a D request, some of the traffic can be moved to neighboring APs, hence reducing the overall load and allowing, in the RoD scenario, the switching off of additional BSs. We assume that the maximum capacity available for WiFi offloading corresponds to 10% of the peak traffic load handled by the 6 micro BSs. This allows to achieve an average offloading efficiency approximately between 10-20%, depending on the specific case, envisioning a scenario in which the number of available neighboring APs is limited [3, 18, 21].

Furthermore, a RE generator and a storage system are considered to power the cluster of BSs, in order to investigate the effect of local solar energy production and the presence of batteries on the interaction with the SG. The RE generator consists in a set of various PV panels, built up by standard modules of crystalline Silicone, whose efficiency is 15% [8]. The nominal capacity of the modules, denoted as S_{PV}, is the maximum DC output power that can be produced under standardized environmental conditions from the sun radiation and it is measured in peak W [Wp]. The range of S_{PV} considered in this work is [5,25] kWp. Real data about RE production are derived on a half an hour basis from the tool PVWatts [8] in the city of Sydney, over the Typical Meteorological Year. In [1], the RE powered network interacting with the SG was investigated in the city of Turin, in Italy. Here, since the energy prices available are derived from the Australian Energy Market Operator (AEMO) [2], the city of Sydney has been selected as location to conduct the performance analysis. Both locations are placed in comparable latitude bands (45.07° N for Turin, 33.87° S for Sydney) in terms of solar radiation, and the seasonal patterns of RE production follow a quite similar average behavior. A DC-to-AC inverter efficiency of 96% and typical performance losses of 14% observed during actual operation are assumed for the PV system.

The battery set is composed by 5 to 25 lead-acid batteries, each with capacity 200 Ah and voltage 12 V, which represent a common storage technology adopted in RE system [14]. The number of batteries is denoted as B. The total nominal capacity of the entire battery bank may sum up to a value between 12 and 60 kWh, depending on the value of B. A maximum Depth of Discharge (DoD) of 70% is assumed, in order to prevent charging efficiency impairment [26], battery aging [25] and capacity loss [14]. A lifetime duration of 500-600 cycles can be assumed under DOD=70% [16]. Therefore, assuming 5 to 25 battery units, the maximum storage capacity that is actually available is limited by the DOD, resulting between 8,4 kWh ($B = 5$) and 42 kWh ($B = 25$). Charging and discharging losses, amounting to 25%, are considered as well in our work [9]. Finally, high charging and discharging rates may reduce battery lifetime and impair its efficiency, especially in case of frequent charging and discharging events occurring in RE systems. Constraints on the maximum charging and discharging rate are therefore taken into account, by assuming a conservative value for the maximum charge and discharge current of C/10 A, where C is the numerical value of the battery capacity in Ah [17]. This means that, for example, the energy drawn in an hour from a battery of 200 Ah will be at most 240 Wh, from which efficiency losses must then be curtailed. The same holds in case of battery charging.

7 Performance analysis

The system performance has been investigated in terms of energy yearly taken from the grid, probability of providing ancillary services, effect of system dimensioning and cost analysis, considering the possible application of WO, either alone or combined with RoD, and examining the impact of the introduction of a PV system. The results derived in our work are extensively detailed hereafter. Table 2 summarizes the main performance results, along with the experimental settings under which our simulations have been conducted.

Table 2: Performance results

Performance metrics	RE generation	PV panel size [kWp]	Number of battery units	Values of performance metrics			
				No strategy	WO	RoD	WO+RoD
E_G [MWh]	none	-	-	12.15	11.47	11.77	11.46
	✓	10	15	7.86	7.53	6.84	6.68
p_U	none	-	-	0	0	0	0
	✓	5	5	0.87	0.87	0.82	0.82
	✓	10	15	0.35	0.34	0.33	0.33
p_D	none	-	-	0.00	0.75	0.37	0.75
	✓	5	5	0.71	0.87	0.78	0.88
	✓	10	15	0.95	0.98	0.97	0.98
E_{U_+} [MWh]	none	-	-	0	0	0	0
	✓	10	15	4.01	3.84	3.59	3.51
E_{D_+} [MWh]	none	-	-	0	0.68	0.38	0.69
	✓	10	15	4.65	4.77	4.74	4.78
Cost saving [%]	none	-	-	0	115.34	201.87	87.61
	✓	5	5	14.57	118.7	214.28	92.63
	✓	10	15	8.12	121.38	217.59	101.11
	✓	10	15	14.91*	122.82*	222.82*	102.92*

* In this case extra amounts of produced RE are sold back to the SG.

