POLITECNICO DI TORINO

Master Course in ICT for Smart Societies

Master Thesis

Managing the mobile access network under unreliable power grids

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Summary

For the power grids the mobile access network is among the most critical power consumers, in case of faults on the power grid it is important to find solutions to guarantee to the users the communication capabilities with the best quality available for as long as possible. The aim of this thesis is to study the case of power outages in the Turin Metropolitan area by analyzing the data provided from a local power distribution company in order to model the impact of these even on the radio access network. By cross analyzing the data about power outages with information about the RAN of one of the major Italian carriers it is possible to simulate a realistic scenery and to develop suitable management strategies. The simulations carried out take advantage of real traffic profiles from comparable urban areas and provide hints to which are the best choices to make in these events to meet the users expectations in terms of coverage and service quality.

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Chapter 1

Introduction

The electrical networks are a crucial asset for the modern telecommunications networks. Climate change is causing stronger storms which along with the increasing consumption for heating and cooling in the ever more extream weather conditions put the reliability of the electrical networks at risk. Along with these problems we are now also facing the challenge of migrating towards more sustainable energy sources. This historical transition is profoundly changing the energy market and the infrastructure is struggling to keep the pace of the changing generation and demand profiles. The energy consumption of the ICT has also seen a steady rise in the last years and this makes it vulnerable to faults on the power grids due to increased dependency on power. These issues have often consequences on the correct operations of the network often resulting in interruptions in the power delivery. These energy interruptions interfere with the normal operations of the equipment outside of the grid, compromising all the services that rely on this infrastructure. The telecommunications networks are no exceptions and while the core network and the backhaul have backup generators the *radio access network* - **RAN** - is more difficult to power due to its large extension and to how different are the devices it is composed of. Up to this day the solution to this problem is providing generators or batteries to the *base transceiver stations* - **BTSs** - in order to keep them operational in case of a power outage.

In this work the impact of the power outages on the RAN is investigated. First the phenomenon is examined in an urban scenario along with the characterization of a typical structure for a RAN in an urban environment considering cells of different sizes and using different technologies. Each *base station* - **BS** - inside the RAN is considered to be equipped with a battery backup that in case of a power outage is used until its depletion. However batteries are costly in deployment, maintenance and in terms of environmental impact, so their usage must be kept at a minimum. The optimal size of the battery is eventually discussed in order to ensure a certain *Quality of Service* (**QoS**) during power outage events.

1.1 Introduction to electrical networks

The electricity network is an heterogeneous system composed of different actors each in charge of a specific task. The electricity system can be divided into various subsystems which are responsible for the generation, transmission, distribution and consume of the resources.

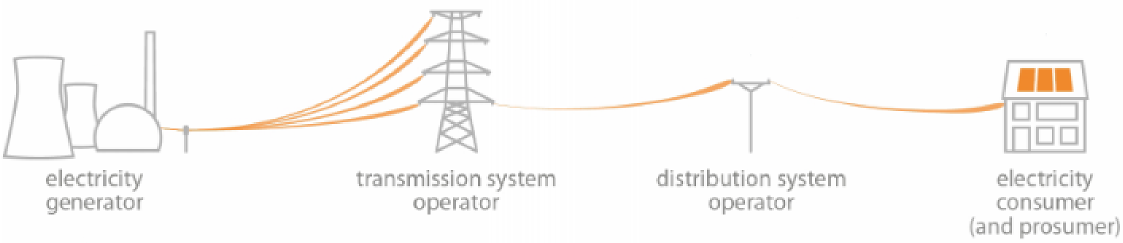


Figure 1.1: Power network structure

Source: EPRS | European Parliamentary Research Service

- The **electricity generation** comes in traditional networks form huge power plants which are slow in reacting to the demand change during the day and in case of major events impacting the network. In recent years the network has started to evolve by using new smaller generation sites which can help the network to cope with response time problems, however since their power is limited those need to be in a huge number and to be distributed on the territory Rooftop solar panels and small wind turbines for example are able to produce power in the order of some kW while big generation plants such as dams and coal power stations which can easily reach several GW of power produced.

- **Transmission networks** are the set of high voltage lines in charge of delivering power across long distances. Since losses depend on the current flowing in a medium, those high voltages ranging from 220kV to 1000kV are used to reduce the current in a line even with huge power loads.
- **Distribution networks** take electricity from the transmission networks and prosumers and bring it to the final users. Voltages in this area of the network are lower since it covers a smaller area.

In Italy the generation is performed by ENEL and some private companies, transmission by TERNA and distribution by companies operating on a local scale such as IRETI and companies operating on a national scale such as ENEL Distribuzione.

1.1.1 Power outages

Power outages happen when a fault happens in one of the components of the grid happens. Those events can be more or less widespread according to the section of the network where the incident happened. The electrical grid is structured as a **meshed system** to be more fault resistant but it is operated as a **radial system** which can be reconfigured in order to exclude from the network faulty branches. The network can also be reconfigured in case of a change power need or in order to match the power generation with the power distribution. Because of this design feature faults on the transmission network do not always result in a power outage on the distribution network. This happens thanks to the *Supervisory Control and Data Acquisition* - **SCADA** - systems installed on the network which allow - when possible - to reconfigure it automatically according to events provided directly from sensors deployed on the grid components. The events impacting the RAN are those with consequences on the distribution network which is where the BTSs draw their power from.

1.2 Introduction to the Cellular Networks

1.2.1 Useful definitions

- **Mobile Station** (**MS**) is a term used to denote a mobile device which is used from a user to access the network.
- The **Base Transceiver Station** (**BTS**) consists of an antenna and the transceiver radio equipments needed to communicate with the MSs on the field.
- A **Cell** is the area covered by a single BTS in which the MS can roam and still get service.
- **BSC** stands for **Base Station Controller** which is the main network element inside the BTS. It allows the communications from and to the core network.
- The **Base Station Subsystem** - Figure 1.2 - is an apparatus which is in charge of managing one or more BTSs and their BSC. Its tasks include managing the radio resources, the transmission quality and the channel allocations. Since one BSS can manage more than one BTS a BSS can cover quite a large area.

1.2.2 The cellular network

A **Cellular Network** is a network which allows user to communicate in mobility from one small sized zone to another using personal mobile devices. Nowadays those infrastructures are critical also for data transmission for people, appliances and sensors belonging to the internet of things. Internet connected devices exploit the cellular network to make intra-cell or more frequency inter-cell communication.

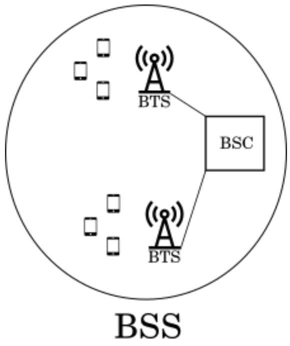


Figure 1.2: Portion of the cellular network composed of a single BSS and multiple BTS

The need for small cells happens since it is not possible to cover large areas with the everyday higher bandwidth requests. Not all zones have the same density or size since it depends on the number of devices in the area covered from the cell. In a cellular network in order to satisfy the user demand, since the bandwidth is finite, the **BTS** can be installed for a smaller area with more power by using a directional antenna to cover a specific sector. This allows from a single installation on a tower to give more coverage to a specific zone underneath. Traffic between zones is almost never equally distributed as in fact when estimating the maximum network capacity, [5], always assumes that it is those 15% of the cells that become congested and limit the total capacity. At the same time, 85% of cells are not assumed to be congested.

1.2.3 Cell types

In order to satisfy the different needs for transmission power and coverage different types of cellular base station, known as cells, exist:

- **Macro cells** are base stations suitable for larger area such as suburban or countryside areas. Those cells need specific towers to be installed on, require more power and can serve many users although with an impact on performance. Older standards rely mainly on this type of cells.
- **Umbrella cells** are a special kind of macro cells. Since micro cells can cause lots of handovers if the MT is travelling at a fast speed, the umbrella cells aim

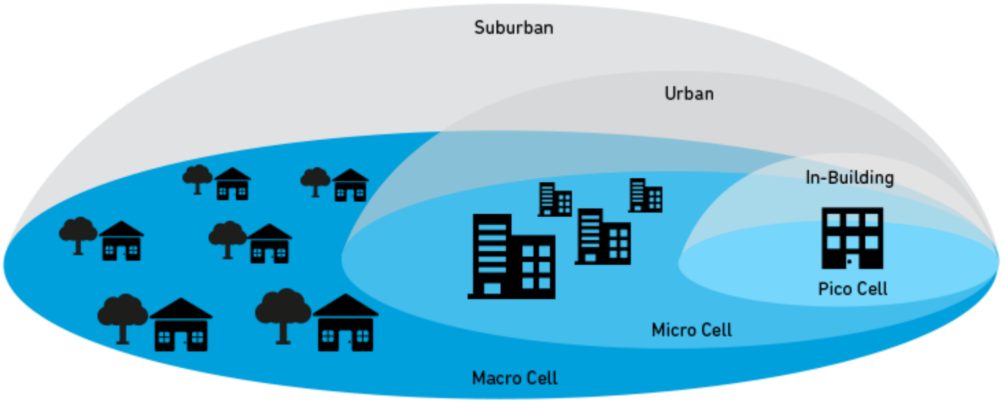


Figure 1.3: Coverage area for cells using different technologies

Source: Qorvo

at solving this problem by covering an area with a dense presence of micro cells.

- **Micro cells** have gotten more popular since the introduction of 4G and are frequently found in metropolitan areas, to improve service quality for densely populated areas such as train stations or sport venues.
- **Pico cells** are even more compact and low power, their usage is common in theaters and other indoor locations.
- **Femto cells** are the smallest tier and provide coverage for single rooms or floors inside buildings.

1.2.4 Cellular standards

Since the RAN has evolved during the years and still is, various technologies power the BTSs that it is composed of. Those different technologies are categorized into 3 main generations, each improving on the predecessor in network capacity and power consumption, however the older standards are maintained for compatibility purposes.

2G

Also known as GSM was introduced in 1992 and as opposed to 1G it is completely digital. Even if it is almost 30 years old it is still widespread nowadays. Being digital it has been the first mobile packet service used for both data and SMS. With the growing data demand 2G was evolved and the release of **GPRS** and **EDGE** specifications allowed for an improved data transfer speed up to 250 Kbps. The GSM standard uses the 900 Mhz and the 1800 Mhz bands. In cities and urban areas the larger band is more used since it allows for more users on the same BTS. Also the data transfer speeds improve on this band reaching the 250 Kbps limit. In rural areas the 900 Mhz band is preferred since this frequency has a better propagation in zones with a presence of vegetation which could disturb the signal. When covered by this frequency band the performance drop only allowing the calls and SMS throughput since the average 20 Kbps internet speeds are too low for today's internet.

3G

This standard has been introduced to cope with the ever growing data demand from the mobile customers in 2003. Since the introduction of 3G users have been able to browse the internet and even watch videos from their devices. The first evolution of the 3G standard allowed internet speeds ranging from 500 Kbps up to 2 Mbps. During the years through evolutions such as **HSPA** (*High Speed Packet Access*) the internet speed has grown up to 20 Mbps. 3G mainly runs on the 2100 Mhz band which has a shorter propagation distance with respect to 2G frequencies, to cope with this problem 3G signals have been also transmitted on the 900 Mhz band to improve reception in rural areas and to create umbrella cells in densely populated zones.

4G

Launched in Italy in 2012 4G is the direct evolution of the 3G standard. Data transfer rates, in the first evolution, for the users can reach 50 Mbps, this coupled with the reduced latency allows for a wider application of the standard from the wireless sensors networks to the HD video calling. With subsequent evolutions such as **LTE Evolution** speeds over 1 Gbps can be reached. Phone traffic in 4G is routed through the internet in a packet switched domain;**VoLTE** allows for a more efficient call management and a better quality for the user. In Italy carriers have licensed 3 bands, 800 Mhz 1800 Mhz and 2600 Mhz. Having those bands allows for an efficient spectrum management in 4G since the lower frequency bands can more easily propagate in rural areas and indoor with lower speeds; while the 2600 Mhz band allows for more speed and capacity in dense urban areas or in aggregation places.

1.2.5 Power Consumption

In literature are present power consumption models for each BTS standard and size, useful for modelling these objects.

2G & 3G

In [7] a power consumption model for 2G and 3G BTS has been calculated with the main goal of "making realistic input parameters available for the simulation of total network power consumption in mobile communication networks and to compare different heterogeneous cell deployments." In 1.2 the main parameters of their model are shown. As stated in their research, "the power consumption of a base station consists of two parts, modeled concurrently;the first part describes the static power consumption, a power figure which is consumed already in an empty base station", a second dynamic part instead models the load dependent consumption. When developing that model it has been noted that power consumption variations varied only up to 5% while the traffic load varied from a no load to a peak level. Because of this it can be assumed that for older BTS the dynamic part is negligible.

$$P = N_{\text{sector}} \cdot N_{\text{PAperSector}} \cdot \left(\frac{P_{TX}}{\mu_{PA}} + P_{SP} \right) \cdot (1 + C_C) \cdot (1 + C_{PSBB}) \tag{1.1}$$

Parameter	Description	Parameter	Description
$N_{\mathbf{sector}}$	Numer of sectors	P_{SP}	Power for signal processing
μ_{PA}	Power amplifiers efficiency	C_C	Cooling consumption
$N_{\mathbf{PAperSector}}$	Number of PA per sector	$C_{\mathbf{PS}}$	Power supply consumption
P_{TX}	Tx power		

Table 1.1: Power consumption parameters description for 3G and 2G model

Source: A. Oliver, 2010 [7]

BS Type	$N_{\mathbf{sector}}$	$N_{\mathbf{PAperSector}}$	P_{TX}	μ_{PA}	P_{SP}	C_C	$C_{\mathbf{PS}}$
2G Macro	3	2	40	0.35	54.8	0.27	0.11
3G Macro	3	2	20	0.4	127.7	0.29	0.14

Table 1.2: Power consumption parameters for 3G and 2G model

Source: A. Oliver, 2010 [7]

4G

In [2] an analysis of the power consumption of a 4G BTS is made, both for macro and micro cells. It has been followed the same approach as in [7], describing a static and a dynamic power consumption model; in this case as opposed to the older BTS there is a significant power consumption reduction associated with the load reduction.
"The power consumption depends on the traffic load; it is mainly the PA power consumption that scales down due to reduced traffic load. This mainly happens when, e.g., the number of occupied subcarriers is reduced in idle mode operation, and/or there are subframes not carrying data. Naturally this scaling over signal load largely depends on the BS type; for macro BSs the PA accounts for 55-60% of the overall power consumption at full load, whereas for low power nodes the PA power consumption amounts to less than 30% of the total."
The relation of the power consumption with the RF output power P_{out} - generated

from the traffic load - and BS power consumption P_{in} are nearly linear. The power consumption model is stated in Equation 1.2.

Parameter	**Description**	**Parameter**	**Description**
$N_{\mathbf{TRX}}$	Numer of transceivers	Δ_P	Dynamic power
$P_{\mathbf{max}}$	Max output power	$P_{\mathbf{sleep}}$	Sleep power
P_0	Idle power		

Table 1.3: Power consumption parameters description for 4G model

Source: EARTH Project [2]

BS Type	$N_{\mathbf{TRX}}$	$P_{\mathbf{max}}$	P_0	Δ_P	$P_{\mathbf{sleep}}$
4G Macro	6	20	130.0	4.7	75.0
4G Micro	2	6.3	56.0	2.6	39.0

Table 1.4: Power consumption parameters for 4G model

Source: EARTH Project [2]

$$P_{in} = \begin{cases} N_{TRX} \cdot (P_0 + \Delta P_{\text{out}}) & 0 < P_{\text{out}} < P_{\text{max}} \\ N_{TRX} \cdot P_{\text{sleep}} & P_{\text{out}} = 0 \end{cases} \tag{1.2}$$

1.2.6 Estimation of inter cell interference

Inside the RAN the BTSs are placed in order to cover the most of the users with the least number of BTSs in order to keep the costs as low as possible. However due to the propagation of the signal not being easily predictable and manageable, especially in dense areas it happens that a certain percentage of the area covered from a BTS is also covered from other BTSs. In [3] is provided a mathematical formulation for the estimation of the area inside an hexagonal macro cell overlapping with the adjacent cells. This happens because even if cells are modelled as hexagons - Figure 1.4a - , in order not to leave any spot without coverage, in the real world the signal distribution works by using circular shapes. This leads to areas covered by multiple BTSs as shown in Figure 1.4b. The area subject to interferences χ -

shown in grey - is function of the area of the BTS expressed in km^2, the variable x in Equation 1.3. The variation of the percentage of the BTS area subject to interferences according to the BTS area is shown in Figure 1.5.

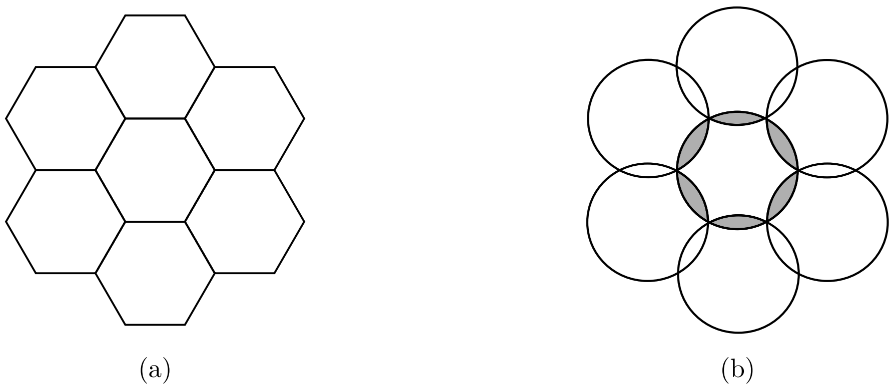


Figure 1.4: BTS transmission and interference area

Source: [3]

$$\chi = \frac{4 \cdot (2\sqrt{3} - 3)}{\pi x} \tag{1.3}$$

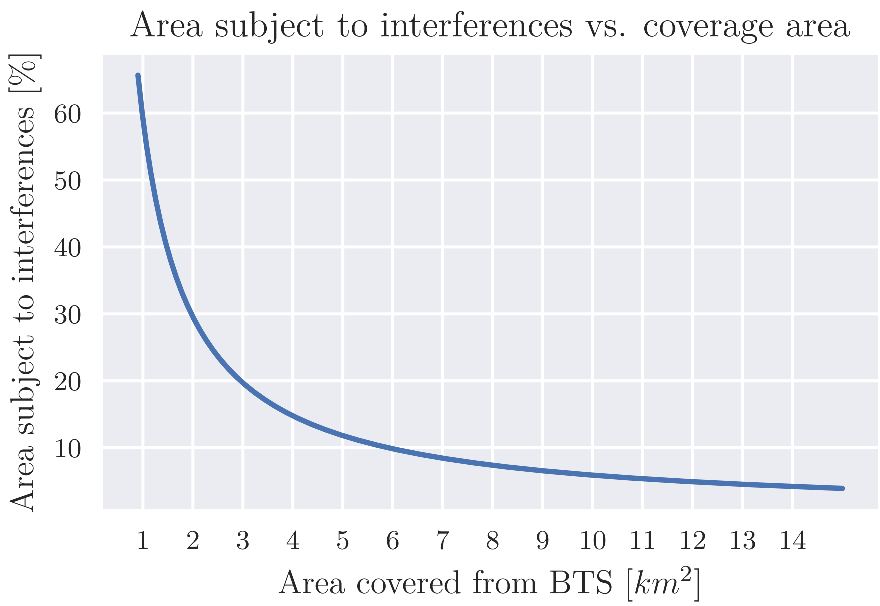


Figure 1.5: Percentage of BTS coverage area subject to interferences

Source: [3]

1.3 Batteries

Each BTS is equipped with a *uninterruptible power supply* - **UPS** - containing battery cells to provide emergency power in case of the grid being unable to ensure the correct operations of the equipment.

