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***Abstract*—In a foreseen "post-peak" era, when oil production declines making energy price increase and leading to important economical implications descending from oil being the foundation of our industrial system, the development and maintenance of large infrastructures will become the more and more difficult due to possible power distribution outages and instabilities. The situation for communication infrastructures will probably be particularly critical due to the expected growth of service demand which will require the expansion of the networks and, corresponding, a growth of the power needs that could become difficult to continuously guarantee. Hence, critical infrastructures like communication networks will have to be equipped with power backup systems. In this paper, we focus on the effect of possible power outages on heterogeneous mobile networks. Starting from the characterisation of today outages, we assess the impact of outages on Quality of Service (QoS) of Radio Access Networks (RANs) and we discuss power backup system sizing.**

***Index Terms*—wireless cellular network, power outage, base station, energy battery, PV panel**

I. Introduction

The electric grid is a complex system, sometimes affected by external or internal factors that compromise the quality of the provided service. Storms, equipment failures, the presence of untrimmed trees, excessive customer demand, or unusual operating conditions, might generate outages of the energy supply. Since more than 60% of the electrical energy is still generated from fossil fuels [1] nowadays, the potential instabilities of power distribution will get worse in the next years by effect of what is called the consequences of the "post-peak" period, in which we are entering [2]. The peak oil is the moment of maximum oil production after which the post-peak period starts: oil production declines, with energy price growth and important economical implications descending from oil being the foundation of our industrial system. The economical implications of the post-peak will make power distribution more unstable, and the development and maintenance of big infrastructures much more difficult. Electricity has become a vital part of modern societies, being fundamental in our daily life, as well as in many sectors, such as governmental, commercial and industrial areas [3], [4]. For this reason, energy interruptions paralyse the daily routine, compromising all the services which directly rely on the power supply. Among these, mobile communication services are not an exception. Indeed, all devices of the communication network require electrical power to operate. Typically, this power is provided by the connection to the electrical grid. While devices in the core and backhaul networks that aggregate large amounts of traffic can rely on costly backup power systems, on the RANs, the situation is more complex, due to the large number of Base Stations (BSs) that are distributed all over. BSs rely on the power grid or where this is not available, such as in disadvantaged areas, on standalone diesel generators [5]. More recently, many studies present RANs whose BSs rely on Renewable Energy (RE) that is locally produced by generators, such as wind turbines or photovoltaic (PV) panels systems, in addition to the power provided by the electrical grid. Indeed, this new scenario is very attractive since it is a promising alternative to make the networks more sustainable and self-sufficient, while reducing also the electricity bill [6]–[9]. Various papers address the critical issue of properly dimension RE generation systems to power mobile networks [10], [11]. The sizing process entails trading off self-sustainability, cost and feasibility constraints due to the installation of a RE generation system. In [10], the problem of a proper dimension of the PV panels is investigated via simulation, whereas authors in [11] deploy models to derive the optimal RE system dimension for powering a BS.

In this work, we investigate the impact on mobile communication services of the occurrence of outages of the electric grid; the scenario is quite common in countries where the electric grid is not reliable but are expected to occur the more and more frequently also in other regions in which the power infrastructure is more reliable by effect of the power demand increase. These electric provisioning interruptions cause interruptions of the mobile communication service, if some elements of the networks are not equipped with energy backup systems. Since the most costly and complex segment to protect is the RAN, we focus on the energy provisioning of BSs under power outages. We consider a portion of an heterogeneous RAN, composed by 3 macro BSs, supported by 4 micro cell BSs and we consider two scenarios. First, each BS is equipped with energy storage. In case of power outage, each BS is supplied by its battery, and can run until its depletion. In the second scenario, each BS is equipped with a PV panel and when an energy outage occurs, it is powered by that, if the produced energy is sufficient for its supply. In the first part of our work, a first characterisation of the outages occurred in the city of Turin between 2014 and 2018 is proposed. Then, we discuss the benefits provided by the installation of backup batteries or PV panel. These backup systems allow to make the network more robust, reducing the risk of service interruptions with the consequent QoS deterioration.

II. Methodology

As already mentioned, in this paper we look at a portion of an heterogeneous RAN, which is composed by 3 macro BSs, implementing the standard of different generations of radio access technologies, respectively: Long Term Evolution (LTE), Universal Mobile Telecommunications System (UMTS) and Global System for Mobile Communications (GSM). These 3 macro BSs are supported by 4 LTE micro

BSs, whose area coverage overlaps with the coverage of the macro cells. Thus, each micro BS defines small cells providing additional capacity during peak traffic demand.