7.1 Energy demand from the grid

Fig. 2 reports the amount of energy taken from the grid over one year, E_G, for the cases without RE production (orange bars) and under RE supply (green bars), under various possible configuration settings:

1. no strategy is applied (baseline scenario);
2. only WO is applied;
3. only RoD is applied;
4. both WO and RoD strategies are applied.

In the baseline scenario, without RE production, E_G=12.15 MWh; this value is considered as the reference value, E_G*, with respect to which the energy saving is computed. Under RoD, 11.77 MWh are consumed and drawn from the grid, with a 3.1% saving with respect to E_G*. The application of WO allows to reduce E_G by 5.6% without RoD and by 5.7% under RoD, again with respect to E_G*. Interestingly, the impact of WO in reducing the energy taken from the grid is higher than RoD. Furthermore, the additional reduction in E_G provided by RoD when WO is running is almost negligible. Theoretically, under RoD strategy higher energy savings would be expected, since the energy saved by completely switching off a micro BS is higher than the energy amount that can be saved by transferring the traffic

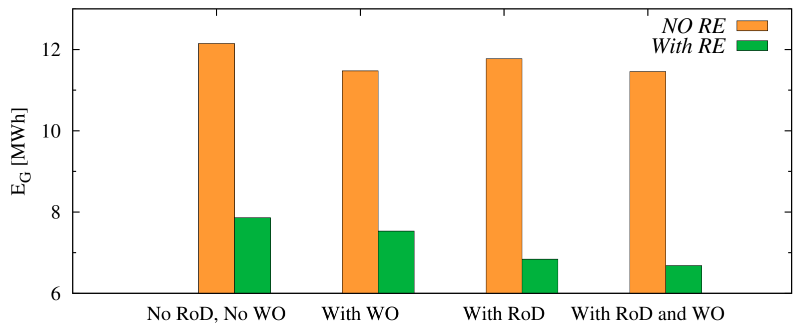


Fig. 2: Grid demand, E_G, without and under RE production.

load to neighboring APs. Nevertheless, in our case it is more advantageous to apply WO rather than RoD, since at every timeslot in which a D request is issued, it is more likely that the network is able to offload traffic rather than to switch off micro BSs. This is due to the fact that whereas both WO and RoD can be applied only in case of D requests, two additional constraints further limit the application of RoD: a micro BS can be switched off only if its traffic load is below a given threshold and if the macro BS still has enough residual capacity to carry the traffic moved from the micro BS.

This trend is different with respect to results obtained in [1] under the same config-

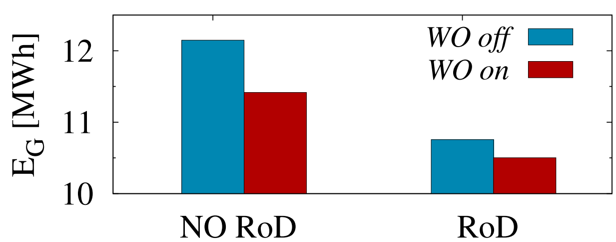


Fig. 3: Grid demand, E_G, without RE production, under the energy management strategy proposed in [1].

urations, that are shown in Fig. 3. This figure reports E_G in two scenarios, without and under RoD, comparing the case without WiFi offloading (blue bars) and the case in which WiFi offloading is applied (red bars). The application of RoD shows a larger impact than WiFi offloading only, reducing E_G by 11.5%, almost twice the 6% reduction obtained under WO. In addition, by applying RoD on the top of WO a more significant reduction of E_G is achieved with respect to results reported in Fig. 2, with a saving more than doubled if compared against the WO-only policy (from 6% to 13.6%). These differences are due to a twofold reason. First, the en-