1.3.1 State of the art

As stated in [9], self-discharge, ageing mechanisms and depth of discharge are the main problems to tackle when dealing with batteries and those must be taken into account when simulating a battery.

Losses can occur while the energy remains stored into the battery, namely self-discharge or idling losses, and determine the maximum storage duration in which the battery holds its charge before needing to be topped off. Energy expenses are required to compensate for self-discharge losses and/or sustain certain conditions of operation such as being ready for when an outage happens. These energy expenses are known as parasitic losses and common examples include the trickle charging of batteries, where attention must be paid so that the rate of supplied energy does not overcome the respective self-discharge, leading to system overcharging. These can be taken into account into the simulator by using a multiplicative factor when calculating the energy needed for charging the battery. This extra consumption will compensate for both parasitic losses during charging and while holding the charge.

Ageing mechanism is a phenomenon which is common in all battery technologies and sizes and applies to "any chemical or mechanical reason leading to system failure". These mechanisms can be described as "long-term gradual degradation and or abrupt causes that, along with stress factors, configure the system service period expectancy".

The maximum depth of discharge, "determines the maximum exploitable energy storage capacity of a system in order for smooth operation to be guaranteed". The state of charge of the battery should always be over the defined minimum value, defined as 1 - DoD, while it should be noted that both charging and discharging efficiency are considerably affected once certain SoC values are exceeded so it is convenient to provide more battery capacity than needed in order to preserve battery efficiency.

Other than the technical constraints posed from the battery itself when dealing with batteries coupled with network equipment also the challenges posed from the network equipment itself must be taken into account.

1.3.2 Battery technologies

In [8] is stated that among the four more widespread technologies in the battery industry, some technologies outperform the others in certain indicators. The battery systems taken into account consist of battery cells, which are connected in parallel and series, coupled with power, which include DC/DC and DC/AC transformers, and conditioning facilities needed to keep the battery at the optimal working point to allow for optimum charging and discharging process. In Table 1.5 are shown the main metrics used for different battery technologies. The technologies taken into account are:

- **LAB** *Lead Acid Battery*
- **LIB** *Lithium-ion Battery*
- **NAS** *Sodium Sulfur Battery*
- **VRB** *Vanadium Redox Flow Battery*

Looking at the values in the table it is possible to understand why LAB batteries are the choice for giving backup energy to BTS. While having the least DoD and thus requiring more installed capacity in order to provide the same energy with respect to the other technologies iy has the smallest rating costs for energy and power. Even the smallest number of possible cycles before degradation happens is not a problem, in fact these batteries are not supposed to perform many cycles since outages are supposed to be an exceptional event with only some occurrences during the year. Since the huge number of BTS installed it is important to maximize the interval between the installation of a battery and the moment it needs to be replaced. LAB batteries prove to be the best in this field since if operated according to their characteristics they can last up to 30 years before needing to be replaced.

[1]The number of cycles with maximum DoD

Technology	**LAB**	**LIB**	**NAS**	**VRB**
Charging Efficiency (η_{ch})	0.78	0.99	0.89	0.85
Discharging Efficiency (η_{dis})	0.78	0.99	0.89	0.85
Maximum DOD (DoD_{max})	70%	80%	100%	75%
Maximum SOC (SoC_{max})	100%	100%	100%	100%
Minimum SOC (SoC_{min})	30%	20%	0%	25%
Number of cycles [1](N_{cycle})	1500	2500	2500	12000
Power Rating Cost(€/kW)	256	975	413	717
Energy Rating Cost(€/kWh)	264	2030	413	359
O&M Cost(€/year/kW)	20.7	17.9	42.5	40.6
Lifespan (years)	15-30	10	15	10

Table 1.5: Battery performance indicators

Source: [8] and [4]

Chapter 2

Data analysis

2.1 Outage analysis

In Italy companies which operate in the energy transmission and distribution market have to report the information about the quality of the service provided to ARERA (*Autorità di Regolazione per Energia Reti e Ambiente*).
One of the most important **metric** when measuring the **quality** of the electricity supply is the service continuity which means the absence of interruptions in the supply of electricity. Interruptions can have different origins, they can be originating on the high voltage national transmission network or they can be due to force majeure reasons. Those events can be divided into two main categories, those "**with notice**" (at least one day of forewarning) and those "**without notice**". Those without notice can be themselves divided into "**long**" (longer than 3 minutes), "**short**" (between 1 second and 3 minutes long) and "**momentary**" (less than one second long).
Each year companies operating in the electricity market have to report to the Authority the continuity data about the previous year, a set of informations about the number of interruptions, their origin points, their causes and their duration. However these data are subject to aggregation and because of this are less useful because it is impossible to select data about a selected region or a certain time slot.

However some companies release the data reported to ARERA on their own. These data are not subject to aggregation and are therefore more suitable for research purposes. It has then been decided to focus on the main transmission company, TERNA, and the distribution company operating in the urban area of Turin. In the first place the transmission network has been taken into account to check how many events have a direct impact on the distribution network the RAN is connected to. Then the analysis switched its focus to the distribution network which the RAN draws the power it needs from.

2.1.1 Outages on the TERNA network

TERNA, the company responsible in Italy for managing the transmission network publishes each year a report containing along with other information, the **cause**, the **duration** and the **energy not supplied** to the distribution network for each event. A couple of rows from this dataset are visible in Figure 2.1 the complete data set is available in Appendix A, section A.1. In Figure 2.2 is shown the distribution

n° Disalimentazione	Area	Data (gg/mm/aaaa)	Ora (hh.mm.ss)	Descrizione elemento di rete origine della disalimentazione	Titolare rete origine della disalimentazione	Tensione rete origine della disalimentazione (kV)	Codice causa AEEG - 1° livello	Codice causa AEEG - 2° livello	Tipo interruzione	Configurazione rete all'istante della disalimentazione	Nome del Sito utente AT disalimentato	Codice univoco del Sito utente AT	Connessione alla RTN	Tipologia di connessione	Tensione Sito utente AT (kV)	Titolare del Sito utente AT	PI (MW)	Durata disalimentazione AT (mm.ss)	ENS/ENR lorda (MWh)	ENS/ENR netta (MWh)	NF/NR/SD	N° Incidente rilevante	N° Potenziale Incidente rilevante	Durata effettiva di disalimentazione degli Utenti finali MT e BT (mm.ss)	Indennizzo a Cliente finale AAT-AT	Versamento al FEE	ENS-U lorda (MWh)	ENS-U netta (MWh)	ENR-U lorda (MWh)	ENR-U netta (MWh)
1682	PA	01/08/2017	06:30:00	Linee	TERNA	150	5DP	500	L	S0	FRANCOFONTE	PPALFRNP	R	M	150	ENEL DISTRIBUZIONE	0,00	120,00	0,00	0,00	NF			120,00	NO	NO	0,00	0,00	0,00	0,00
2512	NA	01/08/2017	08:00:00	Stallo linea	TERNA	150	5DP	500	L	S1	CELLE S.VITO	NNAPECEN	R	R	150	E2I ENERGIE SPECIALI	0,00	480,00	0,00	0,00	NR			480,00	NO	NO				
2512	NA	01/08/2017	08:00:00	Stallo linea	TERNA	150	5DP	500	L	S1	IVPC4 CELLE S.V.	NNAPICLN	R	R	150	ERG WIND 4	0,00	480,00	0,00	0,00	NR			480,00	NO	NO				

Figure 2.1: Example rows from the TERNA data set

Source: TERNA Group

of all the events except for the planned outages for which the network could be reconfigured in advance. In Figure 2.3 is shown the distribution of the outage events which had an impact on the distribution network. Comparing Figure 2.2 and Figure 2.3 it can be seen that only a small part of the events on the transmission network have an impact on the distribution network; as stated before this happens since the transmission network was built using a meshed structure. This structure by allowing fast reconfiguration according to automatic and manual reports leads to more robustness towards these events. The events on the transmission network

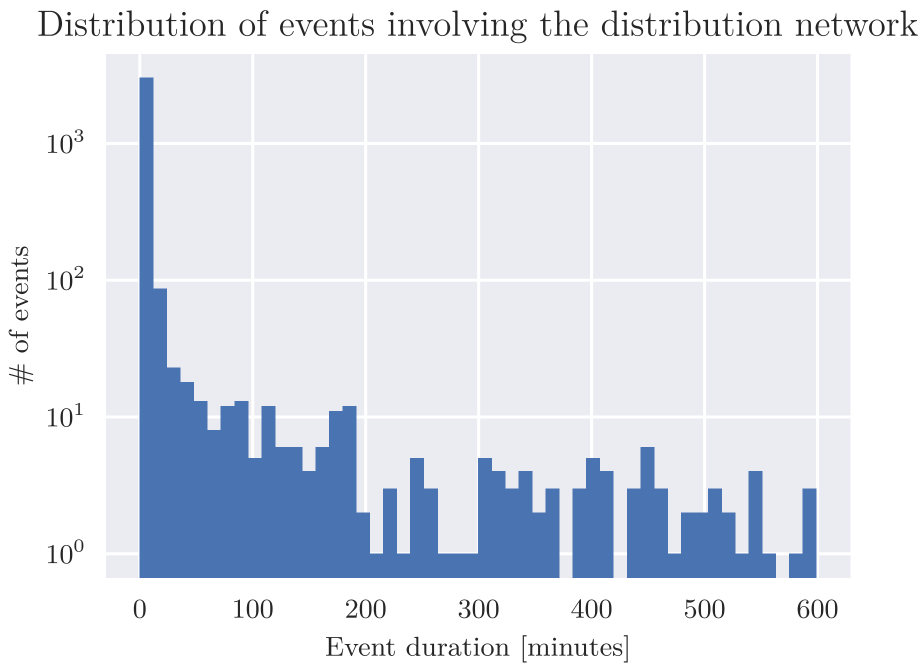


Figure 2.2: Outage event distribution

Source: TERNA data, 2016-2018

have a duration that is exponentially distributed with more than a thousand short events (lasting $\leq$ 10mins.) and few longer events lasting more than an hour. Even when an event has an impact on the distribution network the outage duration is usually lower than 10 minutes as visible in the spike in Figure 2.3. In fact during the period 2016-2018 the outages lasting more than 10 minutes across the national territory were numerically negligible.

2.1.2 Outages on the IRETI network

IRETI is a private company part of IREN group which manages electricity, methane and water distribution all over the Italian territory. Through a 7700 km long network made of high, medium and low voltage lines this company manages electricity distribution in the cities of Parma, Turin and Vercelli to around 720000 customers. In 2018 the company distributed around 4000 GWh of electricity to the end users.

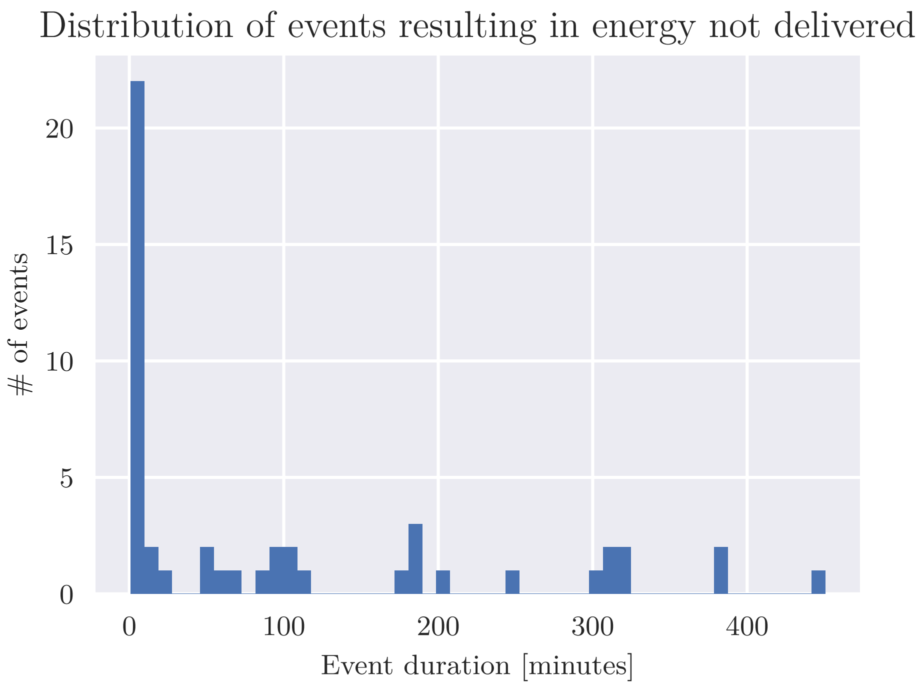


Figure 2.3: Distribution of events with impact on the distribution network

Source: TERNA data, 2016-2018

Because of European transparency laws, all the utility companies are forced to provided metrics on their performance to the customers to allow choosing the best performing company in the free market regulations. IRETI because of the regulations provides an API which by inserting a POD number and the year of reference can be used to retrieve the information about all the outages relative to that pod for the year of reference.

The POD is an alphanumeric code which identifies in a unique way the withdrawal point of the electric energy from the grid. The end user can find the POD on the electricity bill. Usually, the POD is composed of 15 alphanumeric characters and it starts with the letters IT. The three following numbers are the unique identifiers of the distribution company; then the letter E follows and it represents the "Energia" word. The next 8 or 9 numbers are the identifier of the withdrawal point, the 9^{th} is optional. This code is like the license plate of the electricity meter and it does not change if the user changes the electricity distribution company.

With the help of a *Python* script a dataset has been populated. This script is built to simulate a user navigating the IRETI site and inserting the appropriate POD number and year in the apposite fields. In order not to flood the IRETI servers and not to get banned from querying the API the script was limited to one query every 5 seconds. To keep the time in a reasonable range the script collected data only for $\frac{1}{100}$ of the possible POD codes and it searched only the last 6 digits of the codes because of errors that arose when trying higher codes. In the future the data collection could be extended by providing more time to the scraper and by increasing the search space.
The queries to the API returned a web page that had to be processed in order to extract the data. After extracting the data it was divided into the following fields: **POD**, **address**, **event code**, **time**, **duration**, **type**, **fault location** and **cause**. The API provides in fact not only information about the outage date and duration but also the meter address, the internal classification of the event and the possible cause. The **event code** groups entries corresponding to meters affected by the same outage with the same cause. The **time** is the timestamp of the instant in which the meter first detects the outage which extends for as long as described in the **duration** field. The **type** field classifies the event as *short*, *medium* or *long* as described in the legislation guidelines.The **fault location** describes the section of the grid where the fault originating the outage happened. It can be *high voltage*, *medium voltage* or *low voltage* lines, or it can be on the *interconnection network* or on the *national grid*. Finally the **cause** field generically describes the cause of the fault. After gathering the data the first step has been cleaning it so the entries having the same code have been dropped to avoid getting duplicate information about the same event. In order to put the dataset on a map as in Figure 2.4 it has been required to extract the geographical coordinates from the **address** field. To do so a *Docker* **container** running a **Nominatim** instance has been setup. This was needed since the online *Open Street Map* version which provides the geocoding APIs had a limited number of requests. By running the server locally with the needed data stored on the hard drive this limitation has been bypassed.

The first analysis on the data was getting information about the distribution of the duration of the outages. The average outage duration has been fist calculated while grouping the data by hour of the day and by month of the year. When looking

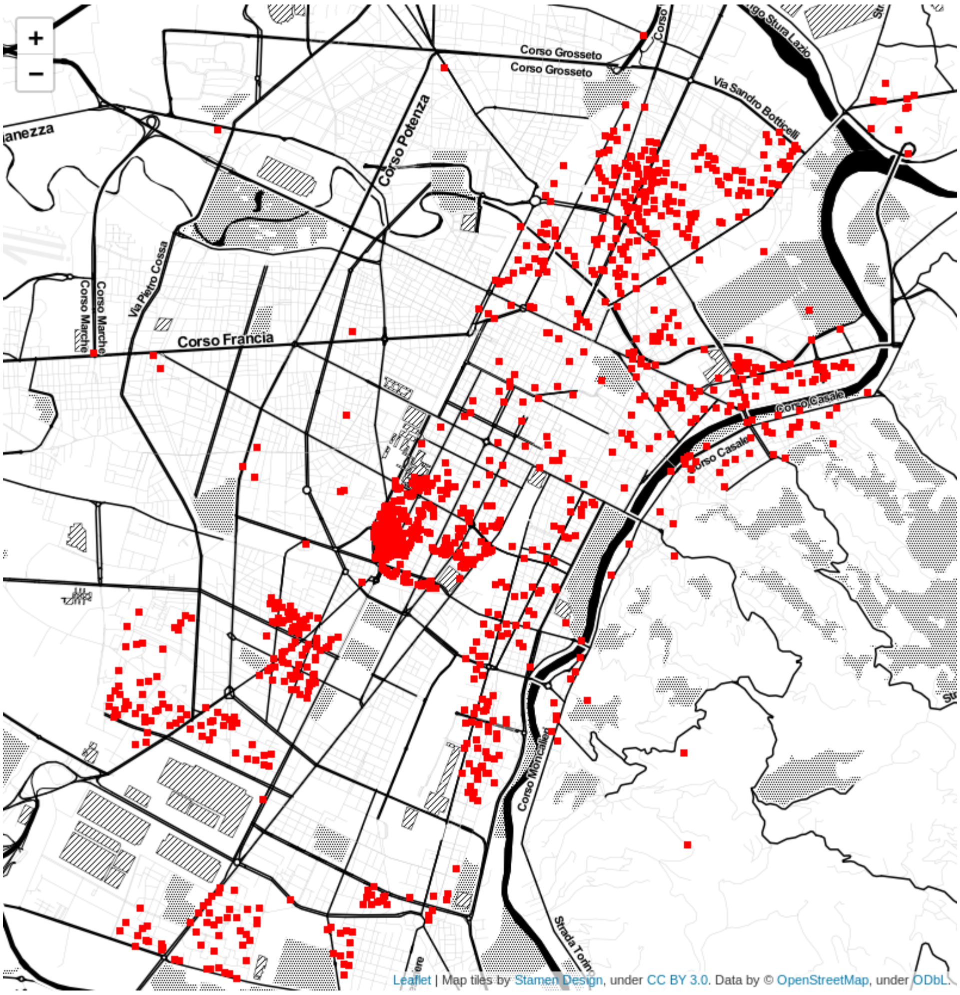


Figure 2.4: Map of PODs with outage data in the area of the city of Turin

Source: IRETI data, 2014-2018

at Figure 2.5 it can be seen that the average outage duration drastically increases in the morning at 4AM and at 1PM in the afternoon. By looking at Figure B.4 and Figure B.3 in Appendix A.2 it can be seen that while having some outlier at 4AM there is effectively an increase in the outage count and duration in these time slots. This could be due to energy demand ramping up at these times across the year which could increase the strain on the distribution grid leading to an increased number of faults and an increased difficulty in fast repairs.
Looking at the monthly average outage duration trends in Figure 2.6 there is a peak in December and two pits in August and January. The pit in August can

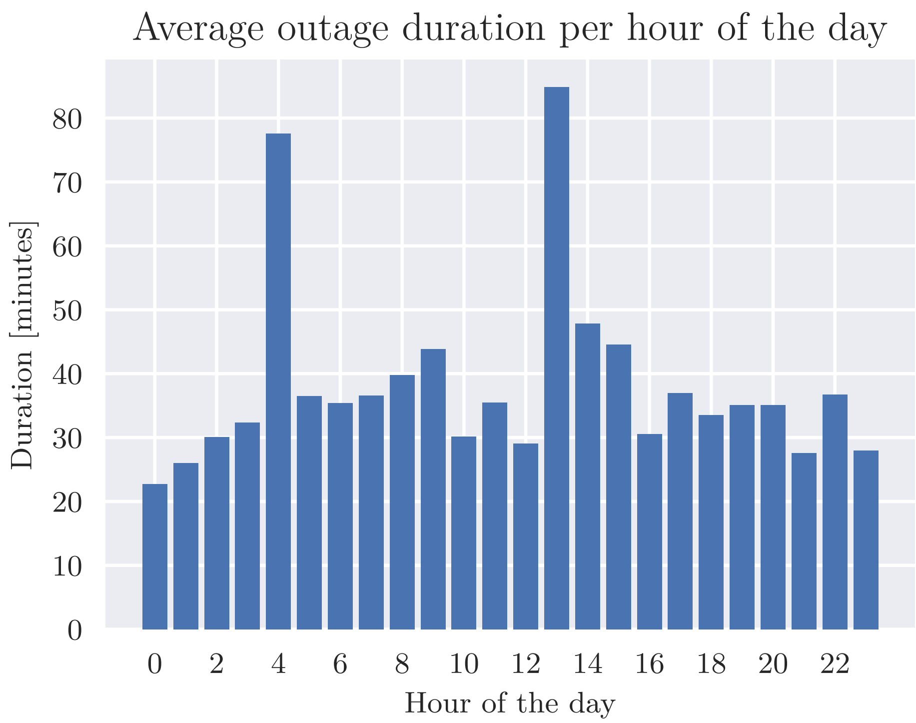


Figure 2.5: Average outage duration per hour of the day

Source: IRETI data, 2014-2018

be explained since although electricity demand peaks in summer months due to increased cooling demand, many people during this month leave the city for the summer holidays so demand is effectively reduced. As for the December peak a possible explanation may be that in December there are usually the first frosts of the year which may cause damages to electrical equipment which may have already been compromised.

