Design of a Backhaul Network for Wildfire Monitorization in Madeira Island

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Abstract- Telecommunications count with several communication systems, including the microwave radio links. Currently, these are used less frequently taking into account the development of technologies such as the optical fiber, however, they continue to be used having characteristics that may constitute differentiation factors in certain situations. Microwave radio links are systems of quick implementation with reduced installation and maintenance costs, showing even more resilience in the face of natural disasters and extreme conditions. In this project, it is intended to carry out a survey of the current networks of microwave radio links existent in the Região Autónoma da Madeira (RAM) and study them, seeking then to propose the implementation of a backhaul network by microwave radio links for data transmission in order to ensure the transport of fire monitorization data in the East zone to a data center, the several links being simulated using Feixer.

Keywords- Microwave Radio Link, Data Transmission, Future Trends, Backhaul, Wildfire, RAM.

I. INTRODUCTION

Microwave radio links have been used in point-to-point links for a long time, having the first link been established around 1931 between Calais, in France and St. Margarets Bay, in England, being implemented after two years the first permanent link between the airports of Lympne, England and St. Inglevert, in France [1].

This type of systems is considered advantageous in situations where transmission is made to long distances and when there are obstacles such as mountain ranges or rivers that make the installation of physical support difficult. The propagation is done in line of sight without the need of a wired link, constituting an advantage for the most varied situations where it is impossible to implement wired links.

Despite the importance that microwave radio links had at the beginning of point-to-point links, with the advancement of technology, optical fibers assumed greater prominence and overlapping microwave radio links over time, however, the microwave radio links communication systems assume another importance currently. In extreme situations, as in the case of the most diverse natural disasters, microwave radio links constitute a reliable alternative, as it was seen in the alluvium of February 20, 2010 in Madeira, in which many mobile communications were lost due to the fall of backhaul links, specifically those that are constituted by cables and optical fibers, while the operators that used microwave radio links managed to keep mobile communications running in this weather.

Forest fires constitute another phenomenon, in which the use of microwave radio links constitutes an asset, these can be used during the fire and after it until communications are restored by the main transmission solution. As long as you are not facing extremely high temperatures and intense smoke, the microwave radio links are a solution with high service availability [2].

In the past few years, a greater frequency of forest fires has been registered in Portugal, these are reaching increasingly larger proportions and have had more devastating effects. In terms of communications infrastructures, there are more than two hundred locations of radio communication station installations affected by these phenomena’s, forcing the Autoridade Nacional de Comunicações (ANACOM) to find strategies and implement measures that allow to deal with this situation [3].

In this way, working groups for different areas gathered and the strategies and measures to be implemented in each area were defined. Relatively to the radio communications, there was a need for microwave radio links to constitute an alternative to overhead cable traces, this is because through microwave radio links it is possible to have a transmission network that is not susceptible to fires and other natural disasters. This solution is especially important for more rural regions, with low population density and, essentially, in places with difficult access and whose forest fire hazard class is "High" or "Very High". This measure aims essentially to expand the network without excluding the routes that already exist and are in operation [3].

However, the microwave radio links are limited in bandwidth, so they may not be the main communication solution, although they may still be a viable hypothesis for implementing redundancy. Thus, they serve only as an alternative and act in case of failure of the main communication solution.

II. CURRENT AND FUTURE TRENDS

This sub-chapter seeks to portray the usefulness of microwave links in the world of telecommunications, as well as some innovative aspects that have allowed their continued use and their improvement. The changes that the microwave links bands have undergone with the entry of 5G technology into the market were also analyzed.

A. *Microwave Radio Links as Backhaul*

Microwave radio links are a precious tool to serve as a backhaul service to mobile networks, serving as a link between the core of the network and the mobile network stations. Technological advances have facilitated the transmission of high-capacity data in a reliably way, allowing wireless backhaul to remain a competitive alternative to optical fiber in mobile access networks [4].

Ericsson [5] predicts that by 2023, even with the addition of optical fibers and the disappearance of copper cables, about 40% of stations worldwide will be connected by microwave links, increasing to 65% when excluding countries such as China, Taiwan, South Korea and Japan (Figure 1). The Northeast Asian market has grown disproportionately with large LTE implementations registered and a high fiber integration, significantly conditioning and influencing the result of the global market.