ergy management algorithm proposed in [1] is slightly different with respect to that adopted in this work. In [1], when the RoD strategy is active, it is run at any time, disregarding the type of SG requests. Only WO is applied in case of a request of type D is issued. Conversely, according to the energy management algorithm proposed in this study, when either WO or RoD strategies are active, they both operate just in case of request of type D. Second, as already mentioned, the impact of RoD in reducing the energy drawn from the grid is further limited by additional constraints with respect to the case of WO. Indeed, under WO some of the traffic can always be transferred to neighboring APs without any constraint. Conversely, under RoD strategy, micro BSs can only be switched off if their traffic load is below the threshold ρ_{min} and as long as the macro BS has still enough capacity to carry the additional traffic moved from the micro BSs. Hence, RoD may not be applied at any timeslot in which a request of type D is issued.
Although under this energy management alorithm the RoD shows a smaller impact in reducing E_G with respect to [1], this may not result in relevant differences in terms of energy costs, as it will be shown in Sec. 7.3. Indeed, the application of RoD at any timeslot in [1], regardless the type of SG requests, may contribute to reduce the overall energy consumption from the grid, without significantly improving the capability of matching the SG requests. Conversely, although the application of RoD only in case of D requests may not reduce the overall E_G to the same extent, it may nevertheless be able to timely reduce the grid consumption when needed, i.e. when D requests are issued and rewards are provided for accomplishing the SG requests, thus achieving a better demand-supply match and still providing significant cost saving, without impairing the bandwidth availability if not strictly needed. Note that Mobile Operators are typically reluctant to apply on their networks any strategy that may impair the Quality of Service to some (although limited) extent. Hence, an energy management strategy that limits the application of RoD to periods when it is strictly required, still capable to effectively reduce cost, may represent a good tradeoff for real network implementations.
The case with RE production is also shown in Fig. 2 (green bars), assuming S_{PV}=10 kWp and B=15. Without WO and RoD running, a reduction of 35.2% in E_G can be achieved. The introduction of WO allows to reduce E_G by 38%, whereas RoD, unlike the case when no local RE is produced, results to be more effective than WO in decreasing the energy drawn from the grid, showing a trend coparable to that observed in [1]. Indeed, the provided E_G reduction is 43.7% for RoD alone and 45% when RoD is applied on the top of WO. This means that, when a local RE generator is installed, in order to further reduce E_G, it is more convenient to apply a RoD strategy rather than WO alone, although this may not necessarily reflect a relevant difference in terms of cost reduction, as it will be shown.

7.2 Providing ancillary services

Here we investigate the capability of WO to enhance the interaction of the mobile network with the SG and improve the ancillary service provisioning, either alone or when combined with RoD. Furthermore, we analyse the effect of local renewable energy production on the system performance. Finally, some results are presented to show the impact of the RE system dimensioning on the capability of the cellular network to accomplish the requests from the SG under various configuration setting. The capability of providing ancillary services is evaluated both in terms of probability of responding to U and D requests from the grid and in terms of the amounts of energy traded with the SG to provide ancillary services, for which proportional rewards are envisioned.
Probabilities of providing ancillary services are defined as follows:

- P_{U_+}: probability of satisfying a grid request of type U (the SG asks to increase the consumption from the grid and the network is able to do that);
- P_{D_+}: probability of satisfying a grid request of type D (the SG asks to decrease the consumption from the grid and the network is able to do that).

The energy amounts traded with the SG are defined as follows:

- E_{U_+} represents the portion of the yearly cumulative amount of energy drawn from the grid that exceeds the forecast consumption, in case of U requests;
- E_{D_+} corresponds to the absolute value of the yearly cumulative amount of energy that represents the negative energy gap with respect to the predicted consumption from the grid in case of D requests.

7.2.1 Role of WiFi offloading

Fig. 5 shows the results in case no RE is locally produced. U requests can never be satisfied as it can be seen from P_{U_+}=0 under any scenario (WO on or off, without and under RoD). This is due to two reasons: first, the traffic patterns are assumed to be exactly known in advance so that the forecast traffic load results perfectly accurate; second, the absence of any energy storage does not allow to draw and harvest extra energy from the grid to answer its U request. WO allows to achieve a P_{D^+} of 74.7%, twice the value provided in case of RoD. In [1], D requests can be satisfied only when WO is applied, due to the same assumption of exact predictability of traffic. Indeed, in that case, RoD is always applied under any type of SG request and the grid consumption is forecast assuming the application of RoD, hence no reduction can be achieved in E_G by simply applying RoD and without RE production. Conversely, in this study, the application of RoD just in case of D requests allows to achieve a P_{D^+}=37.2% (against P_{D^+}=0 in [1]). Note that the reward for providing ancillary services in case of D is 2.5 times higher than for answering U requests. Furthermore, combining WO and RoD is not useful at all to increase the capability of providing ancillary services, since P_{D_+} is exactly the same as the case of WO only application.