To cope with a power outage, when it is not possible to power the BSs through the grid, we consider two possibilities:

- *Battery* scenario: each BS is equipped with an energy battery that it is used to power the BS during the outages; in case the battery discharges before the outage is over, the BS switches off.
- *PV Panel* scenario: each BS is equipped with a PV panel system, and, when an energy outage occurs, each BS is powered by it. If the panel production is not sufficient for the supply, the BS is deactivated.

When a micro LTE BS turns off, its traffic is managed by the macro LTE BS, given that it has enough capacity to carry it. If this is not the case, the traffic is moved to the UMTS macro BS, if it has power supply and enough available capacity. In case also this macro cell BS is saturated or turned off, the traffic is moved to the GSM macro BS, if it is working. When, also for this BS, the available capacity is not enough or its battery or its PV panel are not providing the sufficient energy, the traffic is lost. Similarly, when the local energy is not enough to power a macro BS, the corresponding traffic is moved to one of the other macro BSs, if possible.

The system is simulated using an ad hoc developed discrete time simulator, with the time slot equal to 1 minute. The simulation lasts one day during which we assume that at some time during the day an outage occurs.

A. Power supply systems

In the scenarios considered in this paper, each BS is equipped with an energy battery, whose capacity is 1 kWh. The considered maximum Depth of Discharge (DOD) is 70% in order to maximise the battery life cycle duration and optimise the charging efficiency. Indeed, with this value of DOD, the battery operates for more than 500-600 cycles before being replaced [12], [13]. As in [14], the loss of energy during charging and discharging processes accounts for 25%. When BSs are equipped with PV panel systems, the capacity of the panel is 1 kWp (the kWp is the measure of the maximal theoretical production of the panel) and two cases are considered. The worst case corresponds to the day characterised by the lowest yearly solar energy production, and the best case to the day which presents the yearly largest solar energy production. They are denoted as *MIN* and *MAX* day, respectively.

B. Input data

1) Traffic data: In our study, we use traffic data provided by a large Italian MNO (Mobile Network Operator). The data report the hourly traffic volume at many BSs, in the city of Milan and in a wide area around it, for a duration of two months in 2015. In our work, each LTE BS is associated to one of these traces. According to [15], the users of a 3G network could generate up to 65% of the traffic generated in an LTE network. For this reason, we use a trace scaled by a coefficient 0.65 to generate the traffic carried by the UMTS BS. The traffic managed by the GSM BS is assumed negligible.

TABLE I: Values of the parameters of the consumption model for macro and micro LTE BSs.

BS type	N_{sec}	N_{trx}	P_{max} (W)	P_0 (W)	Δ_p
Macro	3	2	20	130	4.7
Micro	1	2	6.3	56	2.6

TABLE II: Values of the parameters of the consumption model for UMTS and GSM BSs.

	N_{sec}	N_{trx}	P_{tx}	P_{sp}	P_{cool}	C_{sl}
UMTS	3	2	50	127.7	0.29	0.14
GSM	3	2	114	54.8	0.27	0.11

2) Energy outage data: The data about outages are collected using [16] api, provided by an Italian Distribution System Operator (DSO). Given the year and the ID of an energy meter, it returns the outages occurred during that year, which involved that user terminal. Each record reports the location, the duration and the starting time of an outage. Data from 2014 to 2018, in the city of Turin, Italy, are collected for our study. Information about users, e.g., energy meters, spread over the whole city are collected in order to have representative data for the considered urban area.

C. Energy consumption model

The energy consumption of a BS strictly depends on the technology which is implemented by that BS. The energy consumption model of the LTE BS is given by:

$$P_{in} = N_{sec} \cdot N_{trx} \cdot (P_0 + \Delta_p P_{max} \rho), \qquad 0 \le \rho \le 1 \quad (1)$$

where N_{sec} is the number of sectors, N_{trx} is the number of transceivers, P_0 represents the power consumption when the radio frequency output power is null, Δ_p is the slope of the load dependent power consumption, ρ is the traffic load and P_{max} is the maximum radio frequency output power at maximum load. Table I summarises the value of the parameters for macro and micro BSs [17].

According to [18], the energy consumption of UMTS and GSM BSs is not load dependent and it is given by:

$$P_{in} = N_{sec} \cdot N_{trx} \cdot (P_{tx} + P_{sp})(1 + P_{cool})(1 + C_{sl}) \quad (2)$$

where, as before, N_{sec} and N_{trx} are the number of sectors and the number of transceivers, respectively. P_{tx} is the transmission power, P_{sp} is the signal processing overhead, P_{cool} is the power used for the cooling and C_{sl} is the power supply loss. These values are reported in Table II.