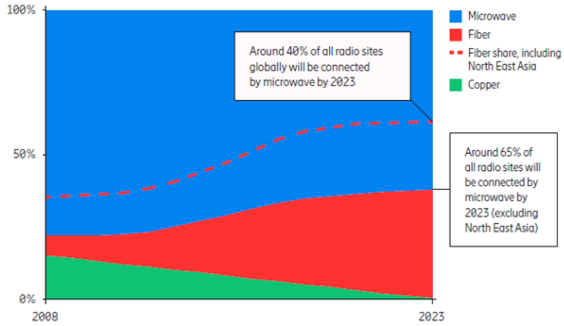


Figure 1 – Backhaul distribution by 2023 [5].

In developed regions of mobile broadband, such as Western Europe, there are examples of big operators that already use up to 80% of microwave links, who are now planning to introduce 5G using existing microwave links networks [6].

The combination of fiber and microwave links solutions remains an ideal backhaul strategy for the development of 4G and 5G networks. Network cores and intercity aggregations are generally implemented with fiber backhaul, while the respective branches are implemented using microwave links [5].

B. *Spectrum Trends*

Higher capacity requirements are driving the introduction of 5G in microwave bands, which means that the availability and use of the microwave spectrum for fixed services will undergo a major transformation in the next five to ten years, causing major impacts to operators [7].

The E band (71–76 GHz paired with 81–86 GHz) will grow, being more used and assuming great importance, thus satisfying the demand for high capacities in current and future networks. With the introduction of 5G, the interest in the E band becomes quite relevant, since it can provide up to 10 Gbps, even for densely urban locations, representing 25% of all microwave links resources available [8]. However, in the long term, additional spectrum for backhaul will be needed in order to support transmission rates up to 100 Gbps, leading to the introduction of new W and D bands [5] [9].

W and D bands are not made up of a continuous spectrum block, but by several blocks, and the total amount of spectrum of the two bands is almost 50 GHz, that is, five times more than in the E band, representing an important goal for the future [5] [6].

Until 2025, the 15–23 GHz spectrum will remain as global high-volume microwave band. While the E band will become a high-volume global band on its own and in combination with 15–23 GHz, estimating a 20% growth since its emergence. The use of the W and D bands is expected from 2020, however, it does not show as strong growth as the E band (Figure 2) [6].

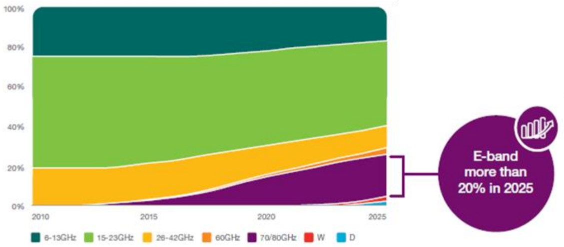


Figure 2 – Evolution of the microwave links frequency range until 2025 [6].

For long jumps and as an economical replacement for optical fiber, the 6 to 13 GHz band is also important, although in Figure 2 there is a decrease in its use. Due to their good propagation properties in geographical areas with high precipitation rates, these low frequencies will continue to be essential for the construction of transport networks in certain regions [6].

C. *Spectrum and Capacity Efficiency*

Since the spectrum is a scarce resource and cannot meet the growing demand for high bandwidth, it is essential to develop solutions to make this resource more efficient. These spectrum monetization solutions, as well as the increase in capacity, may be [10]:

- **Multi-Band:** The combination of the E band with a traditional frequency on the same radio link, allows you to get the best out of the two bands, thus increasing the link capacity [6];
- **Elevated Modulation Schemes:** As expected, the increase in the modulation index implies a greater capacity to condense more information, so this technique allows to increase the link capacity. However, above 1024 QAM, the spectral efficiency gain is less than 10% in each degree [11];
- **Multiple-Input Multiple-Output (MIMO):** MIMO is a technology used to multiply the capacity of the links, using several transmission antennas and reception to explore the propagation of multiple paths.