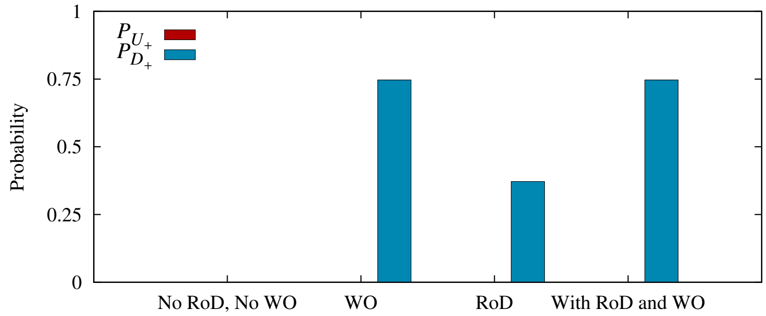


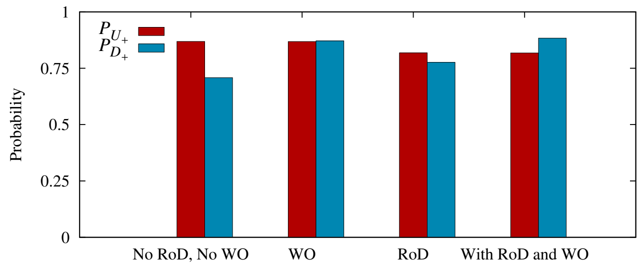
Fig. 4

Fig. 5: Probability of providing ASs under no RE production.

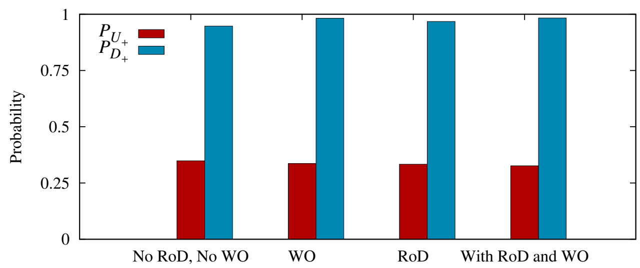
This behavior is consistent with results obtained in [1] without the use of RE. In that case, not only the combined application of RoD on the top of WO is not helpful, but it even reduces P_{D_+} (hence the probability of obtaining the corresponding rewards) by more than 30%. The probabilities of not answering U or D requests clearly result complementary to P_{U_+} and P_{D_+}. However, no penalties must be paid under any scenario, since no opposition to the SG requests is ever registered.

7.2.2 Effect of local renewable energy production and system dimensioning

In Fig. 6 the probabilities of providing ancillary services are reported for the case in which RE is produced, comparing two different system dimensioning. Fig. 6a shows the values of P_{U_+} and P_{D_+} under different scenarios, in the case with an intermediate system syzing, i.e. a PV panel with capacity 5 kWp and a storage consisting of 5 battery units. The probability of satisfying either U or D requests is always above 70% under any strategy configuration. WO allows to increase P_{D_+} by up to 22.9%, at the price of a negligible reduction in P_{D_+}. RoD strategy provides a smaller contribution in increasing P_{D_+}, of up to 13.9% at most, at the price of lower values of P_{U_+}. Fig. 6b depicts the case with a larger RE system sizing, i.e. $S_{PV} = 10\ kWp$ and $B = 15$. Whereas P_{U_+} results to be more than halved, the probability of answering D requests, P_{D_+}, is almost equal to 1 ($P_{D_+} = 0.95 - 0.98$). Unlike the case with intermediate sizes for PV panels and storage, under a larger RE system dimension no remarkable differences can be observed between the various combination of strategies, although WO can provide slightly higher increase in P_{D_+}. This means that the effect of higher RE production is dominant in this case. P_{U_+} is decreased when using a larger system sizing, due to a higher average level of battery charge determined by the higher levels of RE generation. Although this leads to a lower probabilility of receiving rewards for satisfying UP requests, a higher average level of battery allows to better answer D requests. Hence, P_{D_+} results significantly increased, leading to



(a) $S_{PV} = 5\ kWp, B = 5$



(b) $S_{PV} = 10\ kWp, B = 15$

Fig. 6: Probability of providing ASs, comparing cases under different sizes of RE generation system.

higher probability of receiving a reward that is twice the reward envisioned in case of UP, thus providing remarkable gains.