In Figure 2.7 it is shown the average outage duration on a 2D plane showing months of the year on the x-axis and hours of the day on the y-axis. By comparing with Figure B.5 and Figure B.6 in Appendix A.2 it can be seen that outages happening during peak hours such as in the time slot 13:00-14:00 have faster recover time rather than those happening in the early morning in the time slot from 4:00-6:00 or in the slot 22:00-23:00. Because of this we get a longer average duration even if there are less events.

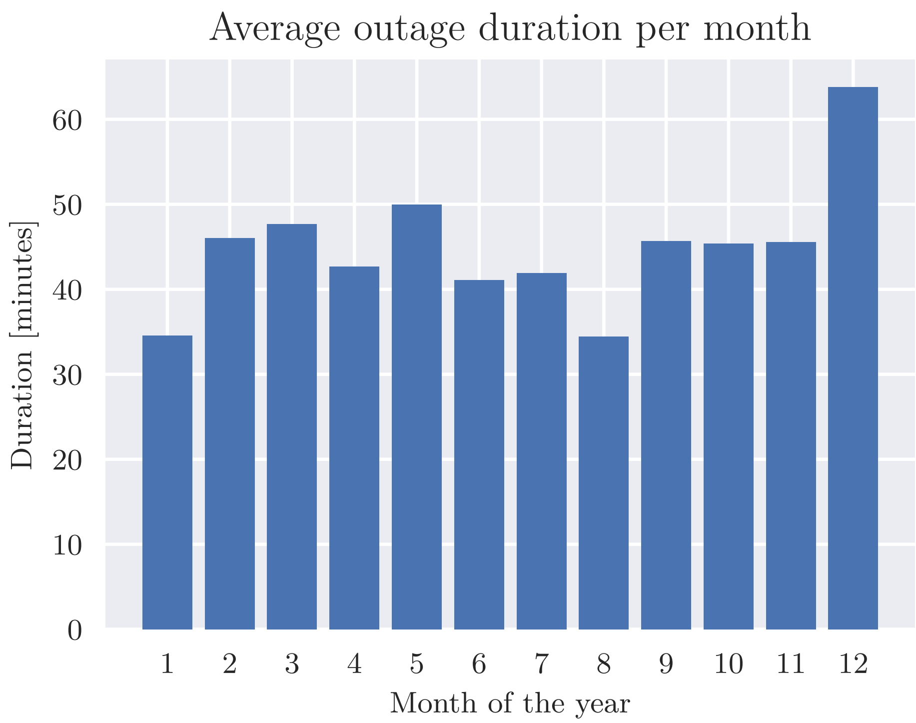


Figure 2.6: Average outage duration per month

Source: IRETI data, 2014-2018

By using the *Fitter Python 3* module the *probability density function* **PDF** of the outage duration in Turin has been fitted. A naive approach would be comparing the histogram of the data with known PDF of common probability distributions to find the most similar one. However the parameters are unknown and there are a lot of distributions. Using *Fitter* it is possible to automatically find the best parameters which minimise the error for a set of given distributions thus speeding up and improving the process. In order to minimise the error all the outages falling in the *short* category have not been considered while fitting the PDF this means that the PDF is shifted by a factor of 10. It has been found that the best matching distribution is an **exponential distribution** as in Equation 2.1 The tuning of the distribution resulted in the scale $\beta = \frac{1}{\lambda}$ parameter to be equal to $\beta = 61.93$ with $\lambda = 1.615 \cdot 10^{-2}$. From this PDF it is possible to derive some useful metrics as shown in Table 2.1. In Figure 2.8 it is possible to see the fitted PDF superimposed

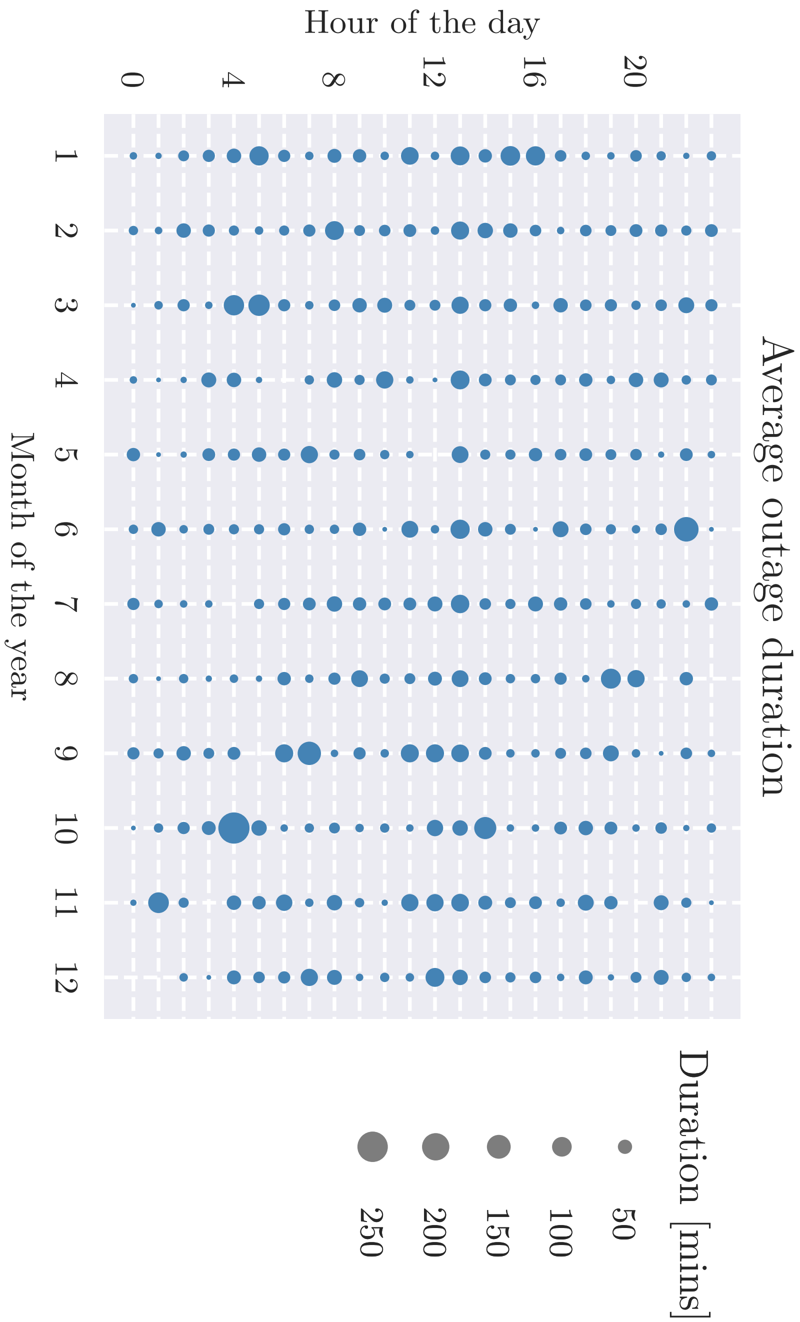


Figure 2.7: Average outage duration per hour / month,

Source: IRETI data, 2014-2018

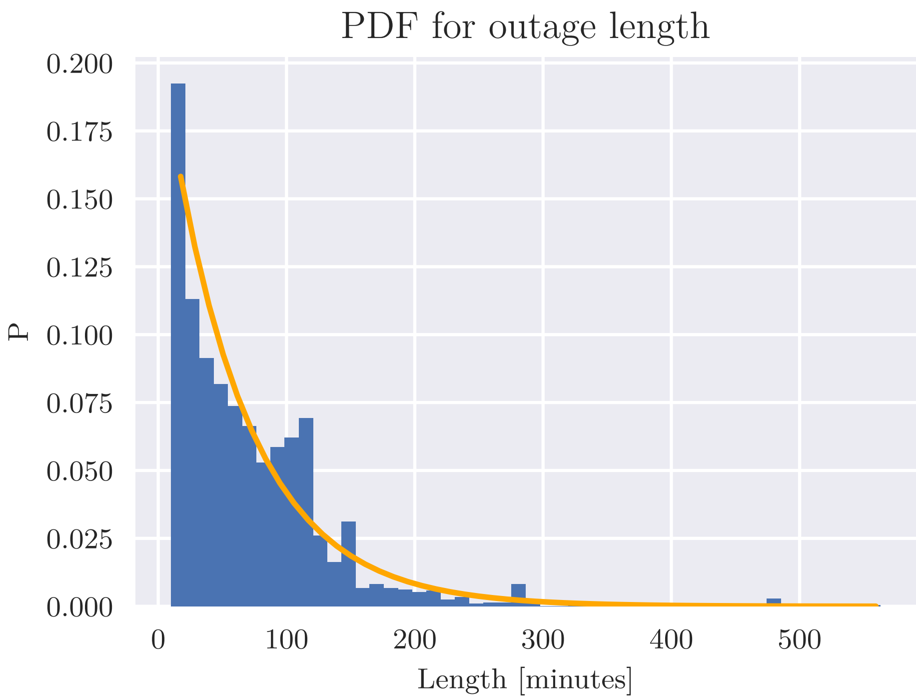


Figure 2.8: Fitted PDF from outage length data

Metric	Formula	Value
Mean	$\mathbf{E}[\mathbf{X}] = \frac{1}{\lambda}$	62 [min]
Variance	$\mathbf{Var}[\mathbf{X}] = \frac{1}{\lambda^2}$	384 [min]
First quartile	$Q_1 = \frac{ln(\frac{4}{3})}{\lambda}$	18 [min]
Median	$m[\mathbf{X}] = \frac{ln(2)}{\lambda}$	43 [min]
Third quartile	$Q_3 = \frac{ln(4)}{\lambda}$	86 [min]
Upper outliers[1]	$\mathbf{O} \geq Q_3 + 1.5 \cdot (Q_3 - Q_1)$	150 [min]

Table 2.1: Set of outage duration metrics

over the histogram of the outage duration data.

$$f(t;\lambda) = \begin{cases} \lambda e^{-\lambda t} & t \geq 0 \\ 0 & t < 0 \end{cases} \tag{2.1}$$

2.1.3 Clustering of the data

In order to group the data from each POD into events affecting multiple PODs a clustering technique was needed since some entries were missing the *event code* field. To reduce the memory impact on the clustering algorithm only the information needed for the clustering has been fed to the algorithm from which the labels and the indexes of the original data have been derived. In this way the entries have been transformed into a triple consisting of **latitude**, **longitude** and the **timestamp** on which the outage on the POD had started. The best choice for clustering the data proved to be the **DBSCAN** algorithm built into the *Python 3 Scikit learn* library. As stated in [1]:

> The DBSCAN algorithm views clusters as areas of high density separated by areas of low density. Due to this rather generic view, clusters found by DBSCAN can be any shape, as opposed to **k-means** which assumes that clusters are convex shaped. The central component to the DBSCAN is the concept of core samples, which are samples that are in areas of high density. A cluster is therefore a set of core samples, each close to each other (measured by some distance measure) and a set of non-core samples that are close to a core sample (but are not themselves core samples). There are two parameters to the algorithm, `min_samples` and `eps`, which define formally what we mean when we say dense. Higher `min_samples` or lower `eps` indicate higher density necessary to form a cluster. While the parameter `min_samples` primarily controls how tolerant the algorithm is towards noise (on noisy and large data sets it may be desirable to increase this parameter), the parameter `eps` is crucial to choose appropriately for the data set and distance function. When chosen

[1] Calculated using Tukey's criterion

too small, most data will not be clustered at all. When chosen too large, it causes close clusters to be merged into one cluster, and eventually the entire data set to be returned as a single cluster.

The chosen values for the algorithm parameters were:

$$\texttt{eps} = 500$$
$$\texttt{min\_samples} = 3$$

In the end `min_samples` was chosen equal to 3 in order to discard outages for which an extension could not be computed, `eps` value has been found with a trial and error approach. This means that the data was clustered on a 3D plane in which the dimensions are the 2D spatial plane and the time. Single outages from this data have thus been created each with its extension and as duration the mean of the durations of the duration for each single POD labelled as part of that event.

In order to find the extension for each event the coordinates have been converted to the **UTM 32N** format from the **WGS 84** they were saved in. It has been chosen to use a **Convex Hull** to represent the area impacted from an outage. The Convex Hull of a group of PODs belonging to the same event can be defined as the smallest convex polygon enclosing all the PODs in the group. Convex means that the polygon must have all of its corners bent outwards.

By comparing the outage duration with its extension in Figure 2.9 it is possible to spot a trend in which the longest events tend to have a smaller spatial footprint while the one with the largest extension tend to have a shorter duration. In Table 2.2 it is possible to see how small is the average area of impact for an outage. Since the upper outlier bound is set at 4.53 km^2 it means that in Figure 2.9 every outage with an area superior to 5 km^2 can be considered as an outlier. Having the mean over the interquartile Q_1 - Q_3 range means that there are a few huge outliers that should be treated as exceptional events.

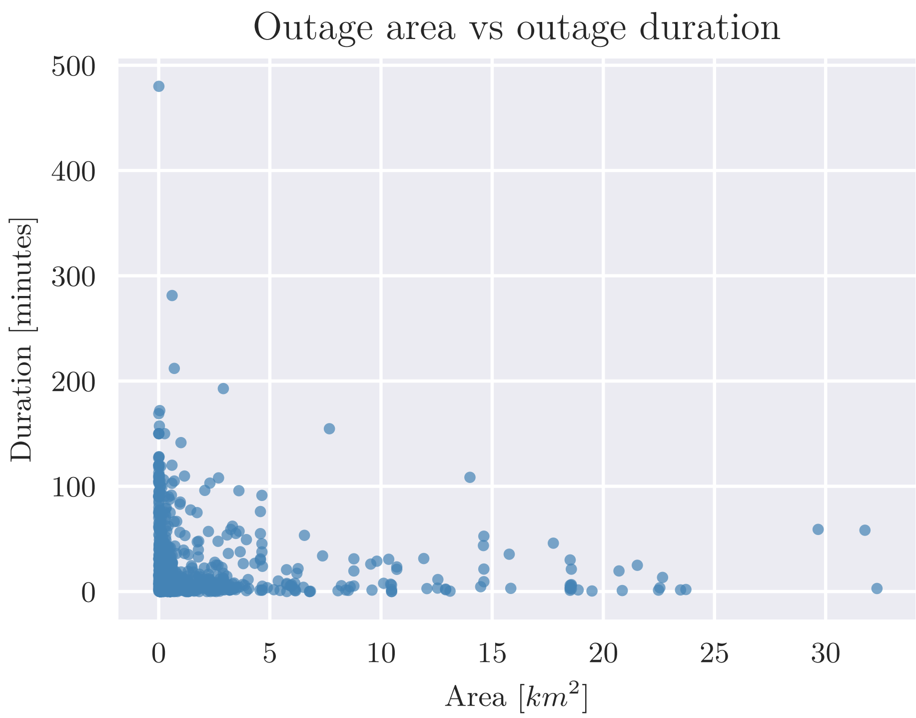


Figure 2.9: Outage area vs outage duration

Source: IRETI data, 2014-2018

Metric	Value
Mean	2.12 [km^2]
Standard deviation	4.44 [km^2]
First quartile	0.07 [km^2]
Median	0.45 [km^2]
Third quartile	1.85 [km^2]
Upper outliers	4.53 [km^2]

Table 2.2: Set of outage extension metrics

2.2 BTS distribution analysis

A *Base Transceiver Station* **BTS** is a transceiver subsystem of a radio signal usually equipped with sectoral antennas in charge of serving the *mobile stations* MS covering a given geographical area called radio cell. Typically the BTS are composed of transceiver antennas placed at a certain height on support pylons in turn positioned in raised locations with respect to the coverage area. This trick is needed to avoid disturbs and obstacles for the propagation of the signal. This allows to maximize the coverage area, the power of the signal and the signal to noise ratio. In urban areas the BTS are usually located on the buildings' roofs with the carriers paying a rent to the owners, while in rural areas, where possible, are placed on high grounds and hills without vegetation which are cause of interferences. A BTS can host more than one antenna and transceiver apparatus relative to different cellular systems such as GSM, UMTS or LTE. This allows the carriers to decrease the infrastructure deployment time and costs which are mostly tied to the pylons installation. The most widespread types of installation sites in urban areas are:

- **raw-land** where the BTS has an installation site which is sited directly on the ground, such as a mast which is a typical rural installation site
- **roof top** where the BTS is installed on the top of a residential or industrial building, more common in dense urban areas
- **carried** suited for temporary loads such as sport events, the BTS sits on a truck and its equipment is stored into a container
- **shared** where multiple carriers share the same site with their BTS
- **microcell** where the BTS is installed along some urban furniture such as street lamps

2.2.1 ARPA Piemonte data

ARPA, *Agenzia Regionale Protezione Ambientale* provides the data for high frequency electromagnetic radiation emission points which include: radio and TV

broadcasters and BTS for various technologies (e.g. GSM, DCS, UMTS, Wi-Fi, Wi-Max). In general, these are the plants for which a request or opinion has been received by ARPA Piemonte in compliance with the current legislation, which is therefore present in the archives of ARPA. The data does not specifies the owner of the site or the technology installed, just the macro category such as radio, TV or mobile phone BTS installation. The dataset includes the broadcasters and the authorized base stations or those for which the request was forwarded. The information comes from EMITEM, the regional register of electromagnetic sources of the Piedmont Region, powered by the technical activity of ARPA. Each source is identified by a pair of coordinates. The last data update is set to 2011-06.
When filtered to include only the mobile telephone BTS on the Turin area the result is as in Figure 2.10.