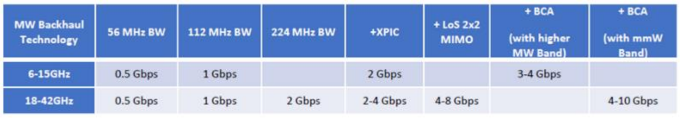
  Without additional spectrum resources, this technology can deliver up to four channels on one frequency, thus providing four times the capacity of a single link, in addition to the reliability of a MIMO channel being greater than a single link, without any increase in power antenna transmission, exploring the diversity gain introduced by the use of multiple antennas (also known as spatial diversity) [12];
- **Cross Polarization Interference Cancellation (XPIC):** The Cross Polarization Interference Cancellation technique follows the overlapping plane concept, assigning the same frequency to the vertical and horizontal polarization in the same link, in which an algorithm is used to suppress the mutual interference

between the two received signals. In this way, it is possible to obtain twice the spectral efficiency [13];

- **Geographical Spectrum Efficiency**: This technology consists in the dense reuse of channels, this is because it is not only advisable to increase the spectral efficiency of a channel, but also the reuse of the channel in a certain area, thus ensuring that there is no interference [11];
- **Orbital Angular Momentum (OAM):** Technology that is not yet on the market, however, there are experimental tests. It is with different antennas that multiple OAM signals, with different modes (orthogonal to each other), are transmitted, making it possible to transmit N different signals in a single channel and in a single polarization [11].

These techniques provide capacities beyond the double of normal systems, with a high capacity performance in the use of high bands, as shown in Table 1, which presents data from a study carried out by [11].

Table 1 – Performance of future technologies in backhaul links [11].



MW Backhaul Technology	56 MHz BW	112 MHz BW	224 MHz BW	+XPIC	+ LoS 2x2 MIMO	+ BCA (with higher MW Band)	+ BCA (with mmW Band)
6-15GHz	0.5 Gbps	1 Gbps		2 Gbps		3-4 Gbps	
18-42GHz	0.5 Gbps	1 Gbps	2 Gbps	2-4 Gbps	4-8 Gbps		4-10 Gbps

III. Study of Microwave in RAM

In this chapter, the existing microwave radio links in the Madeira Archipelago are studied, including the Porto Santo island, and then the data of some institutions with microwave radio links are detailed.

Initially, a generic study of all existing licensed microwave radio links is carried out, based on data provided by the ANACOM, exposing the evolution of their use over the last few years, more precisely between 2009 and 2019.

Posteriorly, a particular case was described of a public entity in RAM, which uses this telecommunications system, even though it does not require licensed bands.

In this sense, this subchapter presents the data of microwave radio links registered by ANACOM, in the bands that need licensing. The only entities allocated in Madeira that need or needed licensing are/were MEO Comunicações, NOS Comunicações, Vodafone, NAV, RTP, EEM and ONITelecom.

In a first phase, ANACOM was asked to provide data indicating the numerical evolution of the microwave radio links over the past ten years, these data being represented in Figure 3. It is important to refer that a point-to-point link with more than one channel per polarization or with a passive repeater, representing two sections, it was considered as a single point-to-point link. All links are bidirectional with the exception of Studio-Emitter (STL) links in the 1517-1525 MHz frequency band.

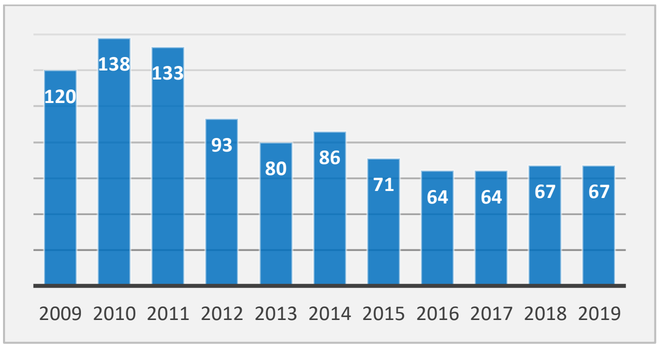


Figure 3 – Number of licensed microwave radio links, between 2009 and 2019, in RAM.