In order to better show the impact of RE system dimensioning, Fig. 7 and Fig. 8 report the probabilities of providing ancillary services for increasing values of S_{PV} and B, respectively, in the case in which both WO and RoD are applied.

According to Fig. 7, showing P_{U_+} and P_{D_+} for increasing panel size, the probability of accomplishing D requests is not significantly affected by the PV panel dimension. Very high values of P_{D_+} (> 0.93) are guaranteed even under the smallest PV panels, whereas only slight increases in P_{D_+} can be observed as S_{PV} grows larger. Conversely, the impact of the PV panel size on the probability of providing ancillary services in case of U requests results more relevant, especially for small values of PV panel capacity. Indeed, from P_{U_+}=0.52 for 1 kWp PV panel capacity, it gradually decreases as S_{PV} becomes higher. However, after P_{U_+} has been reduced by 40% at S_{PV}=10 kWp, no significant additional reduction can be detected for further increasing the PV panel size.

Fig. 8 highlights a similar behavior for the impact of the battery size on the capability of providing ancillary services. Indeed, by increasing the number of battery units, the value of P_{D_+}, which is as high as 0.92 under the smallest storage size, slightly raise to values close to 1 for the largest battery set. On the contrary, the increase in the battery dimension remarkably impairs the capability of accomplishing

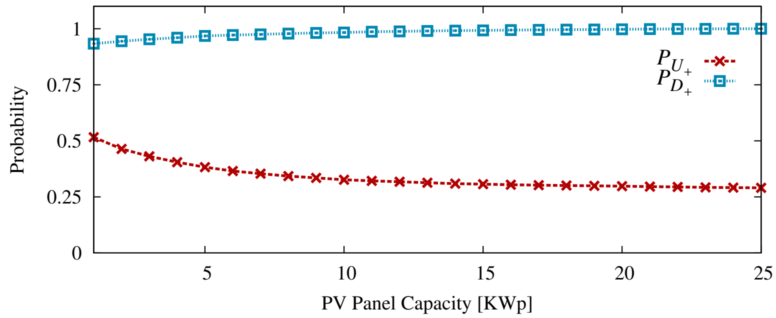


Fig. 7: Probability of providing ASs, without RE production, for increasing PV panel size.

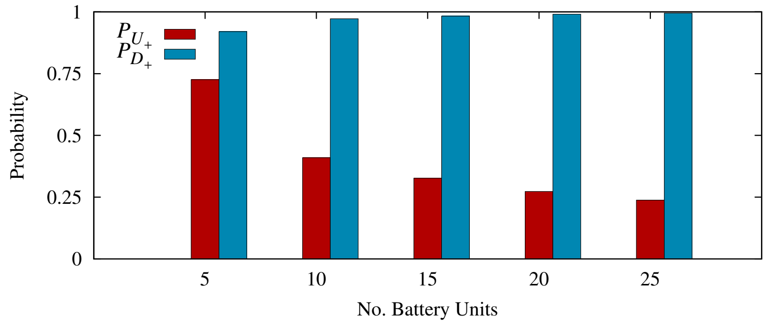
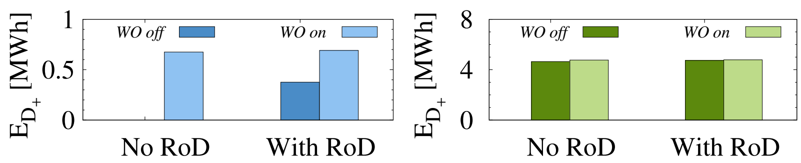


Fig. 8: Probability of providing ASs, without RE production, for increasing battery size.

U requests. A sharp decrease of P_{U_+}, by 44%, is observed moving from 5 to 10 battery units, whereas the P_{U_+} reduction becomes less relevant for further growing of the storage dimension. This behavior sounds rather counterintuitive, since a better response to requests of type U would be expected using a larger battery, capable of storing more energy drawn from the grid in case of UP requests.