D. Performance indicators

As an indicator of QoS we consider the lost traffic during the outage, taking into account that some BSs are active and manage the traffic demand, while some others are switched off because of lack of energy and do not provide any service. It is measured as follows:

- *Percentage of lost traffic at time slot t*:

$$T_{lost,t} = \frac{T_{d,t} - T_{s,t}}{T_{d,t}} \cdot 100 \quad (3)$$

where $T_{d,t}$ and $T_{s,t}$ are, respectively, the traffic demand and the traffic served at time slot *t*;

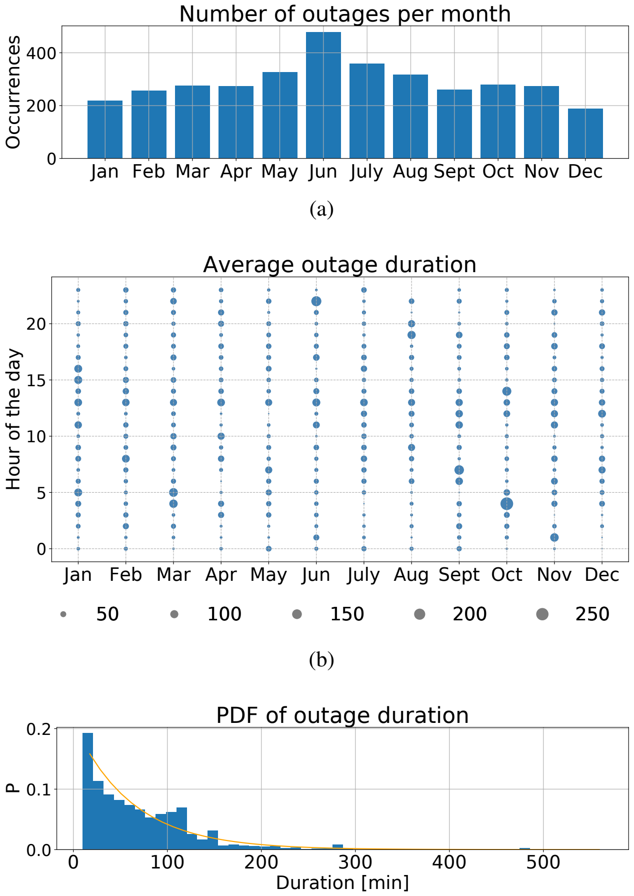


Fig. 1: Characterisation of outages occurred between 2014 and 2018 in Turin: (a) Number of outages per month, (b) Average duration of outages for each hour of the day and for each month, (c) PDF of the outage duration.

- *Total lost traffic (bit)*:

$$T_{lost} = \sum_{t=1}^{K} (T_{d,t} - T_{s,t}) \tag{4}$$

where K is the duration of the simulation.

III. Results

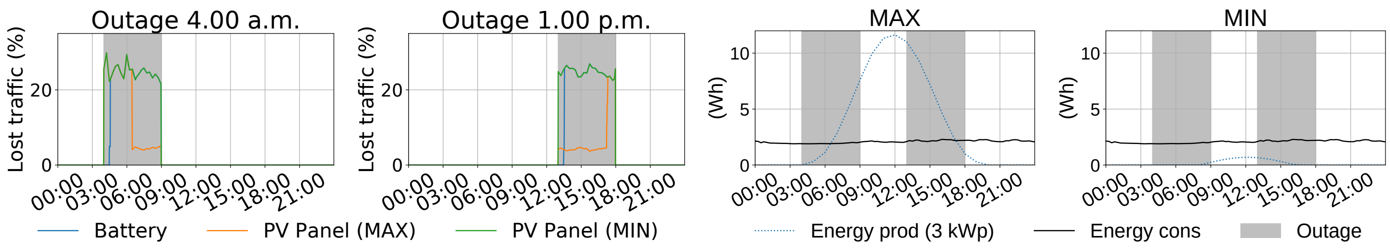
A. Power grid outages

In this section, we discuss the characterisation of the outages as derived from our data set. As mentioned in Sec. II-B, the data set collects the outages occurred between 2014 and 2018 in the city of Turin, Italy. Fig. 1a reports the number of outages which occurred in each month. We notice that between May and August there is a significant increase of the number of outages, with a visible peak in June. This is possibly due to air conditioning systems that are largely used in these months, causing overloads and, hence, faults in the system. Fig. 1b summarises, for each hour of the day, during each month, the average duration of the outages. A larger size of a circle means larger average outage duration. We notice that the longest periods of energy outage occur at 4.00 a.m. and at 1.00 p.m., that is when energy consumption starts growing after a period of time in which it was decreasing. The power grid has to rapidly react to this inversion of trend, sometimes occurring in faults. Finally, Fig. 1c shows the Probability Density Function (PDF) of the outage duration. Notice that half of the outages has a duration lower than 40 minutes, while only 8% lasts more than 2 hours. The red line is the PDF of the exponential distribution with the same mean value. The matching is pretty good, indicating that for possible analytical models or long simulations, the use of an exponential distributions of fault duration provides a good approximation.