2.2.2 INWIT data

INWIT (INfrastrutture Wireless ITaliane) is an Italian company which operates in the electronic communications infrastructure sector, with its roots in the Telecom Italia Group, which was the public owned company that started mobile telephony in Italy over 40 years ago. INWIT is currently the first Italian Tower Operator for the number of managed sites distributed in a widespread manner throughout the national territory on which the transmission equipment of all the main national operators is hosted. In addition to hosting the other operators on its towers, INWIT built its own DAS (Distributed Antenna System) infrastructure to ensure an extensive coverage of densely crowded open spaces such as public squares or leisure centers such as train stations, sports centers and stadiums. Those systems can also be deployed in private places such as malls or health infrastructures such as hospitals. INWIT provides the data about its infrastructure via a web API which is reachable from Section A.3. This data has been extracted from the API and is visible on the map in Figure 2.11.

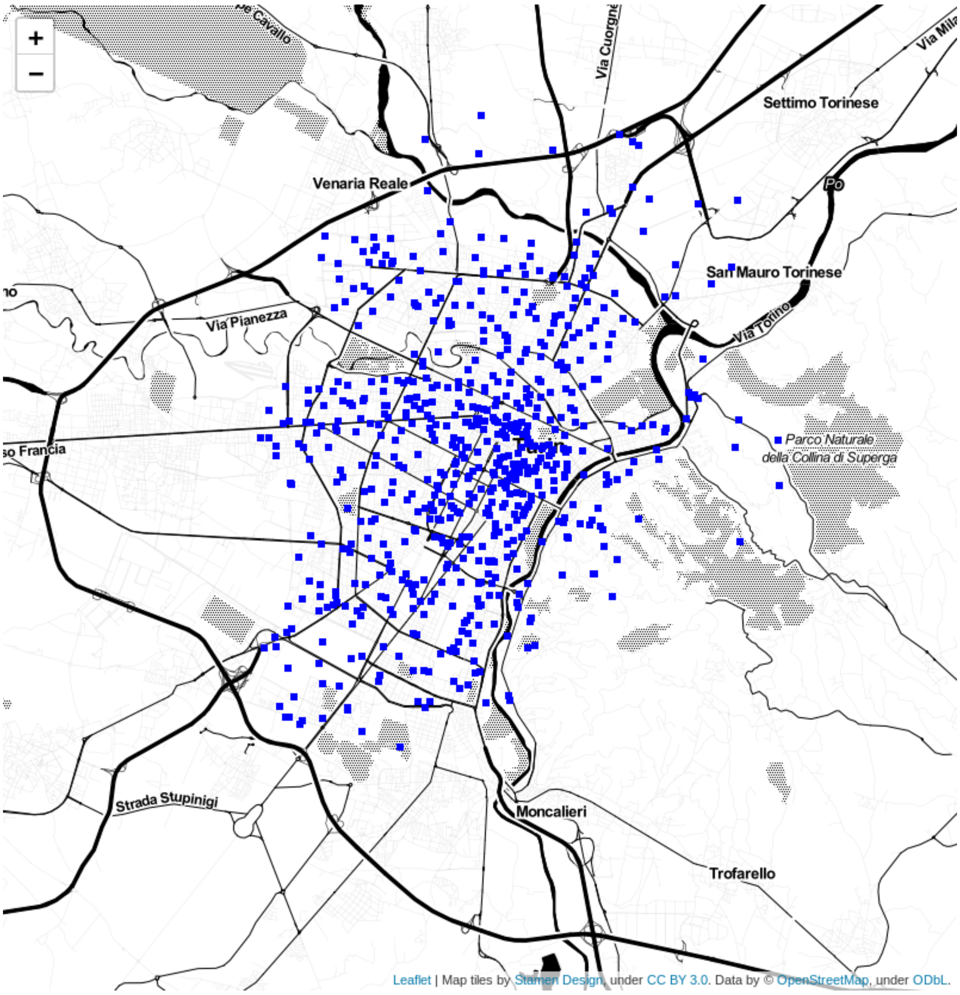


Figure 2.10: Location of BTSs

Source: ARPA Piemonte

2.2.3 CellMapper data

CellMapper is an App used for locating 2G/3G/4G BTS available for Android phones. The application is operated by end users which use it to measure the signal strength and other network data, and it processes the collected data to identify the location of the network's base stations and their estimated coverage. Since the app is user operated there are no guarantees on the coverage or the quality of the data provided. Its main advantage is that it provides the carrier (e.g. TIM, Vodafone, Iliad) and the technology (e.g. 2G/3G/4G) installed for the BTS it finds. However

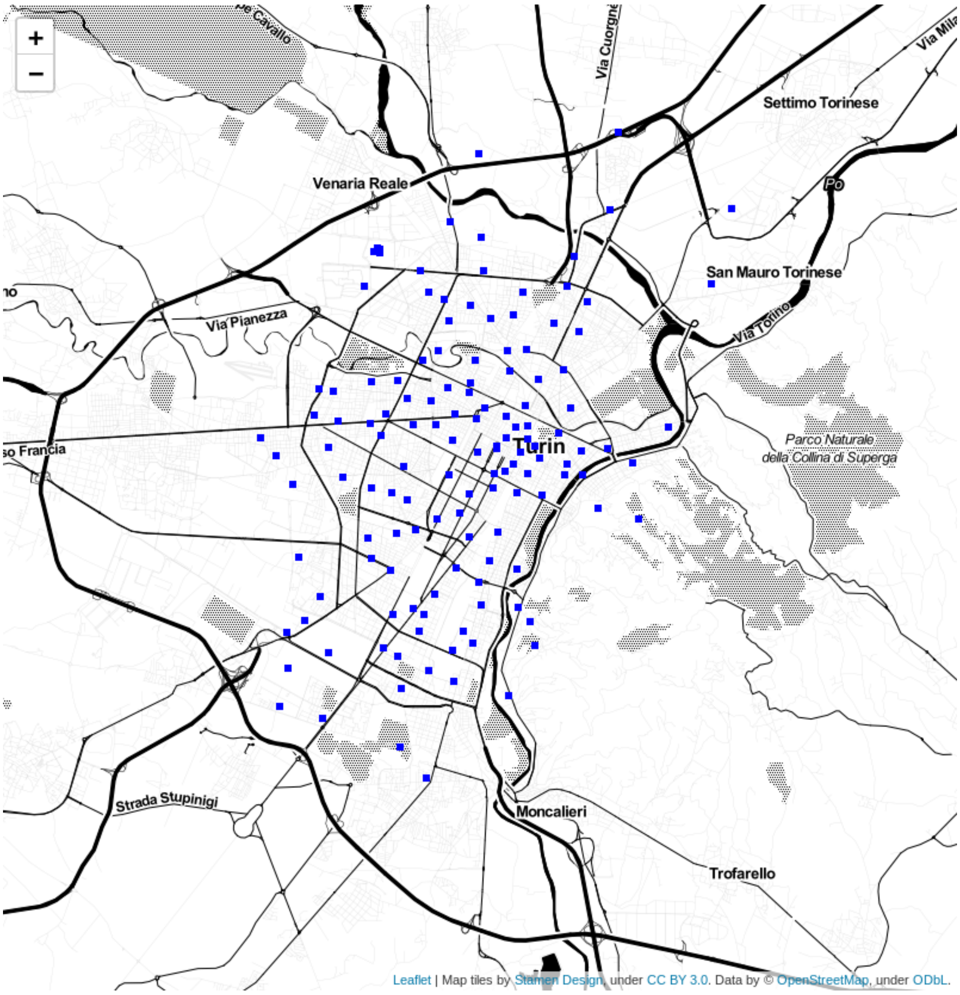


Figure 2.11: Location of BTSs

Source: INWIT

there is no information if the BTS can be classified as a Macrocell or a Microcell. In Figure 2.12 it is possible to see the data about TIM BTS in the city of Turin.

2.2.4 CASTEL data

CASTEL (*Catasto Radio Impianti*) is a service provided by Lombardia region where all radio transmission sites are listed. This is useful because it provides data for a city with a RAN similar in structure to Turin's. Using this data we can extract

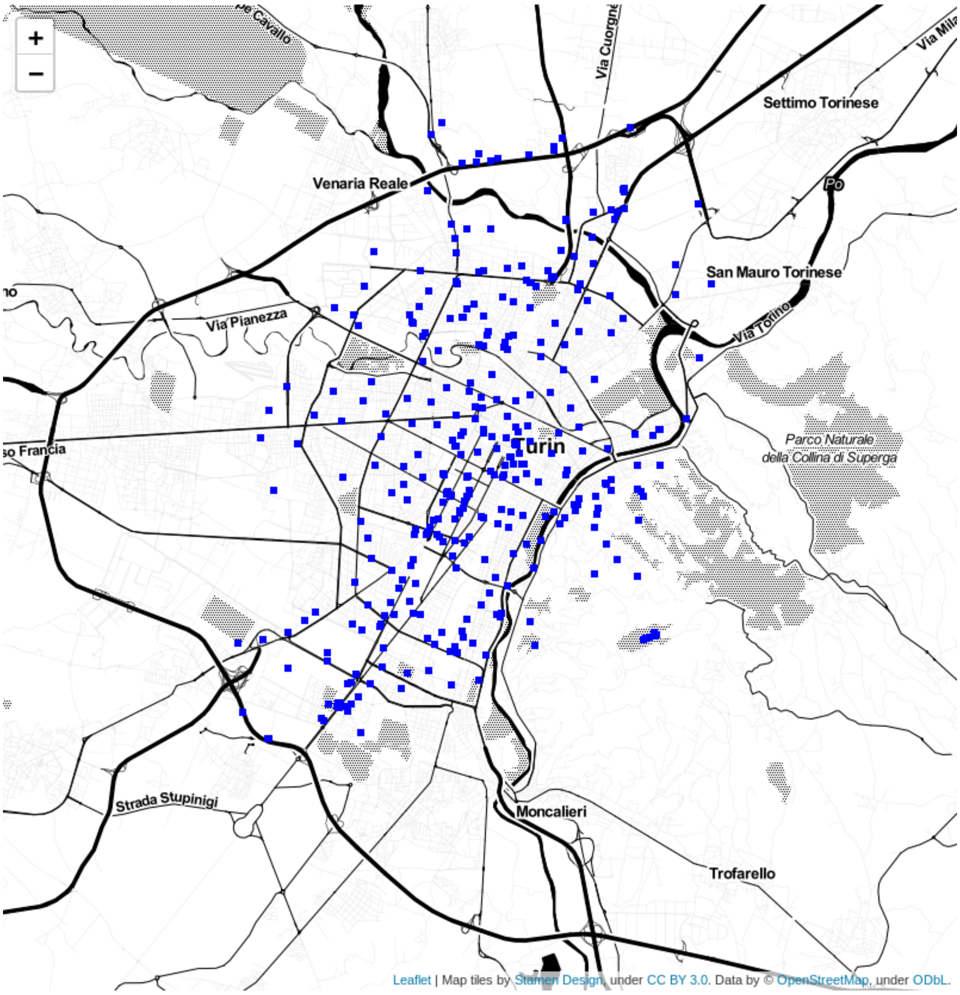


Figure 2.12: Location of BTSs

Source: CellMapper

information about the ratio of *Macrocells* to *Microcells* in a densely populated urban environment. The data is available for all the carriers operating in the city of Milan and it is reported in Table 2.3. This data cannot be seen on a map but it will be used in Chapter 4 to build the simulation scenario.

2.2.5 Merging the data

In order to find a reasonable approximation of the location of the BTS of the TIM carrier in the city of Turin the three datasets mentioned above have been

Carrier	Macrocells	Microcells	Ratio	Total
TIM S.p.a.	334	182	1.85	516
Vodafone S.p.a.	236	108	2.18	346
Wind Tre S.p.a.	190	22	8.64	212
Iliad Italia S.p.a.	14	0	NaN	14

Table 2.3: RAN structure of Italian carriers in Milan

Source: CASTEL

merged into one. The INWIT and ARPA datasets are considered validated while CellMapper is not unless specified from an optional flag inside the entries. It is assumed that the INWIT and CellMapper datasets contain after the cleanup only information about TIM BTS while the ARPA dataset contains correct - but not updated - information about BTS from all the carriers operating in the Turin urban area. The criterion on which the datasets have been merged is to first join the INWIT and CellMapper datasets, considering a BTS from the two different datasets closer than 20m in one with respect to the other as duplicate. Then this new dataset has been merged with the ARPA one as a validation. A BTS present in the intermediate dataset but not in the ARPA one would be present in the final one only if it was marked as coming from the INWIT which is official as opposed to the CellMapper one which is made from the users of the service. The final BTS dataset derived from joining the three previously listed datasets can be seen in Figure 2.13.

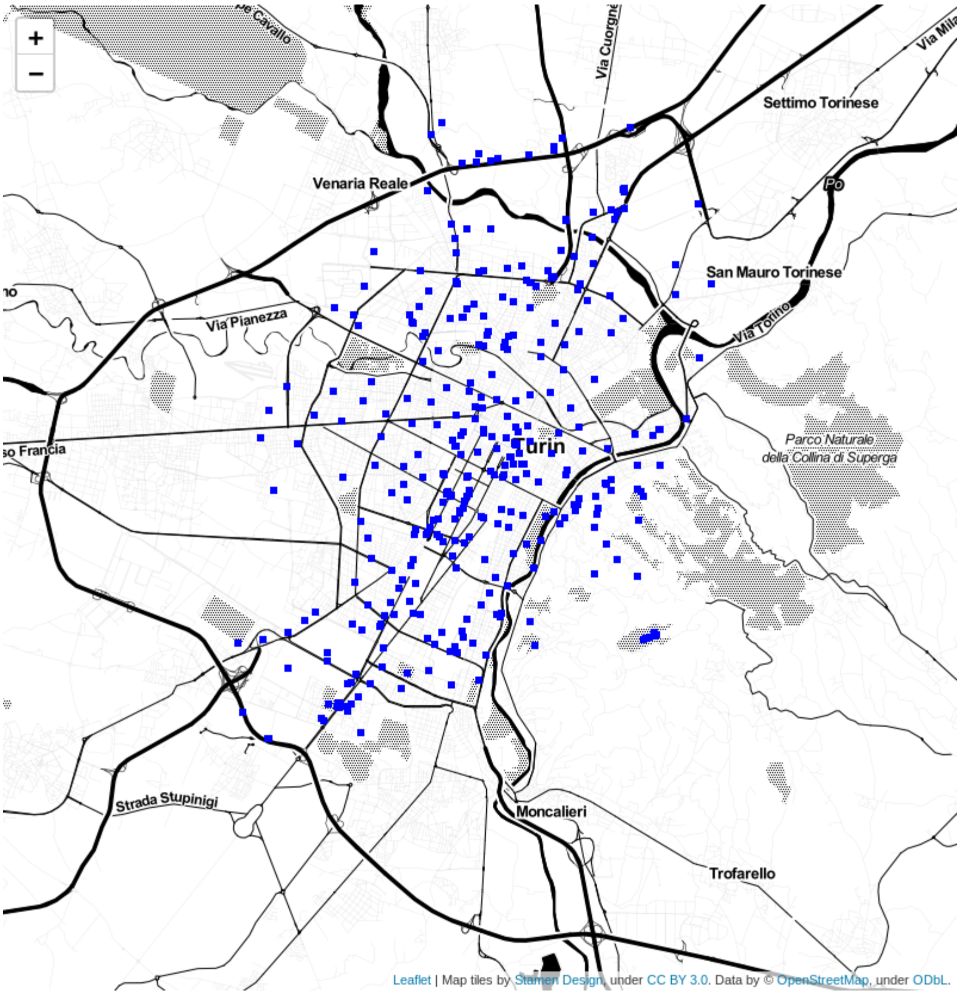


Figure 2.13: Location of BTSs

2.3 Comparing the outage data with the RAN

In order to determine if a BTS can be considered as affected the outage dataset has been compared with the positions of the TIM BTS in Turin. As stated in Section 2.1.3 the outages were defined as a Convex Hull. So to find how many BTS were affected by every outage in the dataset the Convex Hull has been transformed into a Path object. A Path object is defined as the set of points defining the perimeter of the Convex Hull, and it has the property of being able to tell if a point is inside this shape. So for each outage all the BTS are checked to find if they are located in the area defined from the perimeter. If so they are marked as affected and contribute to the count for that outage. As visible in Figure 2.14 most outages are able to affect very few BTS since as stated in Table 2.2 most outages have a limited spatial extension. In Table 2.4 are shown the main metrics to find the impact of an

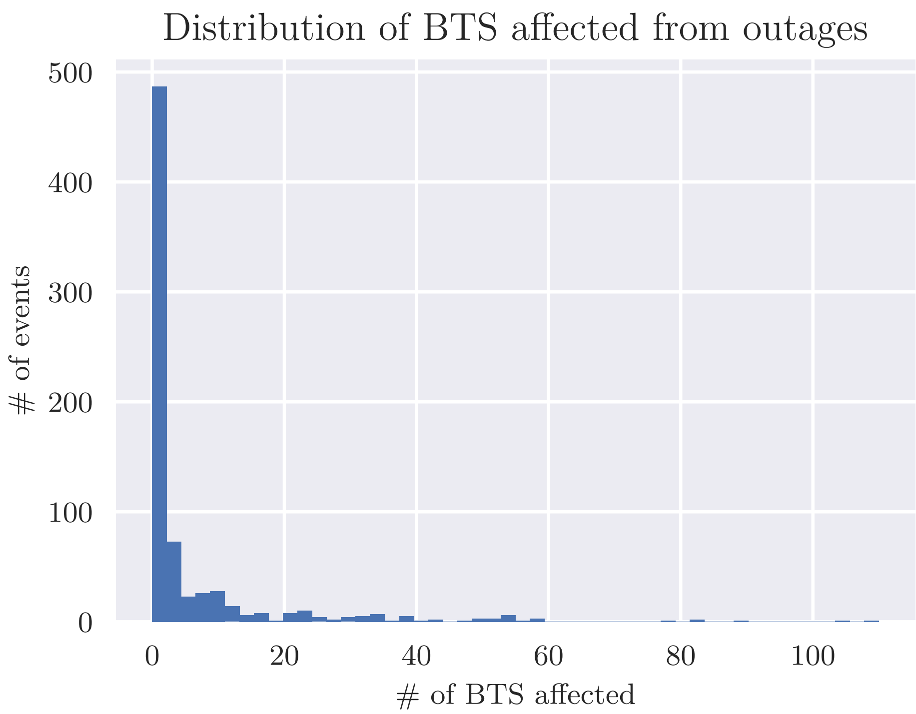


Figure 2.14: Distribution of the number of BTS affected by outages

outage on the RAN of a carrier, the mean is affected by some outages which can be considered as outliers since they had a widespread extension, but as it is possible to see the first quartile is even set to 0. This means that the average outage usually affects few BTS and this will be used in building the scenario for the simulations in Chapter 4.