7.2.3 Energy trades

The energy trades involved in case of D requests when they can be satisfied are represented by E_{D_+}. They provide dominant gains with respect to the amount of energy exchanged with the SG in case of accomplishment of U requests, i.e. E_{U_+}. In fact, the rewards per energy unit envisioned for the energy trades represented by E_{D_+} are 2.5 fold higher than those obtained for E_{U_+}. Our investigation hence focuses on the analysis of E_{D_+} in various scenarios. The values of E_{D_+} are shown in Fig. 9 in the cases without local RE generation and under RE production. When no local RE



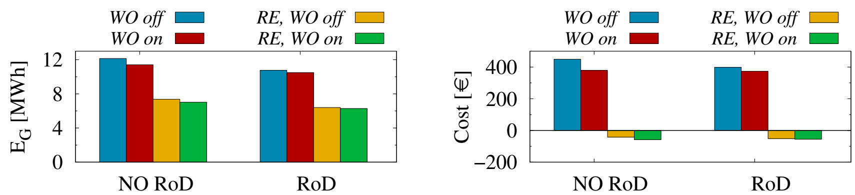
(a) No RE (b) Under RE production

Fig. 9: Energy for providing ancillary services (E_{U_+}, E_{D_+}), without and under RE production.

supply is provided (Fig. 9a), WO results very effective in increasing the level of E_{D_+} with respect to the baseline scenario. Conversely, RoD only provides slightly more than 50% the E_{D_+} gain that can be achieved under WO application. Furthermore, the joint application of WO on the top of RoD strategy does not determine remarkable gain in terms of further E_{D_+} increase. This is consistent with the trend already observed in the probability of accomplishing DOWN requests, P_{D_+}, as reported in Fig. 5. In this case, since P_{U_+} is always null, the values of E_{U_+} are equal to zero in all cases (see Table 2), due to the reasons explained in Sec. 7.2.1.
Fig. 9b shows E_{D_+} when a RE generator and a storage are present, with capacity S_{PV}= 10 kWp and B=15, respectively. In this case, the raise in E_{D_+} can be as high as 7 fold the maximum increase that can be obtained without the presence of local RE supply. Nevertheless, no substantial difference in the levels of E_{D_+} can be observed under the application of WO and/or RoD strategy, confirming that the effect of RE generation on the E_{D_+} gain prevails over the application of WO rather than RoD strategies. Under RE production, the values of E_{U_+} are generally lower than E_{D_+}, resulting up to about 4 MWh at most (see Table 2).

7.3 Cost analysis

The impact of WO on the mobile network operational cost is now evaluated, in order to investigate to what extent operational expenditures (OPEX) can be reduced by applying this strategy, either alone or in combination with RoD, and in case of the presence of a local RE generator. It is worth to be noted that, in a Demand Response context, the cost reduction does not depend strictly on the overall decrease in E_G, that is the amount of energy drawn from the grid over a year, but rather on the capability of raising and decreasing the consumption from the grid at the right moment. Indeed, a good energy management strategy aims at dynamically adjust the energy demand from the grid in order to accomplish the current requests from the grid at each timestep. Therefore, remarkable cost savings may be achieved even in case the total E_G is not significantly decreased, since it is more important to timely increase or decrease the grid consumption when required rather that reducing the overall grid consumption without properly responding to the SG requests, hence missing monetary rewards and receiving penalties to be paid. This can be evinced from Fig. 10,



(a) E_G (b) OPEX

Fig. 10: Energy drawn from the grid, E_G, and OPEX cost when no RE is produced and under RE production (S_{PV}=10 kW_p, B=10).

that reports the values of E_G and the operational cost per year. These preliminary results were derived according to the algorhitm proposed in [1]. They refer to the city of Turin and the grid requests are assumed to be issued according to a uniform probability distribution, like in [1]. Costs have been investigated in the cases without WO or with active WO, assuming that RoD is either active or deactivated, and considering the scenarios with or without a RE generator (S_{PV}=10 kWp, B=10). Fig. 10a shows the energy bought from the grid, E_G, in the various cases, while Fig. 10b reports the operational costs (including energy cost, rewards and penalties) for the corresponding cases. In the baseline scenario, when no RE is produced and no strategy is applied, E_G=E_G*=12.15 MWh and the corresponding reference cost, denoted as c_*, is 450 €. WO alone allows to reduce c by about 16% with respect to c_* and by about 17% when used in a RoD scenario, against a maximum reduction in E_G of 13.6%. Furthermore, when the RE production is introduced, the impact on cost is even more remarkable, with a cost reduction by up to 113% when WO is running. This means that, despite a reduction in E_G by at most 48.3% when RE is locally produced, the operational cost is not only nullified but even becomes negative, thanks to the joint action of the WO strategy and the RE generation, along with storage, in improving the interaction with the SG, providing huge rewards that compensate for energy cost and penalties.