Analyzing the previous graph, it appears that initially, in 2009, there were, in RAM, 120 microwave point-to-point links, with an increase of 15% in the following year. In 2011, there was a drop in the number of microwave radio links in use, with this drop being more accentuated in 2012, with a decrease of 30% in relation to the previous year. This variation between 2011 and 2012 will be analyzed below with more fundamentals.

Between 2012 and until the end of 2019, the graphic illustrates a brief decrease in the use of microwave radio links over the years, although it shows a slight increase of six links in 2014 and three in 2018 compared to the previous years, verifying in 2019, the maintenance of the number of existing links in 2018. In short, a variation rate of approximately -28% was obtained between 2012 and 2019, with a decrease of 44% in the number of licensed links in the integral period analyzed.

These variations deserve a more detailed analysis, so at a more specific level, the segmentation of links by institution is essential to better understand the evolution. In this case, in which the data are individualized according to the institutions, it was not possible to count the Studio-Emitter links as they were not individually quantified by the institutions in the data base provided by ANACOM.

In a first comparative analysis between the beginning of the period (2009) and the end of it (2019), there are major changes in the number of links per institution. Through the analysis of Figure 4 it is possible to verify that eleven years ago Vodafone held more than half, 57%, of the existing links, followed by ONITelecom with only 17%.

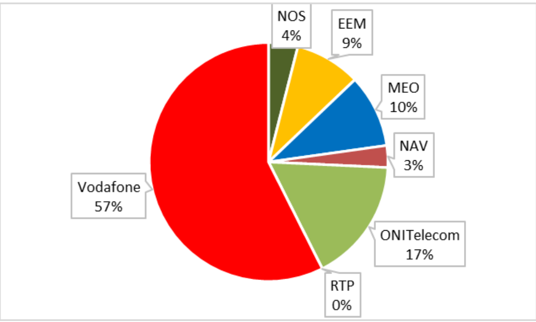


Figure 4 – Microwave radio links existing in 2009, by company.

Ten years later, there are many differences, in addition to the smaller number of microwave radio links in use, there was also a large decrease in microwave radio links from the operator Vodafone, with MEO becoming the largest microwave radio links holder (Figure 5). NOS and Vodafone, together, are equally responsible for another 30% of current links.

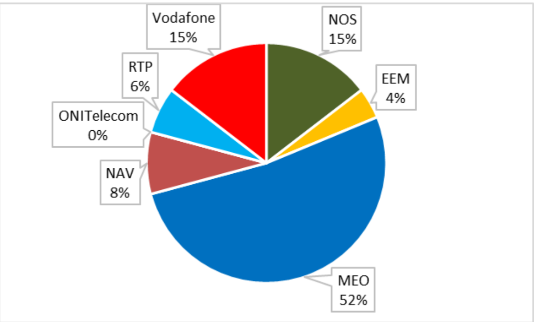


Figure 5 – Microwave radio links existing in 2019, by company.

However, this analysis only allows to understand the panorama eleven years ago and the last complete year compared to the current one, so now it is important to make a more precise analysis. Thus, the previous data was separated into two graphs (Figure 6 and Figure 7) as a function of the number of links per institution over the analyzed period of time.

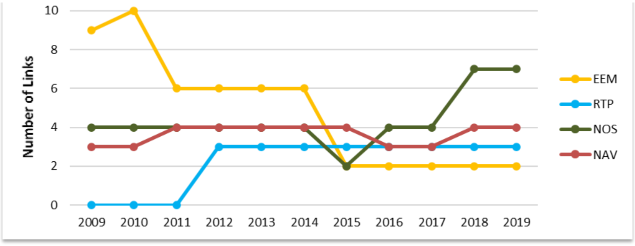


Figure 6 – Number of licensed links per institution (part I).

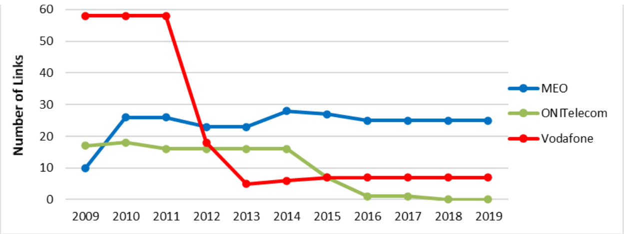


Figure 7 – Number of licensed links per institution (part II).