Metric	Value
Mean	5.83
Standard deviation	13.21
First quartile	0
Median	1
Third quartile	4
Upper outliers	10

Table 2.4: Metrics for the number of BTS impacted from outages

Chapter 3

The simulator

A simulator has been written in the *Python* language to perform the analysis on the performance of a scenario including a certain number of BTS in case of an outage. This simulator has several sub-components such as a BTS simulator handling traffic, a battery simulator handling situations in which the BTS can't be powered from the power grid and analysis tool to calculate various **KPI** *key performance indicators* to understand if the strategies used actually improved the network performance in harsh conditions. This simulator is composed of several classes, in the next sections we will go in deep analyzing the most important ones.

3.1 Traffic

3.1.1 Traffic data

The simulator uses given traffic traces for each BTS in order to work. These traffic traces were provided from TIM and are originated from different BTS located in Milan. Each trace provides two months of data for the BTS it refers to, starting at 00:00 on the 1^{st} April 2015, condensed into 15 minutes intervals. Each entry in the traces provides the bits transferred uplink, the bits transferred downlink and the number of connections sustained during the 15 minute interval. The data has been provided in `.csv` files, one file per BTS. The details of the BTS the data came from were not disclosed but since the traffic volumes were high it was assumed that they belonged to 4G BTS.

3.1.2 Traffic zones

The traffic traces had previously been grouped in sets named after the area in which they belong to:
FS, *Rho*, *Duomo*, *PoliMi*, *San Siro stadium*, *Business area*, *Residential area*, *Industrial area*, *Second residential area*, *Highway*, *Mediolanum Forum*, *Tourist attraction*, *Theatre*, *Linate airport*, *Monza Park*, *Agricultural zone*
Inside each zone data about macro and micro cells has been provided in separate files.

3.1.3 Traffic data inside the simulator

Once the traffic data has been fed to the simulator it needs to be interpolated since the original 15 minute sampling time is too high for analyzing the impact of short lived phenomena such as outages. This data is then up-sampled to obtain a single minute interval between entries. In order to have a linear approximation of the data points between the known entries the y_t entry where $0 < t < 15$ t corresponds to the chosen minute inside the 15 minute original interval is calculated as in Equation 3.1.

$$\begin{cases} y_1 \geq y_2 & y_t = \frac{y_1 + \frac{(y_2 - y_1)}{15} \cdot t}{15} \\ y_1 < y_2 & y_t = \frac{y_1 - \frac{(y_1 - y_2)}{15} \cdot t}{15} \end{cases} \tag{3.1}$$

After up-sampling the data the traces are then modified to fit them to the defined scenarios. This means that each trace for both macro and micro cells are normalized with respect to the maximum capacity per minute of the cell size they belong to. Then each trace is multiplied by a factor of 3 in the case of macro cells since it is assumed that each BTS is split into 3 sectors so the capacity needs to be adequate. We can do so since we are not interested in the actual numbers but rather than in the load profiles provided from these traces. For micro cells we keep the normalized values since those are considered as omnidirectional. In [6] is stated that the users of a 3G network could generate up to 65% of the traffic generated in a 4G network. Because of this, a trace from a comparable zone multiplied by a coefficient 0.65 has been used to generate the traffic carried by the UMTS BTSs in the scenarios. For 2G BTS the same approach has been used and the traces have been multiplied by a factor of 0.17 which made them almost negligible when compared to modern technologies.

3.2 Configuration

In this section are written the main configuration options offered from the simulator.

3.2.1 Scenario setup

Each scenario is defined through a `.json` file and a `.bts` file. Inside the first file is stored a list of `ids` identifying traffic traces defined in the second file. For each trace 3 fields are defined:

- **impacted**: defines wether the BTS associated to the ids is impacted from the outage.
- **time_start**: defines the time from the start of the trace when the outage is supposed to start and the BTS will receive no more the power from the grid.
- **time_end**: defines the time when the outage is supposed to end and the power shall be restored.

Inside the second file there are as many rows as the BTS in the selected scenario, each row composed of 4 parameters

- **trace_file_name**: defines the file name of the file containing the raw data of the trace, it is used to import and process it.

- **cell_id**: defines the id of the cell, it is used to link these information with the first file described.
- **cell_size**: deifnes the size of the BTS it can assume the values of *macro* or *micro*.
- **cell_standard**: defines the standard of the cell, it can assume the values of *4G*, *3G* or *2G*.

3.2.2 Simulation parameters

Inside the file `Constants.py` are defined the constants used from the simulator to work. The parameters defined here are the maximum traffic capacity for the various technologies used in Section 3.1.3, or the parameters used to determine the capacity and the properties of the batteries of the BTS. Those parameters can be changed by the user at runtime if running multiple parametric simulations. There are also defined the simulation intervals which allow for faster computational times.

3.3 BTS Management

In this class are described the algorithms that decide how the BTS are managed in case of an outage. In order to understand how the management algorithms are defined some assumptions need to be made.

In a scenario composed of macro and micro 4G cells, macro 3G and 2G cells it is assumed that the traffic that in the original traces was performed from a micro cell can be performed from a macro cell, however the traffic performed from a macro cell can't be performed from a micro cell. This assumption is done since usually micro cells are placed in order to add capacity to dense zones and are anyways covered by some **umbrella cells** which handle the fast moving traffic as stated in Section 1.2.3. The traffic in zones with macro and micro cells is usually handled through the micro cells so if the traffic has been carried through a macro cell we assume that no micro cell was present in that zone. It is also assumed that 4G traffic in case of a BTS being switched off, should be first assigned to another 4G

BTS - if possible - and then to 3G and 2G BTSs. Obviously these assumptions are not always applicable to the real world but without a traffic generation model we have to use them.

3.3.1 Traffic repartition algorithm

In Algorithm 1 it is described the strategies applied when some 4G or 3G traffic need to be assigned to a 3G cell because all 4G cells are switched off or saturated. The traffic from the switched off BTS is assigned in equal parts to the active 3G BTS. Then each BTS is analyzed to check wether it has too much traffic. If this happens then the traffic over the maximum capacity threshold is marked as lost. The procedure which handles how the switch off of a cell is performed is described

Algorithm 1 Reassign traffic to 3G BTSs *[reassign_to_3g(`traffic`)]*

```
create 3G_BTS_list from available 3G BTSs
for 3G_BTS in 3G_BTS_list do
    BTS_NUM = length of 3G_BTS_list
    traffic_to_assign = traffic divided by BTS_NUM
    sum traffic_to_assign to 3G_BTS own traffic
    if traffic in 3G_BTS ≥ maximum capacity then
        assign maximum capacity to 3G_BTS
        consider the excess traffic as lost
    end if
end for
```

in Algorithm 2. When a 4G micro cell is switched off the procedure described in Algorithm 3 is used to try to redistribute its traffic through the nearby cells. Each micro cell is supposed not to overlap with any other micro cell. However

Algorithm 2 Shut down BTS *[shut_down_bts(`BTS`)]*

```
set BTS status as OFF
set BTS traffic as 0
set BTS consumed power as 0
```

its coverage are can be overlapping with the area covered by a 4G or 3G macro. Because of this its traffic is directly routed to the procedure described in Algorithm 1 if there are no 4G BTS in the same area. If on the other hand there are any

Algorithm 3 Reassign Micro cell traffic *[reassign_micro_traffic(`traffic`)]*

```
create 4G_BTS_list from available 4G LTE BTSs
traffic_over_lte = 0
for BTS in 4G_BTS_list do
    traffic_to_assing = traffic / length(4G_BTS_list)
    assign traffic_to_assing to BTS
    if BTS traffic > maximum capacity then
        traffic_over_cap = traffic over BTS capacity
    end if
end for
if length of 4G_BTS_list > 0 then
    reassign_to_3g(traffic_over_cap)
else
    reassign_to_3g(traffic)
end if
```

4G BTS those have the priority and only if some traffic still can't be processed by those the 3G BTS are called into action. [htp] When the simulation is carried

Algorithm 4 Simulation loop

```
loop
    create BTS_list from available BTSs
    for BTS in BTS_list do
        power_consumption_list = compute p.c. for all BTSs
        if BTS has power from grid then
            update BTS battery according to production and consumption
        else
            update BTS battery according to consumption
        end if
    end for
    feasibility = check_repartition_feasibility()
    if feasibility is true then
        break
    else
        continue
    end if
end loop
```

out for each time instant the simulation loop is run. This process described in Algorithm 4 is needed to ensure the BTS are assigned the correct amount of traffic and because after assigning the traffic to a BTS its power consumption need to be calculated again. Since the power consumption of a BTS is dependent on the BTS load it could happen that the increased power consumption due to the traffic assigned make the BTS battery run out earlier than expected. In this case the traffic assignment needs to be performed again. The loop ensures that for the time instant it is performed on the BTS have all enough energy in their batteries to handle the traffic they are assigned. This check happens in Algorithm 5 which

Algorithm 5 Check repartition feasibility *[check_repartition_feasability()]*

```
feasible = true
for t = 0 to T do
  create BTS_list from available BTSs
  if using single battery then
    for BTS in BTS_list do
      if no grid power and battery is empty then
        shut_down_BTS()
      end if
    end for
  else
    for BTS in BTS_list do
      if no grid power and BTS battery is empty then
        if there is traffic on BTS then
          if BTS is MICRO then
            reassign_micro_traffic()
            feasible = false
          else if BTS is MACRO then
            if BTS is LTE then
              reassign_to_3g()
              feasible = false
            end if
          end if
        end if
        shut_down_bts(BTS)
      end if
    end for
  end if
end for
return feasible
```

checks with the updated battery capacity and power consumptions that each BTS is able to carry the traffic it needs to. If the battery results empty then it tries to assign the traffic to another BTS and it shuts down the BTS with an empty battery. If the algorithm did not need to perform any other traffic assignment it breaks the simulation loop so it can proceed to the next time instant.

3.4 KPI

KPI, *Key Performance Indicators* are a tool to measure performance in order to know if the network is providing the best possible service.

- **Power consumption per device** describes the power consumption per each time slot per each BTS across all the simulation.
- **Scenario power consumption** is the sum of the power consumptions of all the BTS inside the scenario. This is interesting since when some micro cells are shut down the total power consumption could actually increase since those devices are more efficient than the macro cells on which the traffic is moved.
- **Network capacity** is calculated as the percentage of capacity provided from active BTS over the total capacity that all the BTS would provide if they were switched on and fully operational. This value should always exceed the traffic which goes through the network in order to provide optimal service to the customers.
- **Time slots with low coverage** are the time slots during the simulation period in which the lost traffic percentage across all the network is above a certain threshold. This KPI is a stricter performance indicator than the **Network capacity** since it measures an actual loss for the customers.

For calculating the power consumption for a BTS the power consumption models defined in Section 1.2.5 are used. These model are dynamically loaded according to the trace the simulator is processing. When starting the simulation the power consumption model parameters are loaded from a `.json` file and can be adjusted according to the specific BTS model considered. These models are load dependent so those metrics shall be calculated only when the traffic assigning is final.

3.4.1 Lost traffic estimation

The lost traffic estimation can be done in two ways. If the simulator is given a specific outage duration then, after the simulation is complete, the `KPI` class is fed the original traffic traces for each BTS in the scenario and the traces resulting from the simulation. Those updated traces reflect the changes that have been made to cope with the outages in order to loose as little traffic as possible.
To find the total lost traffic the traces elements are summed as in 3.2 where the traces are contained in a structure with B rows corresponding to the number of BTS in the scenario and T columns corresponding to the length of each trace. To find the lost traffic instant per instant we avoid to sum over t.

$$lost\_traffic = \sum_{t=0}^{T} \sum_{i=0}^{B} original\_traces(i;t) - updated\_traces(i;t) \tag{3.2}$$

On the other hand to find the traffic lost due to a generic outage we exploit the probability density function we calculated in Section 2.1.2. In this case the outage starts at time $t\star$ and goes on until the end of the simulation. Taking it into account we get the traffic lost for the average outage. In Equation 3.3 the traces are contained in the same data structures as stated before, we set τ at 0 where we want our outage to start and set T big enough to have tail values for $P(\mathrm{T})$ which is our PDF.

$$lost\_traffic = \sum_{\tau=0}^{\mathrm{T}} P(\tau) \sum_{i=0}^{B} original\_traces(i;\tau) - updated\_traces(i;\tau) \tag{3.3}$$

By multiplicating the lost traffic to the probability of having an outage lasting enough to loose it we get the average lost traffic during an outage.

3.5 Battery

The battery class uses values from Table 1.5 to build a model of a **lead acid battery** since it proved the best for this kind of task. The baseline battery chosen for powering a macro BTS is a 12V 100Ah battery with a DoD of 70% and an efficiency $\eta = 0.78$. A comparable commercial battery with these specification is

329 x 172 x 221 mm for 32 kg of weight which can be too heavy for a micro cell so a 50Ah battery might be advisable.

A battery is cosidered empty when its maximum DoD charge level is reached and stops consuming power when it reaches its $\mathrm{SoC}_{\mathrm{max}}$. When doing a parametrical simulation the battery cell number can be increased to find the optimal battery capacity to satisfy the KPI for a given or the average outage.

Chapter 4

Analysis of the results

In this chapter the simulator is put to work to see the impact of the power outages in 3 main scenarios, a **dense**, a **medium** and a **sparse** urban zones each with its own traffic patterns and RAN topology. The power outage is considered to be 300 minutes long which as stated in Section 2.1.2 allows to reach the tail of the distribution of the length of a power outage. The simulations are run using the macro BTS battery capacity as a variable. We are interested to see which battery capacity allows to have a good balance in costs and lost traffic in the event of a power outage. The base value for the capacity of this battery is 1000 VAh which is roughly the size of the battery used in a truck, this capacity is enlarged up to 20000 VAh in certain scenarios. The capacity of the battery for the micro cells is considered fixed at 100 VAh - roughly the capacity of the battery used in city cars - since those devices are installed in such locations that do not allow big capacity batteries.

4.1 Dense urban zone, train station area

In this scenario a very dense urban area is considered where there are a lot of macro and micro cells condensed in a narrow area of a few km^2. The traffic data comes from the zone around the Milan central train station which is one of the most densely covered zones in the city of Milan, this BTS setup is typical of the centre of big cities / metropolitan areas. The radius of the area covered from a macro cell in this area is supposed to be as little as 1 km, this means that the area subject to interference and hence covered by the other macro BTS in the scenario is up to 60% - as in Figure 1.5 - of the area covered from the macro cell. Assuming an hexagonal coverage area for the macro BTSs in the scenario we assume that the impacted BTS is surrounded by 6 other BTS. Because of this in this scenario we consider 7 macro 4G BTSs - 1 impacted from the outage - and 1 macro umbrella 3G BTS which with its broader range covers the whole area. As for the micro BTSs we assume to have 4 micro 4G BTSs in the scenario all of which are impacted from the power outage.

4.1.1 Off peak

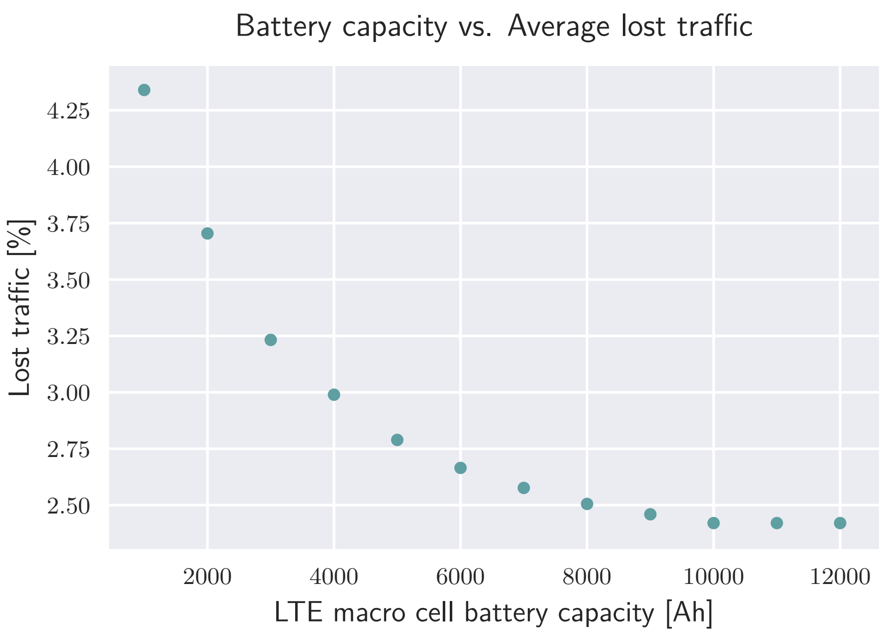
In Figure 4.1a is shown how the traffic is shaped in a typical weekday night from 2 AM to 9 AM which can be considered as the time slot during the day in which the traffic is lower. It is visible that the traffic for the macro BTS during the night is up to 8 times lower rather than during the day. In Figure 4.1b we have the baseline scenario in which the micro batteries last for around 40 minutes and the macro battery lasts for around 10 minutes more. We are not interested in exact values since those are highly affected from the traffic profiles which change everyday. It is possible to see that the traffic assignment algorithms never manage to saturate any of the neighboring 4G cells nor the 3G cell. This means that the only lost traffic is due to missing coverage from the BTSs which have no power left in their batteries. In Figure 4.2a it is shown the average traffic lost during an outage happening in this time slot. These figures are calculated using the lost traffic from the impacted BTSs derived from Figure 4.1 multiplied for the probability that the outage lasts as long as 300 minutes. The traffic lost using the smallest battery is just above 4%, this means that investing in batteries during the night could not be useful since the improvement when going from a 1000 VAh battery to a 12000 VAh battery is only of 2%.