Cost savings have been further investigated in the RE powered mobile access network described in Sec. 6, assuming the city of Sydney as a location, realistic patterns for the SG request occurrences and the energy management algorithm proposed in Sec. 5. Fig. 11 reports the cost savings obtained when no RE is locally produced and in two cases in which a RE generator is present, either with intermediate (denoted as I: S_{PV}=5 kWp, B=5) or large (denoted as L: S_{PV}=10 kWp, B=15) size, and under the possible application of WO and RoD. When no RE is available (orange bars), the application of WO, either alone or running with RoD, allows to achieve up to 14.9% cost saving, almost double with respect to those obtained under RoD strategy only. Indeed, the RoD strategy is less effective, with only about 8.1% cost reduc-

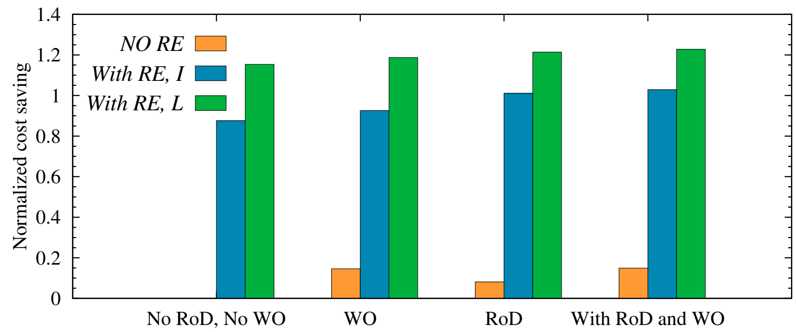


Fig. 11: Cost saving under different RE system size.

tion. The additional cost reduction provided by RoD when applied jointly with WO is quite limited, resulting only 0.3 percentage points higher with respect to the case in which WO is applied alone. When some local RE supply is available, the cost savings are significantly higher (between 7 and 15 times the value of c_*), allowing to completely nullify the energy bill even with intermediate RE system sizing (I, blue bars). Furthermore, results show that the RE generation system dimensioning has a relevant impact on the possible cost savings. Indeed, the installation of PV panels and storage with larger capacity (L, green bars) allows to obtain savings up to 120% of the energy cost, corresponding to positive revenues provided by the SG to the Mobile Network operator. Finally, in presence of RE, the benefits provided by the application of WO are lower with respect to the application of RoD alone, unlike the case when no RE generator is present. A RE generation system with intermediate size provides 88% cost reduction, and the application of RoD permits to nullify the energy cost. With a large RE system, positive revenues are always guaranteed. Focusing only on positive revenues paid by the SG to the mobile network operator, the impact of RoD is more evident, since the revenues are increased by 27% under WO only, by 40% under RoD alone, and by 53% when WO and RoD are combined.

Clearly, in case of RE production, additional capital expenditures (CAPEX) should be considered, due to the installation of the PV panels and the set of batteries. However, although the initial expenditure might be considerable, based on our results derived for several combinations of S_{PV} and B, it would be possible to select the proper dimensioning allowing to minimize the CAPEX+OPEX, taking into account the PV panel and battery lifetime duration. Furthermore, according to [20], after 8 years of RE powered mobile network operation the break-even point for CAPEX cost can be achieved. In addition, the introduction of a new energy management strategy could be envisioned, allowing to sell back to the SGO extra amounts of RE that are not immediately used and, in case they cannot be harvested in the storage, are usually wasted. The cost saving that could be obtained under the application of a similar energy management strategy are shown in Fig. 12, where they are compared against the case without any RE production and the case with a RE generator with intermediate size, assuming the application of the standard energy manage-