B. Performance evaluation

In this section, we discuss the results obtained simulating the described scenarios for one day. We investigate the cases in which an outage occurs at 4.00 a.m. and at 1:00 p.m. This schedule has been chosen since, as discussed in previous section, these ones are the most typical starting times of outages, according to our data set. Moreover, these hours significantly differ from each other in terms of traffic volume: they represent off-peak and peak traffic demand periods, respectively. We suppose that faults last for 300 minutes, which is the longest duration according to our date set (see Fig. 1c).

In Fig. 2a, the percentage of lost traffic is reported in blue, orange and green, when the *battery* scenario, the *PV Panel* scenario in *MAX* and *MIN* day are considered, respectively. Fig. 2b shows the energy production of the PV panel (dotted blue line) and the energy consumption of one of the micro BSs (black line) of the considered RAN. The outage periods are highlighted by grey blocks in these figures. These plots reveal that in the *battery* scenario, the lost traffic behaves similarly in both outage starting times: some traffic is lost as soon as batteries exhaust. This happens later, if the outage occurs in off-peak period, e.g. at 4.00 a.m., since the energy consumption is lower, due to the smaller traffic demand. In both outage starting times, up to 30% of traffic is lost. In case of *PV panel* scenario, performance strictly depends on the production characteristics of that day. In case of low energy production, e.g. *MIN* day, the produced energy is usually insufficient for the supply of a BS, which is then turned off. For this reason, up to 30% of traffic is lost during the outage. The case of *MAX* day, e.g. high energy production day is different. When the outage starts at 4.00 a.m., the renewable energy is not enough for the BSs supply until 6.00 a.m. After that, the energy production increases, and when enough, BSs are activated, generating the lost traffic reduction up to 5% (orange line in Fig. 2a) with respect to the previous case. When the outage starts at 1.00 p.m., the large amount of available energy allows to keep active the BS (Fig. 2b) for a long period since the beginning of the outage, keeping the percentage of lost traffic below 5%. Then, because of the drop of the produced energy, it grows up to 30%. Now, we investigate the effects of the backup capacity dimensioning. In Fig. 3 the total lost traffic is plot increasing the capacity of the back-up energy source. Orange lines show the traffic volume which is lost in the *battery* scenario, while the green and the blue lines represent the lost traffic volume in the *PV panel* scenario, in the *MAX* and *MIN* day, respectively. Lines marked by the circles and by the crosses are used, respectively, when the outage starts at 4.00 a.m and at 1.00 p.m. The figure indicates that the growth of the capacity improves the QoS, reducing the lost traffic, since the survival of each BS, since the beginning of the outage, is longer. In addition, the usage of the PV panel provides



(a)

(b)

Fig. 2: Performance evaluation: (a) lost traffic (%) when the outage starts at 4.00 a.m. and at 1.00 p.m., (b) Energy consumption of a micro cell BS and solar energy production during the day, during low and high energy production days.

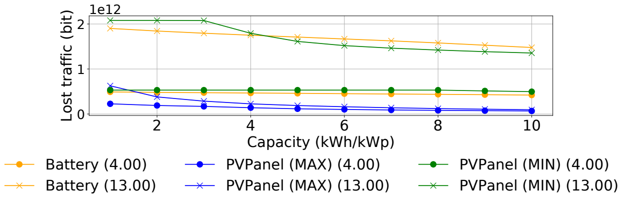


Fig. 3: Lost traffic (bit), when varying the energy battery or the PV panel size

at least the performance achieved with the battery (green and orange lines, respectively). During days characterised by large renewable energy generation (blue lines), the QoS significantly improves with respect to the *battery* scenario.

IV. Conclusion

In this paper, the effects of electric grid outages on the RAN are considered. First, based on real data, we characterise the outage occurrences, as well their duration, in the city of Turin (Italy). We notice that most of the outages occurs during the warmest period of the year, and they last on average 44 minutes. In addition, we realize that the outage duration can be well modeled with an exponential distribution. In the second part of our work, we consider a RAN composed by an LTE macro BS, an UMTS macro BS, a GSM macro BS and 4 LTE micro BSs. Each BS is equipped with a battery or a PV panel, as power backup system, to cope the lack of energy supply, when an outage in the electric system occurs. Results reveal that the presence of this energy backup systems effectively mitigate the effect of electricity system outages on the mobile communication service. Indeed, when it is introduced, the QoS, measured in percentage of lost traffic, is significantly improved. The PV panel employment, besides the benefits in terms of energy bill, sustainability and self-sufficiency, largely demonstrated in literature, is an effective solution to strongly improve the QoS in this scenario. As next steps of our work, we will discuss a scenario in which both an energy battery and a PV panel system are used. We will also introduce a BS switching management, based on the energy locally generated and stored on each BS. The statistical formalisation of results will be derived.

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