(a)

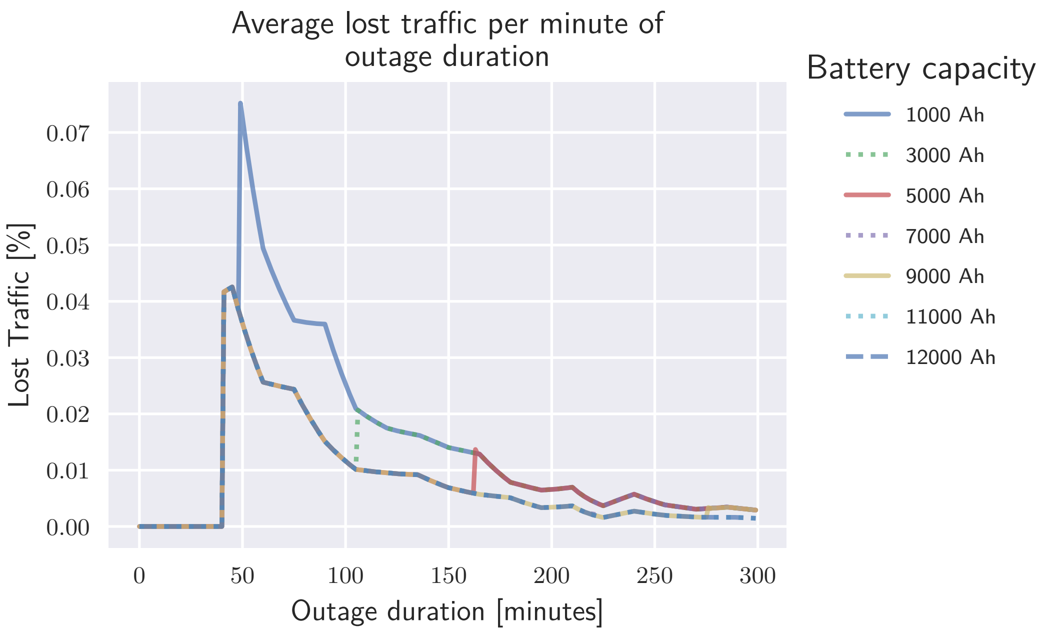
(b)

(c)

Figure 4.1: Traffic profiles, Dense - Off peak scenario



(a)

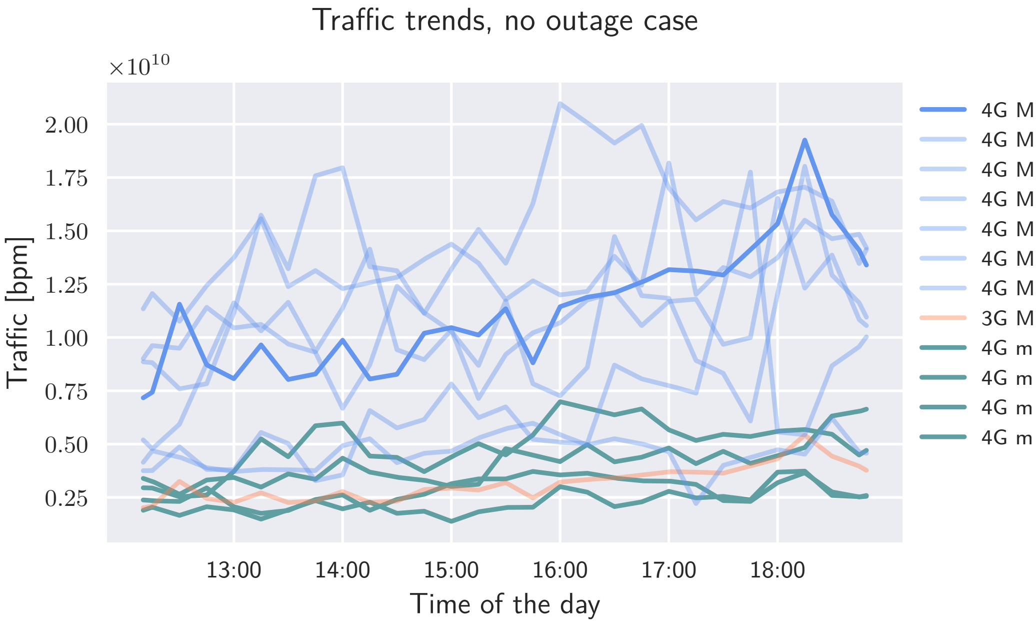


(b)

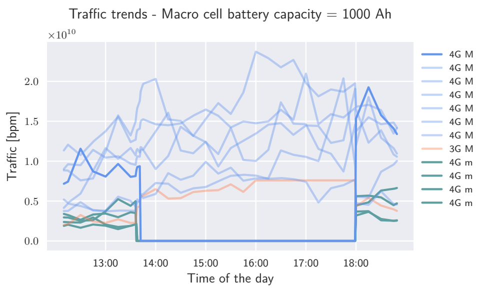
Figure 4.2: Total and per minute lost traffic evolution according to battery capacity increase, Dense - Off peak scenario

4.1.2 Peak

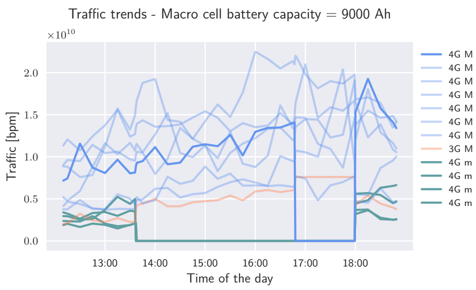
During the peak traffic hour, shown in Figure 4.3a it is possible to notice the high variability in the traffic profiles in the traces included in this scenario. This happens since the users in the city centre are in mobility and the zones with the most traffic consumption can change in a short time interval. The peak traffic timeslot during the day can be then identified as starting at 13:00 all the way through 18:00. While simulating a power outage in this time slot as in Figure 4.3b and 4.3c the increased traffic loads across all the BTSs with respect to what is shown in Section 4.1.1 leads to a saturation of the unaffected 3G BTS. Because of the saturation of the 3G cell, extending the duration of the battery of the 4G cells becomes crucial since this means loosing traffic which could otherwise be performed. In Figure 4.4a it is shown the average traffic lost during a power outage in this scenario. With the baseline battery the lost traffic is over one fourth of the traffic that would be performed on the affected BTSs.



(a) no outage

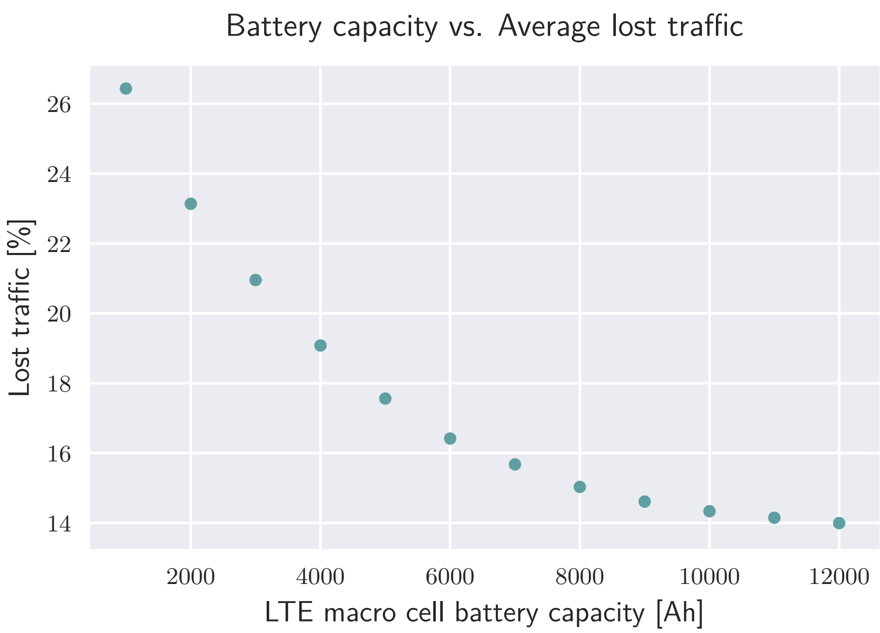


(b) outage

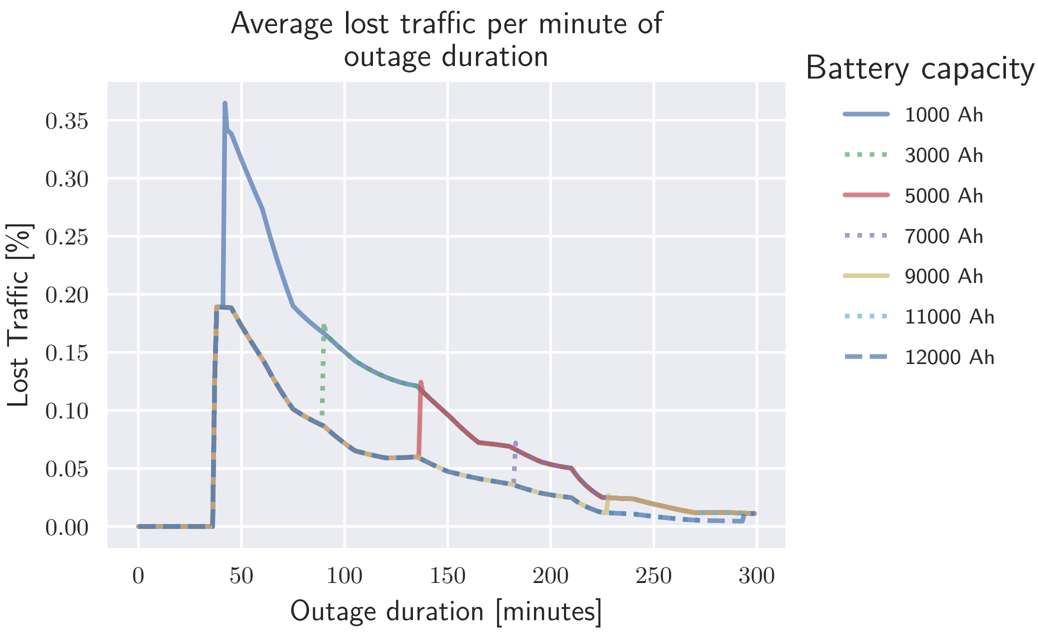


(c) outage

Figure 4.3: Traffic profiles, Dense - Peak scenario



(a) no outage



(b) outage

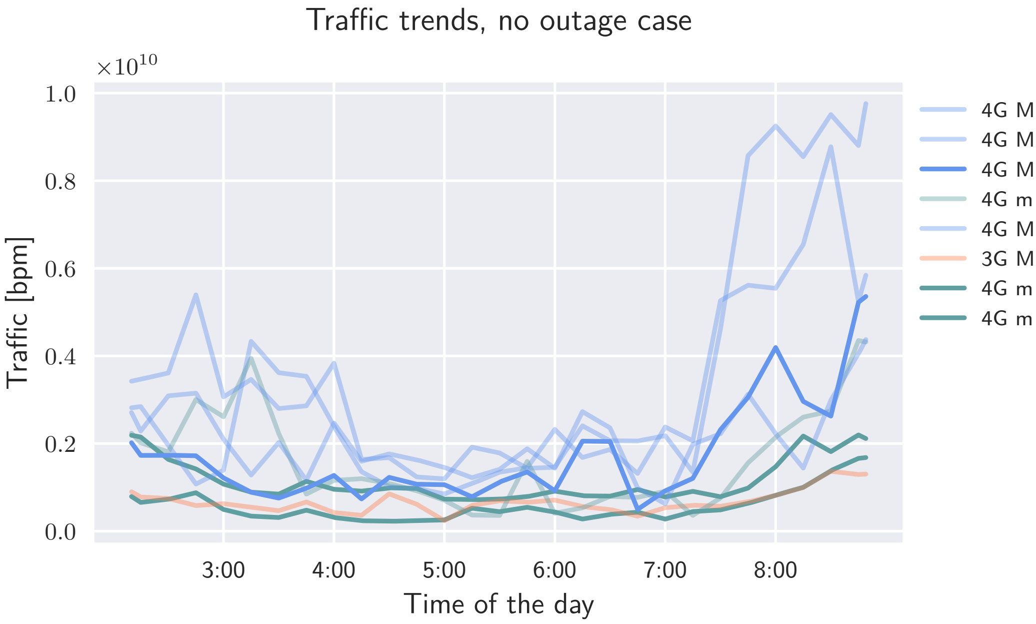
Figure 4.4: Total and per minute lost traffic evolution according to battery capacity increase, Dense - Peak scenario

4.2 Residential medium density zone

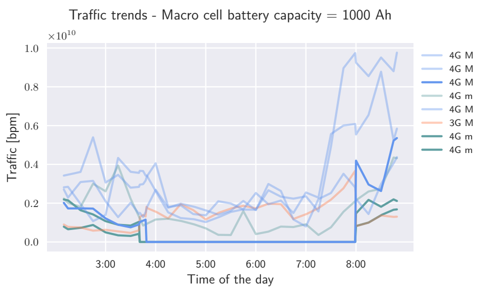
In this scenario a mostly residential typical urban area is considered. In these areas people are considered to be more equally distributed and thus there is less need for micro cells covering dense aggregation points. Moreover people in these areas are assumed to have in large part access to a wired connection thus reducing the need for mobile bandwidth. This scenario has been build with these characteristics in mind considering 5 macro 4G BTS, only 2 micro 4G BTS and 1 macro 3G BTS. The radii of the 4G BTS used for calculating the interference area is considered to be around 2 km thus causing interference on 30 % of the area covered from each cell. One macro 4G BTS and both the micro 4G BTS are considered to be impacted from the power outage.

4.2.1 Off peak

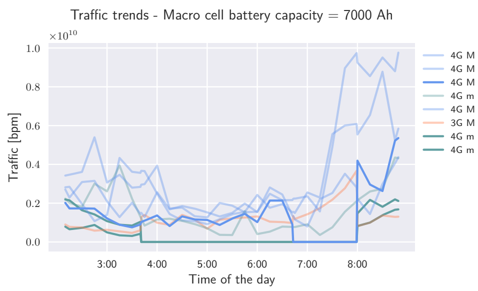
In Figure 4.5a is shown how the traffic is shaped in a typical weekday night from 2 AM to 9 AM as in the previous scenario. During the night the traffic reduces greatly as expected from the results obtained in the denser scenario, the traffic for the macro BTS during the night is up to 10 times lower rather than during the day. In Figure 4.5b we have the baseline scenario in which the micro batteries last for around 40 minutes and the macro battery lasts for around 10 minutes more. Again the results are similar to what has been acheived in the denser scenario and is possible to see that the traffic assignment algorithms never manage to saturate any of the neighboring 4G cells nor the 3G cell. Figures 4.6a and 4.6b are also similar in content to what has been seen in Section 4.1.1. These figures mean that on a small sized outage the battery capacity has not a huge influence on the lost traffic percentage.



(a)

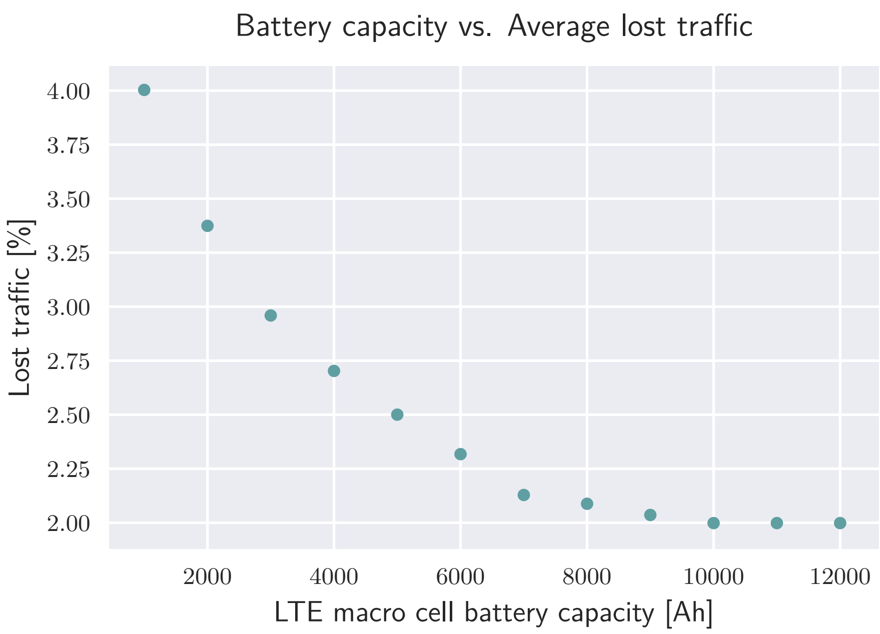


(b)

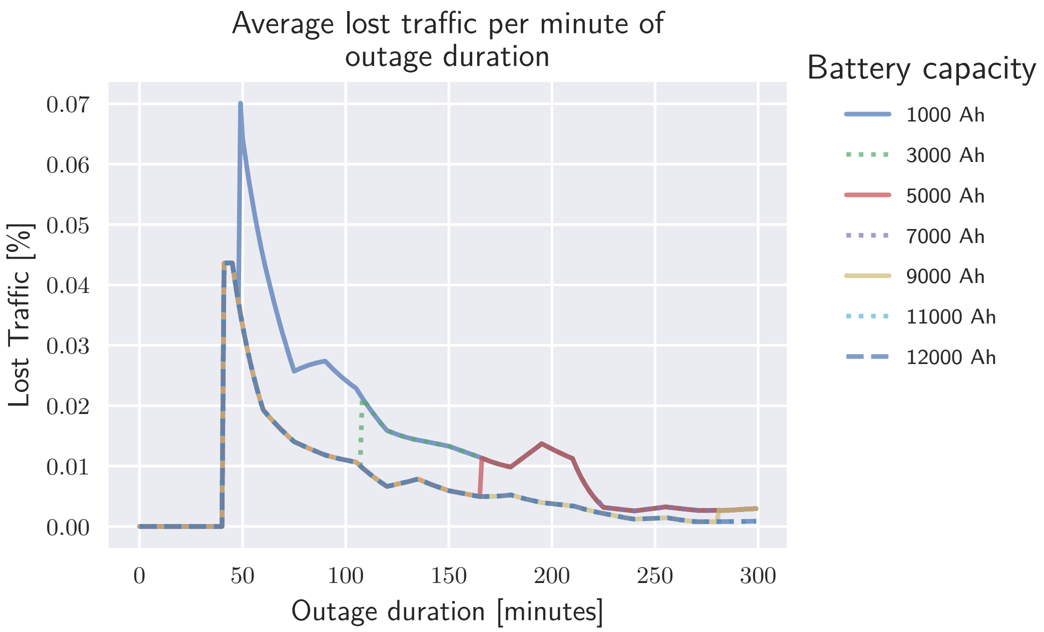


(c)

Figure 4.5: Traffic profiles, Medium density - Off peak scenario



(a)

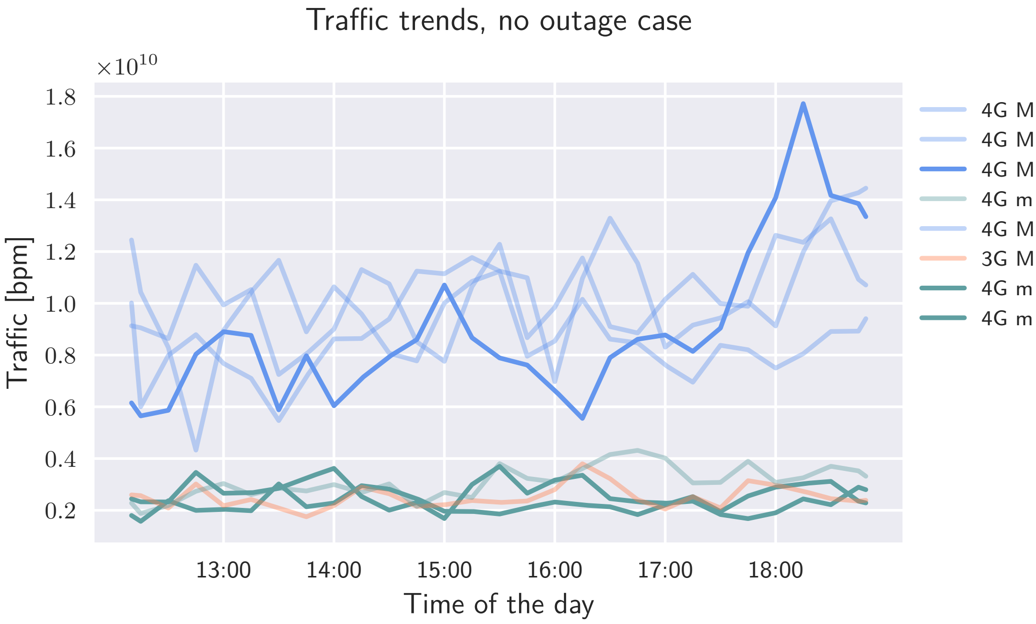


(b)

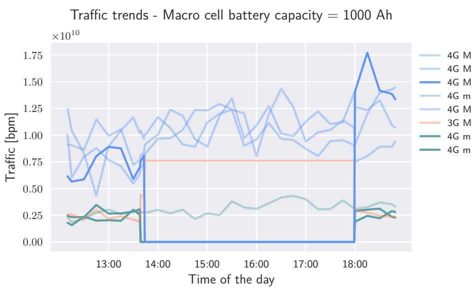
Figure 4.6: Total and per minute lost traffic evolution according to battery capacity increase, Medium density - Off peak scenario

4.2.2 Peak

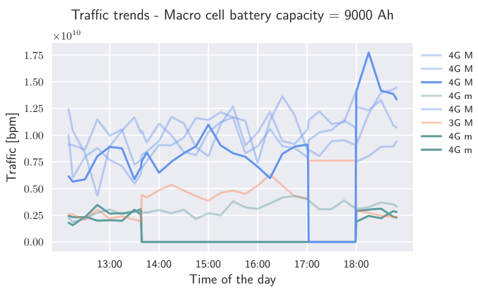
During the peak traffic hour, as shown in Figure 4.7a it is present the same high variability in the traffic profiles shown in the other scenarios during this time slot. During the simulation due to the fewer 4G macro BTS in this scenery the traffic is more often assigned to the 3G macro cell causing its saturation when the 4G macro BTS runs out of power. Because of this, maximizing the duration of the battery of the 4G BTSs becomes crucial since this means loosing even more traffic which could otherwise be performed. In Figure 4.8a and 4.8b it is shown how with the baseline battery the traffic lost from the impacted BTSs is almost one third of the total and to get under 10% there is the need for a battery which is almost 8 times bigger.