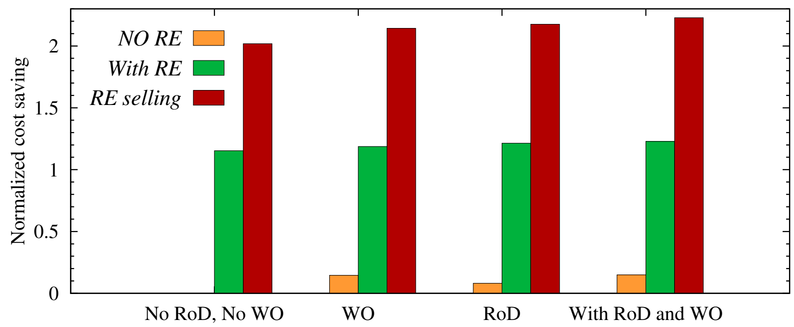


Fig. 12: Cost saving under three scenarios: 1) NO RE - no RE is produced; 2) With RE - under RE production (S_{PV}=10 kW_p, B=15); 3) RE selling - assuming that the extra amounts of produced RE are sold back to the grid.

ment strategy. The price per each energy unit that is sold to the grid is assumed to be half the price due for each energy unit bought by the mobile network operator from the grid, i.e. p_G. Cost savings result remarkably high when extra produced RE can be sold back to the grid, being more than twice the energy bill registered in baseline conditions in case no RE is present and no WO or RoD strategies are applied, c_*. WO alone allows to increase the cost saving by 12 additional percentage point with respect to the case in which no WO is applied. Up to 223% cost saving can be achieved by applying WO in conjunction with RoD. However, in relative terms, WO and RoD are equally effective in raising the cost saving, since they both provide savings that are about 1.8 fold higher those assured with the standard energy management strategy. These revenues may play a relevant role in compensating the higher CAPEX faced for the initial installation of a RE generation system.

Table 3 summarizes the effects on the performance metrics of the various combinations of resource management strategies, either without any local RE generator or under RE production. The main motivations at the basis of the different observed effects in terms of performance are highlighted in the last column.

8 Conclusions

This work investigates the impact of WiFi Offloading, possibly combined with a RoD strategy, on improving the interaction of a mobile access network with the SG in a Demand Response context, considering also the case in which a RE source is locally available to power the BSs.
Results suggest that WiFi offloading can be very effective in enhancing the capability of mobile networks to provide ancillary services to the SG operator. Under WO, up to almost 75% of SG requests of consumption decrease can be accomplished in

Table 3: Effects of strategies on performance indicators.

RE	RoD	WO	E_G	Cost	p_U	p_D	Motivations
-	-	✓	↓	↓	↑↑	-	a
-	✓	-	↓	↓	↑	-	b
-	✓	✓	↓	↓	↑↑	-	a, b, c
✓	-	-	↓↓	↓↓	↑↑	↑↑↑	d
✓	-	✓	↓↓	↓↓	↑↑↑	↑↑↑	a, d
✓	✓	-	↓↓↓	↓↓↓	↑↑	↑↑	b, d
✓	✓	✓	↓↓↓	↓↓↓	↑↑↑	↑↑	a, b, c, d

Motivations: a - Reduced traffic in case of D request; b - Reduced number of active BSs (hence E_G) in case of D request; c- Increased probability of switching off additional BSs; d - Improved capability of timely reacting to U and D requests.

our scenario even when no RE production is locally available. The introduction of a small local RE generation system combined with some storage remarkably improves the probability of positively reacting to the SG requests, that becomes close to 1 under larger RE generators. Furthermore, WO results beneficial even in reducing operational cost, 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 more than the probability of ancillary service provisioning is. Even with relatively small PV panel and storage dimension, the energy bill can be completely nullified, whereas under larger RE system size positive revenues can be achieved. Finally, a reduction of less than 50% in the energy drawn from the grid may correspond to cost saving higher than 100%, resulting in positive revenues, and confirming that a good energy management strategy does not operate by reducing the total grid consumption, but by timely increasing or decreasing the grid consumption exactly when required by the SG. Additional revenues obtained by selling back to the SG the extra produced RE may contribute to compensate for the CAPEX faced by Mobile Network Operators for the installation of RE generation systems. To this aim, optimization algorithms could be deployed as future work with the purpose of properly dimensioning the RE generation system, in order to minimize both CAPEX and OPEX cost for the MNO.

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