(a) no outage

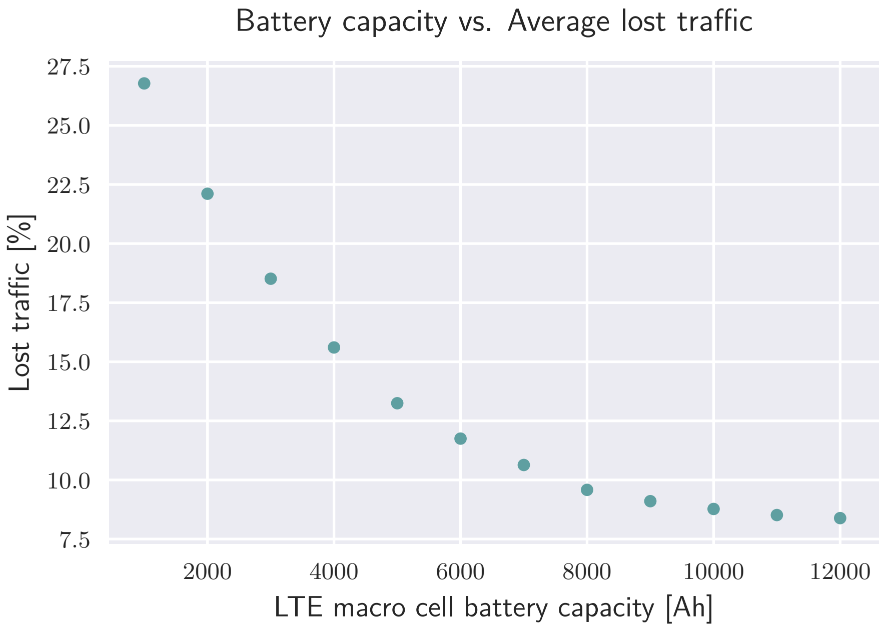


(b) outage

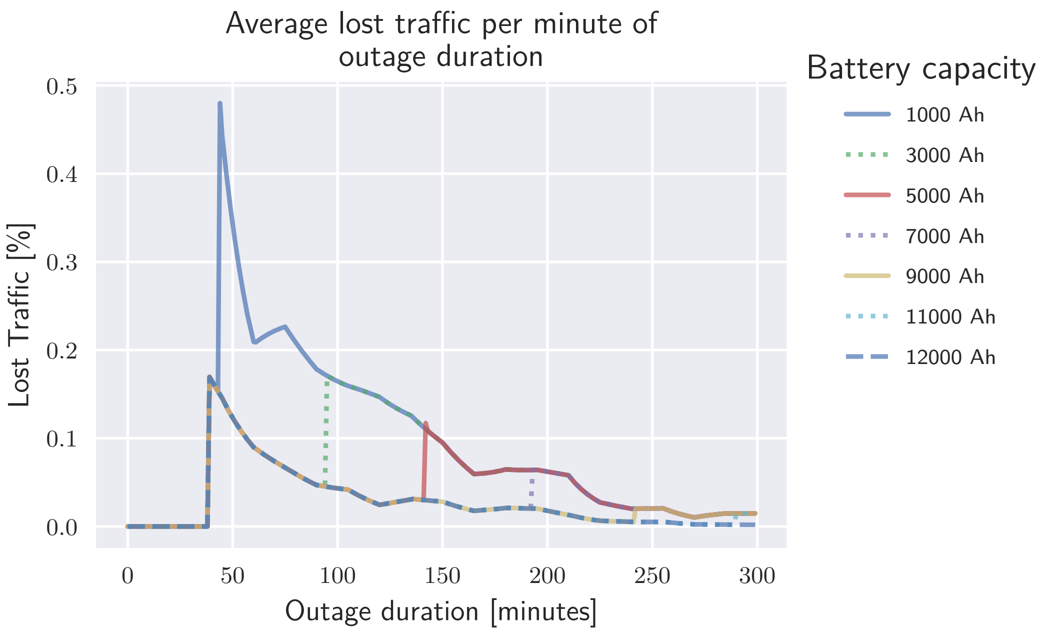


(c) outage

Figure 4.7: Traffic profiles, Medium density - Peak scenario



(a) no outage



(b) outage

Figure 4.8: Total and per minute lost traffic evolution according to battery capacity increase, Medium density - Peak scenario

4.3 Peripheral, sparse distribution zone

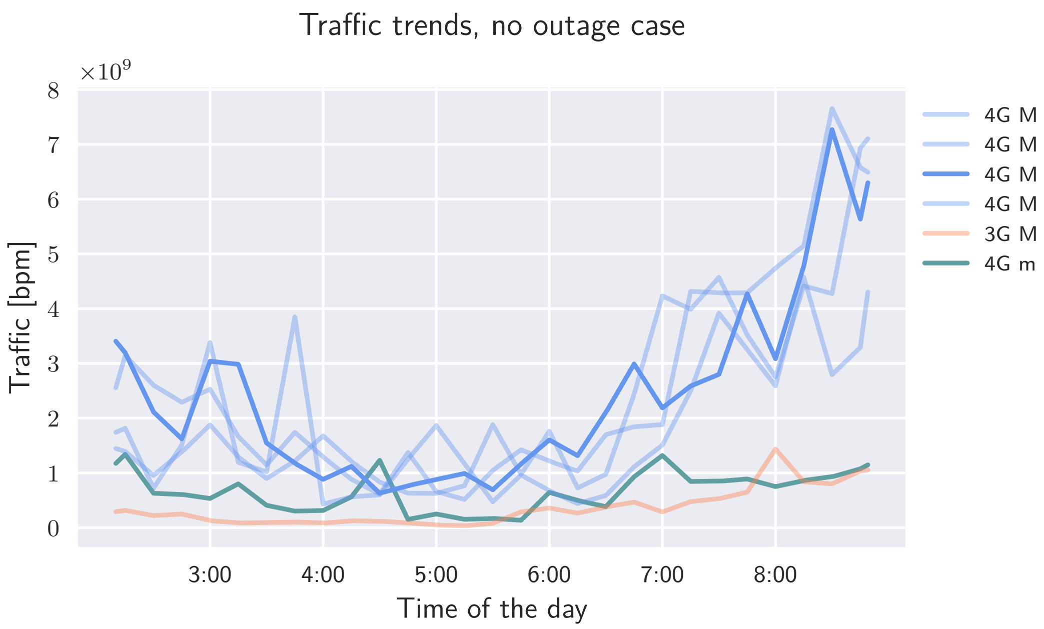
In this scenario a peripheral zone with small urban areas mixed with rural areas is considered. In these zone people are distributed across some small urban clusters and there are vast inhabited/agricultural sub areas. In this areas there is almost no need for micro cells except for industrial plants which could be present and the macro cells are supposed to cover vast areas. This scenario has then set up according to these characteristics including 4 macro 4G BTS, just 1 micro 4G BTS and 1 macro 3G BTS. The radii of the 4G BTS used for calculating the interference area is considered to be around 4 km thus causing interference on 10 % of the area covered from each cell. One macro 4G BTS and the only micro 4G BTS are considered to be impacted from the power outage.

4.3.1 Off peak

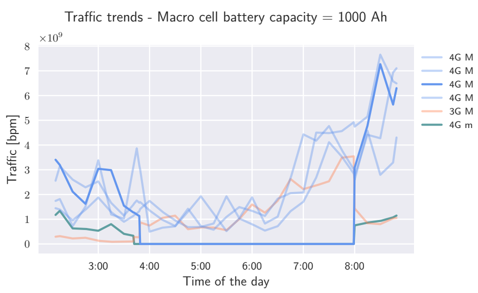
During the off peak time slot the impact of the power outage is mostly similar to the results achieved in Section 4.1 and 4.2. Since the 3G cell is not saturated due to the traffic being reduced Figure 4.9a the losses are mostly mitigated through the 3G BTS, Figure 4.12a

4.3.2 Peak

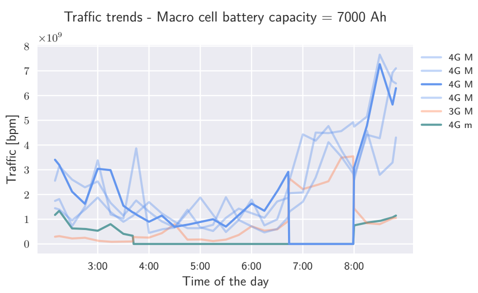
In rural areas, due to reduced cross coverage area percentage and reduced number of available 4G BTS to hand over the traffic, the battery capacity is critical to avoid losses. During peak hours in fact as shown in Figure 4.11 the 3G BTS is saturated as in Section 4.2. The increased losses reported in Figure 4.12a are mostly due to reduced number of available 4G BTS to hand over the traffic. The losses are hugely dependant on the capacity of the 4G BTS to survive the power outage, in fact with a battery with a capacity 6 times greater with respect to the original the losses are reduced of a factor of six.



(a)

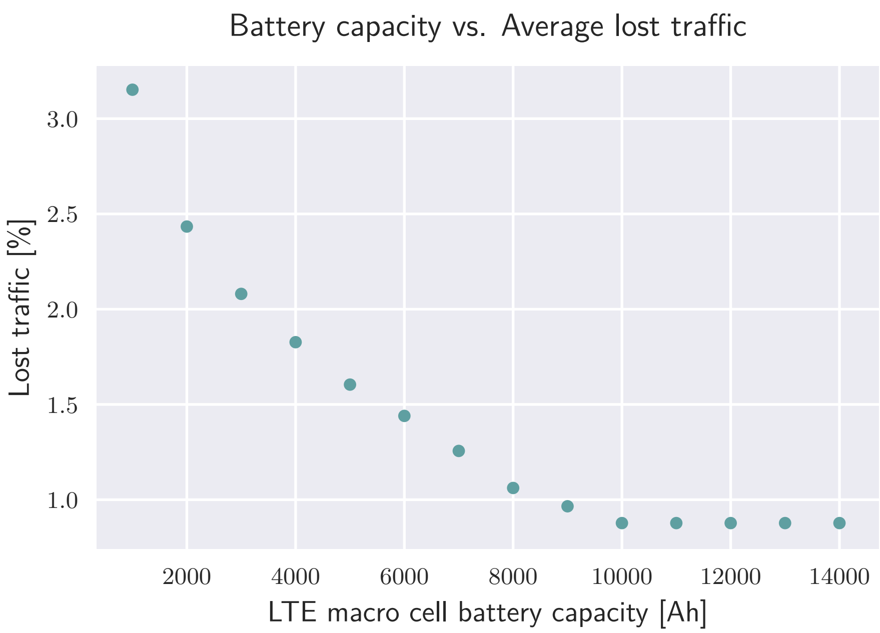


(b)

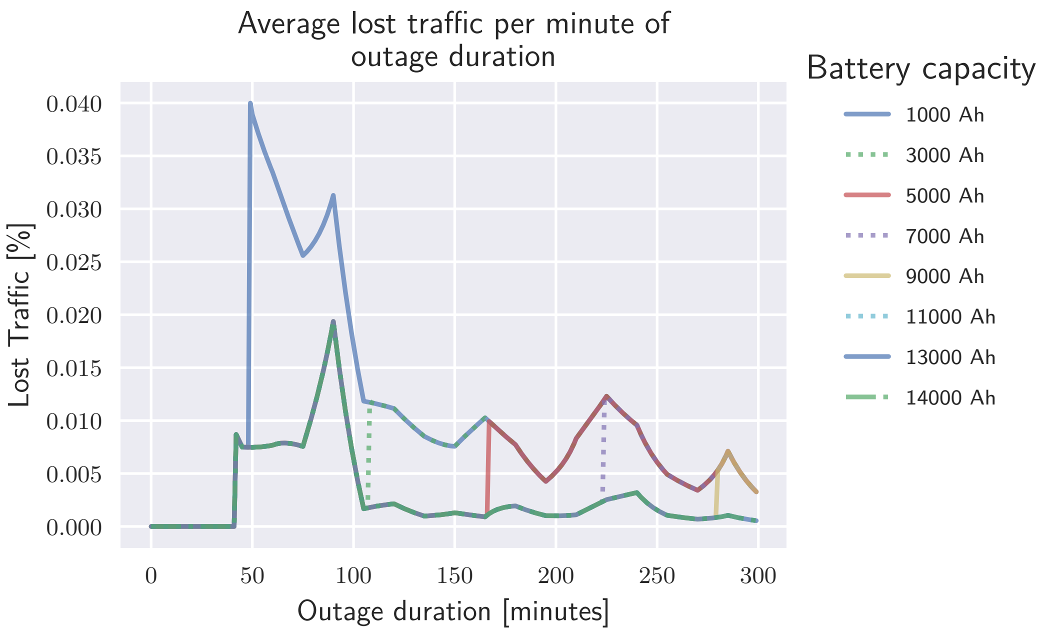


(c)

Figure 4.9: Traffic profiles, Sparse - Off peak scenario



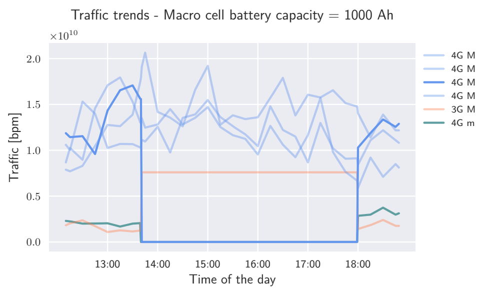
(a)



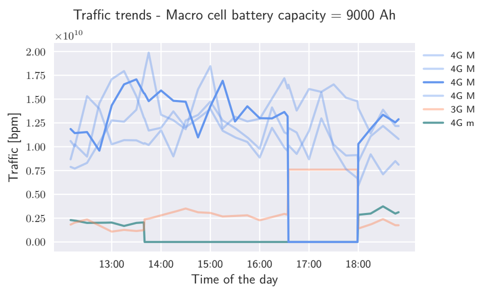
(b)

Figure 4.10: Total and per minute lost traffic evolution according to battery capacity increase, Sparse - Off peak scenario

(a) no outage

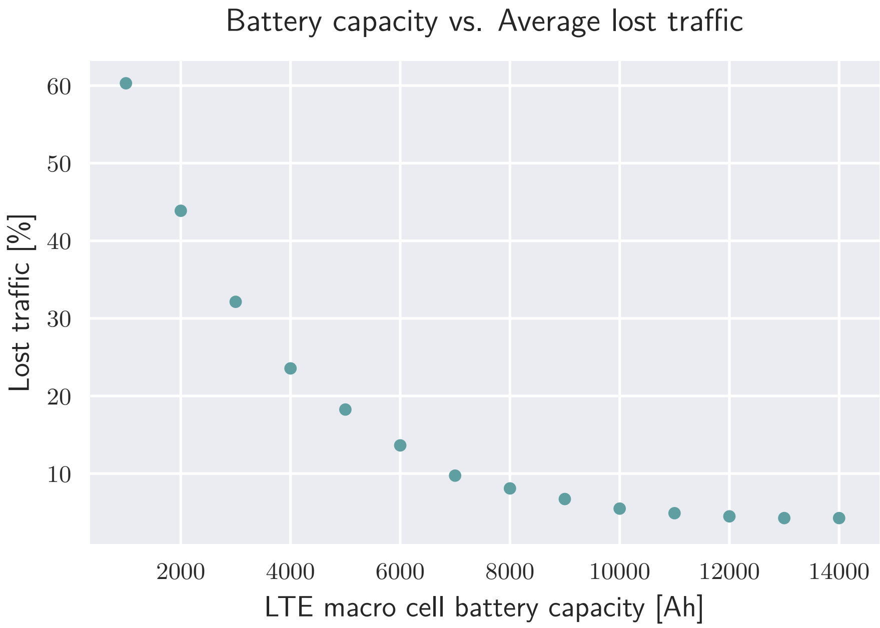


(b) outage

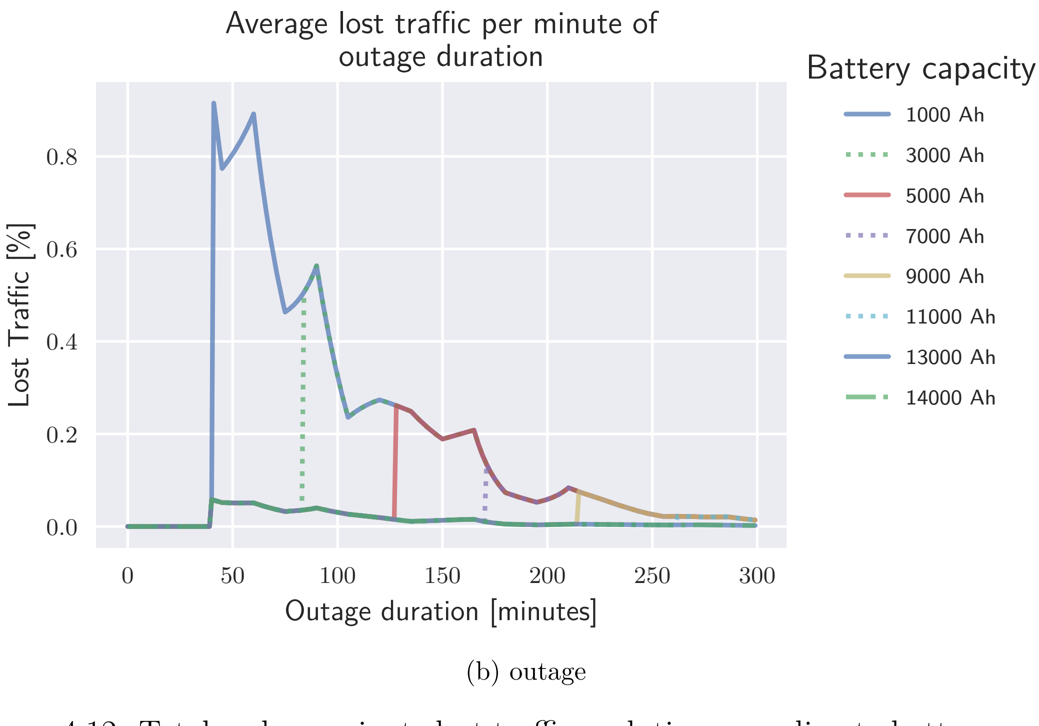


(c) outage

Figure 4.11: Traffic profiles, Sparse - Peak scenario



(a) no outage



(b) outage

Figure 4.12: Total and per minute lost traffic evolution according to battery capacity increase, Sparse - Peak scenario

Chapter 5

Conclusions

The aim of this thesis was building an initial work in how the RAN will have to cope in the near future with the increasing power outages. The thesis focused on an urban area of a developed country but the methodology could be applied to other scenarios such as developing countries where the situation is more critical.

While studying the power outages both the transmission and the distribution networks have been considered, finding the latter to be the main culprit in events involving the RAN. Those events have been characterised, finding useful information about their duration, extension and when their occurrence is most frequent. It has been shown an inverse correlation between the outage duration and its extension, and a prevalence during the summer months at the peak consumption hours for energy. The RAN has also been characterised, finding useful information about its components, the technologies used, the size of the cells and their distribution. The power outages and the RAN have then been correlated looking for a characterization of the impact of a power outages on the RAN.

The median power outage has been seen affecting a reduced number of BTSs, these information has been used to see how battery power could help in those situations. The simulator developed used custom built scenarios and real traffic traces to evaluate the benefits of different battery capacities to cope with the power outage.

The result indicate that the zones suffering the most from power outages are the most rural where the battery capacities needed to keep the network up would make a huge cost.

5.1 Open issues

During the development of the simulator the main issues arose when dealing with traffic traces. Those in fact are not the most accurate method for describing the user behaviour in case of difficulties on the network. The users in fact most probably would not have the same traffic demands in case of a congested network. Traffic assignment should also be improved when a BTS becomes unavailable. In this case the users may switch to another cell or to another network according to network sharing policies. By using better signal propagation models along with traffic generation algorithms there could be a better understanding of how these events impact the users.

5.2 Future works

As a future work the power outage characterization could be improved by getting more data directly from the distributor. This would allow to have a more precise idea about the phenomenon and to perform analysis about its characteristics in different times of the day and of the year. We are also on the verge of 5G networks which will transform the RAN and should be taken into account in future improvements when consumption and usage models become available. An analysis of the impact of renewable sources should be made, which could improve the performance along with a management system according to which the BTSs are switched. This could help reduce the batteries sizes since it has been seen that outages are most frequent during the day when solar energy should be available.

Appendix A

Online data sources

A.1 TERNA data

1. Schede registrazione disalimentazioni (Energia non fornita o energia non ritirata) degli Utenti connessi alla RTN - Anno 2015

2. Schede registrazione disalimentazioni (Energia non fornita o energia non ritirata) degli Utenti connessi alla RTN - Anno 2016

3. Schede registrazione disalimentazioni (Energia non fornita o energia non ritirata) degli Utenti connessi alla RTN - Anno 2017

4. Schede registrazione disalimentazioni (Energia non fornita o energia non ritirata) degli Utenti connessi alla RTN - Anno 2018

A.2 IRETI data

- API IRETI Continuità del Servizio - Registro interruzioni POD / ANNO

A.3 INWIT data

- INWIT Coverage Map

A.4 CellMapper data

- CellMapper Coverage Map

Appendix B

Extra Figures

B.1 Outages

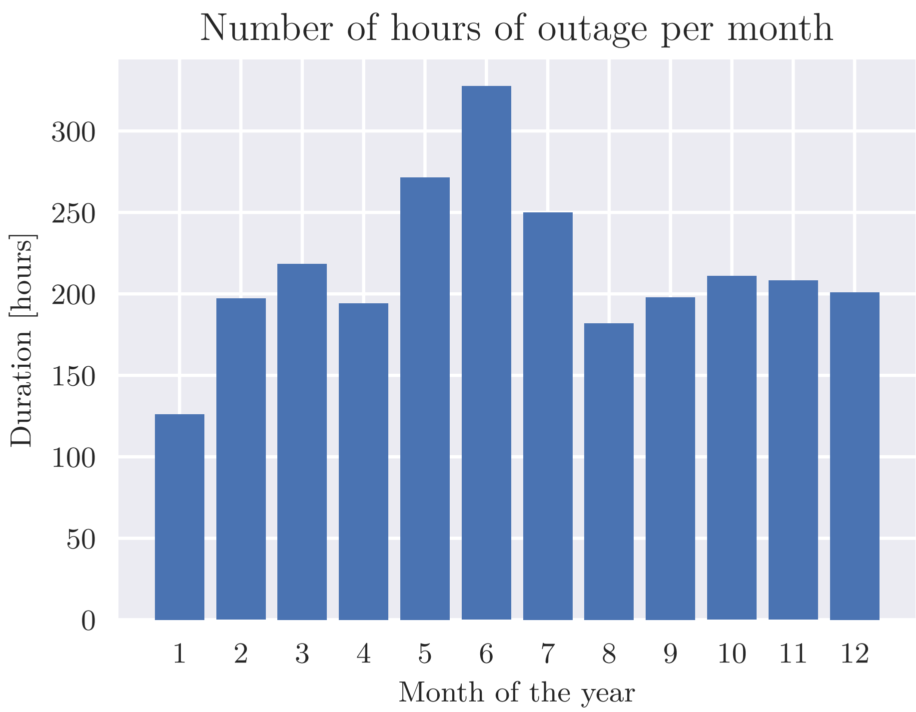


Figure B.1: Total outage hours per month, data IRETI 2014-2018

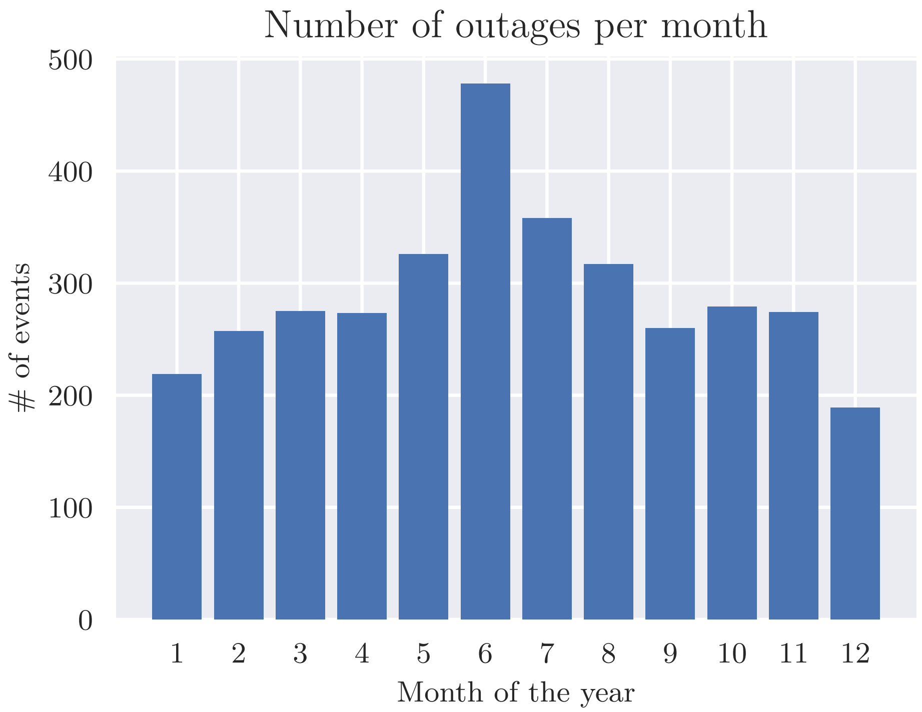


Figure B.2: Number of outages per month, data IRETI 2014-2018

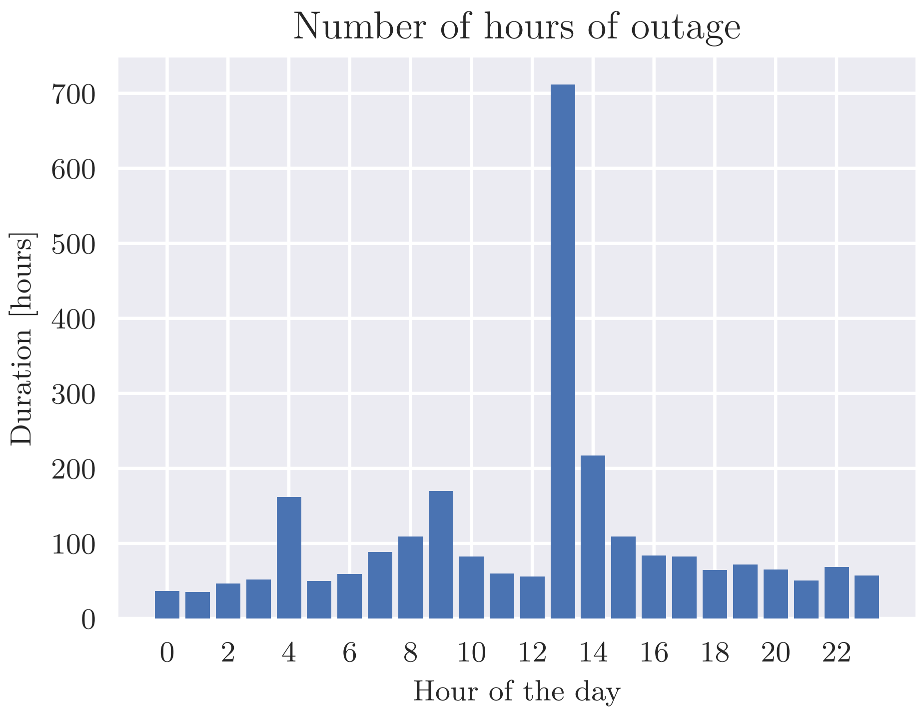


Figure B.3: Total outage hours per hour of the day, data IRETI 2014-2018

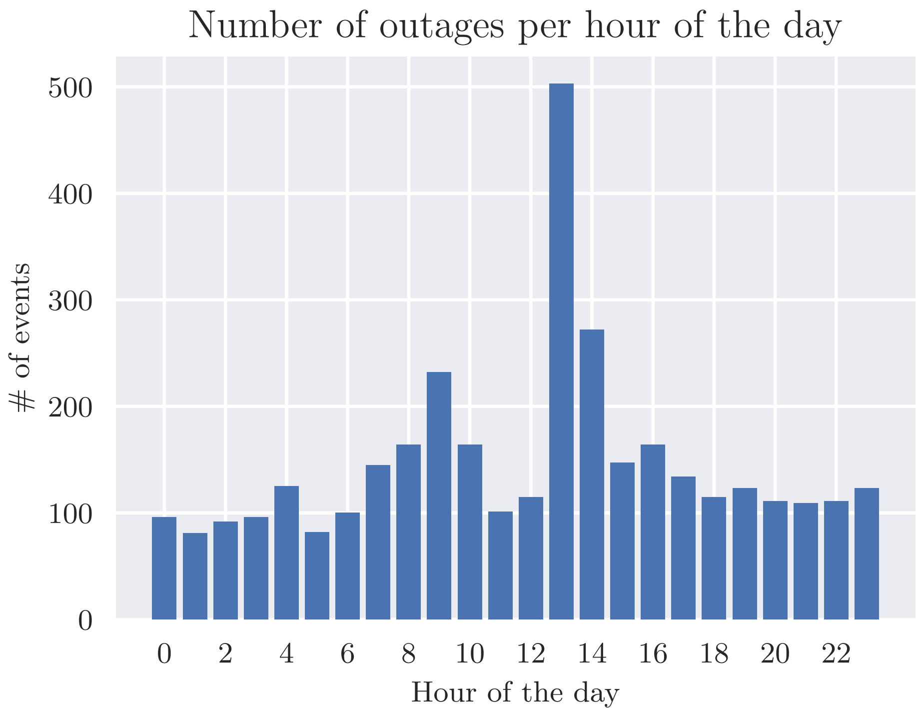


Figure B.4: Number of outages per hour of the day, data IRETI 2014-2018

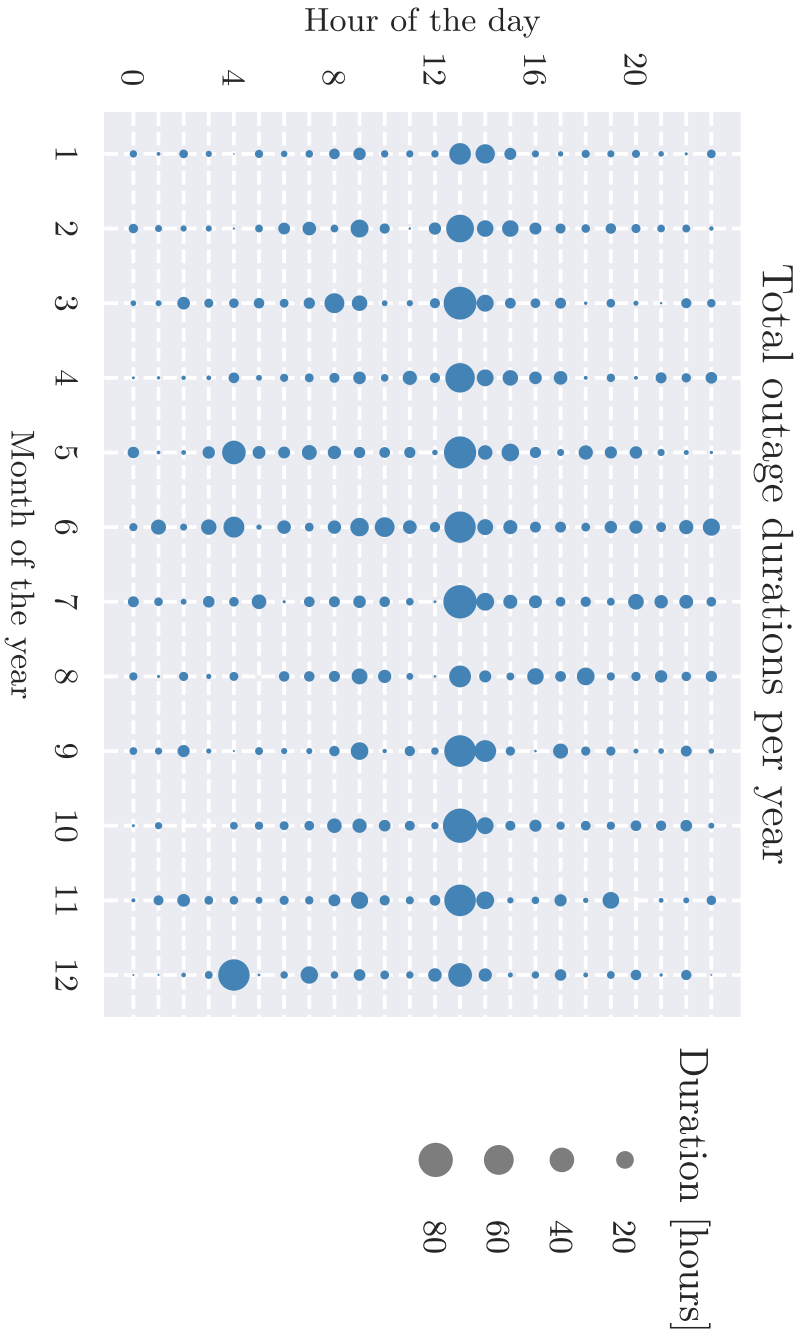


Figure B.5: Total outage hours per hour of the day and month of the year, data IRETI 2014-2018

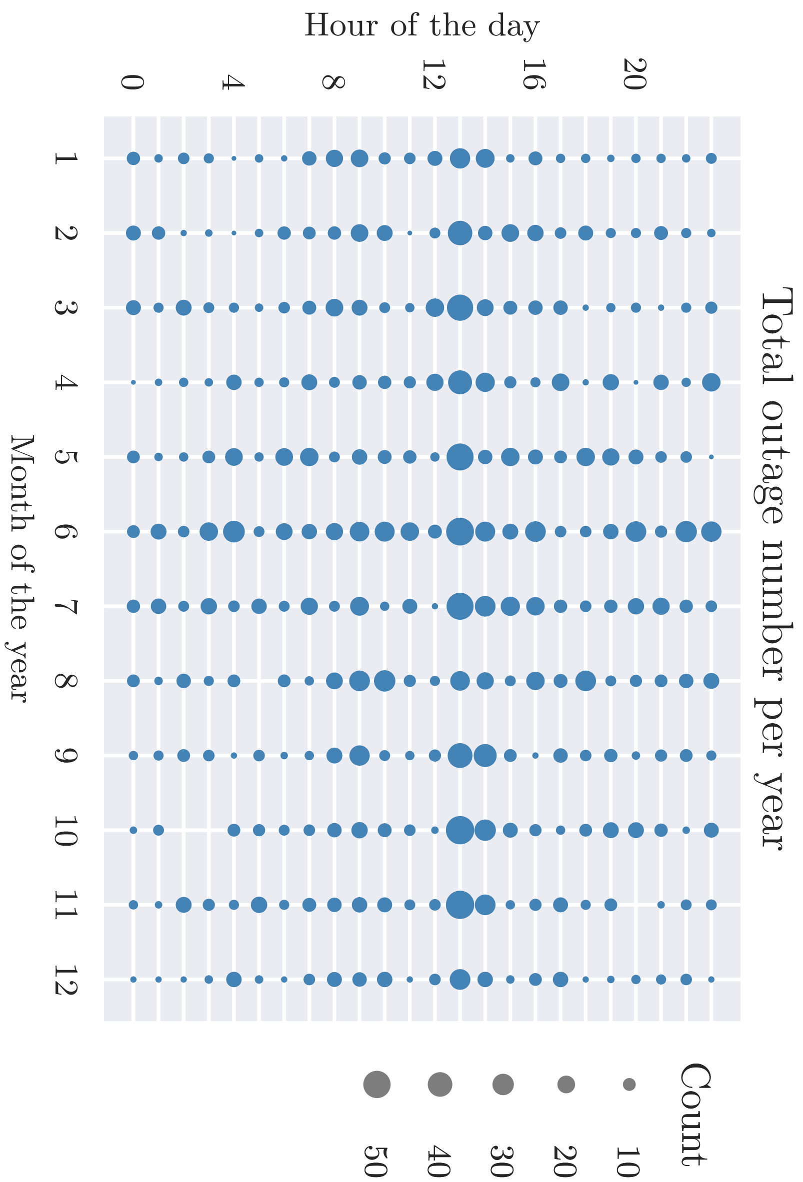


Figure B.6: Number of outages per hour of the day and month of the year, data IRETI 2014-2018

Bibliography

[1] *Documentation of scikit-learn 0.21.3 - DBSCAN*. Accessed 01-November-2019. 2019. URL: https://scikit-learn.org/stable/modules/clustering.html#dbscan.

[2] *Energy efficiency analysis of the reference systems, areas of improvements and target breakdown*. Report. Energy Aware Radio and neTwork tecHnologies, 2010.

[3] M. Iqbal and K. Alimgeer. *Calculation of Overlapping Area for Cellular Systems*. Report. 2013.

[4] R. Michael et al. *Analysis of Energy Storage Sizing and Technologies*. Report. 2010.

[5] *Mobile broadband with HSPA and LTE – capacity and cost aspects*. Report. Nokia Siemens Networks, 2010.

[6] W. Obile. *Ericsson mobility report*. Report. 2016.

[7] A. Oliver et al. *Power Consumption Modeling of Different Base Station Types in Heterogeneous Cellular Networks*. Report. 2010.

[8] Y. Yuqing et al. *A Comparison Study of Dispatching Various BatteryTechnologies in a Hybrid PV and Wind Power Plant*. Report. 2018.

[9] D. P. Zafirakis. «Stand-Alone and Hybrid Wind Energy Systems». In: (2010).