By examining the graphs, it is possible to draw new conclusions about the previously verified changes. It appears that the increase of 15%, in 2010, was essentially due to the bet of the telecommunications company MEO in the band of 11 and 18 GHz. Regarding the decrease observed in 2011, this was due to a slight reduction in the number of links used by the Empresa de Eletricidade da Madeira, in the 7 and 13 GHz band. In that same year, ONITelecom also reduced two links, maintaining the number of links until 2014.

The decrease in the number of links from EEM, in 2011, was due to the arrival of optical fiber to some of its stations, passing the links into the background. The decrease observed in 2015 was essentially due to a change in the legislation where the company was obliged to change the band of some links, ending up definitively deactivating the respective microwave radio links.

The decrease of 30% seen above between 2011 and 2012, was due to the sharp decrease in the number of links from Vodafone. This occurrence is easily explained by the fact that, initially, this operator used microwaves of various frequencies in order to interconnect its base stations, however, later it started to share infrastructure with another operator, uninstalling a large amount of microwave radio links, with greater expression in the band of 18, 23 and 38 GHz, registering all these bands decreases above 85% in a 10-year analysis.

A. *Case of Study – LREC*

The Região Autónoma da Madeira has been plagued by adverse weather phenomena such as the intense flooding that occurred ten years ago, more specifically on February 20, 2010. The high rainfall recorded on that day caused rapid and violent floods, which transported various solid materials in high concentrations.

This phenomenon has caused countless and great damages, leaving the population in shock, and forcing the competent entities to analyse what happened with a view to prevent future action. Thus, the Governo Regional sought to have a scientific study to assess the risk of alluvium on the island, which was developed by a consortium composed by the Instituto Superior Técnico, the Laboratório Regional de Engenharia Civil (LREC) and the Universidade da Madeira that together searched to evaluate and characterize the risks associated with this alluvial phenomenon [14].

The study carried out suggested that a monitoring system in the brooks was implemented on the island in order to prevent these events and reduce the damage caused as much as possible.

In a first phase, between the beginning of 2013 and the end of 2014, LREC and Wavecom designed and implemented a Telemetry and Automatic Surveillance system in the four most affected brooks on February 20, namely Ribeira de João Gomes, Santa Luzia, São João and Ribeira Brava, allowing real-time monitoring of flows and materials coming through the brooks. In these were installed video cameras, ultrasonic level sensors and radar, as well as udometers, these equipment being connected to radioelectric equipment.

Regarding to communications and since the brooks are inserted in very mountainous valleys, sometimes with difficult access and with a high probability of landslides, the most appropriate and robust solution to send information was the use of radio communications.

However, the final solution was the implementation of a hybrid model of radio frequency and optical fiber [15]. This is because it became more profitable to implement optical fiber in certain nodes due to the absence of an unobstructed line of sight until the data center located in the LREC building (GW0). The mapping of this solution is illustrated in Figure 8.

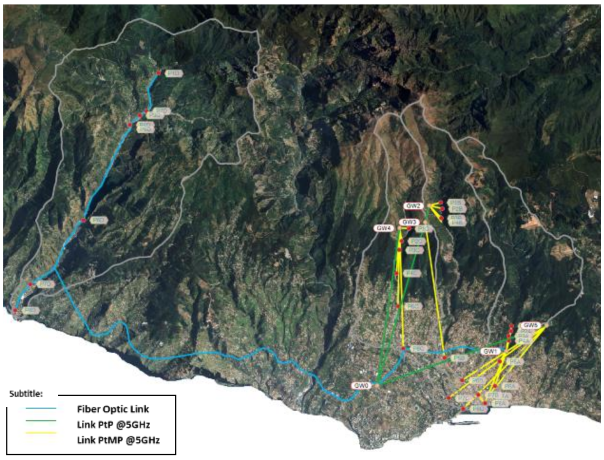


Figure 8 – Network mapping of the brooks monitoring project [15].

The brooks monitorization network consists of five gateways, next to the three brooks in Funchal. These gateways have the function of receiving the data and images sent by the different monitoring points and, posteriorly, the respective routing to the data center. However, one of the gateways, the GW3 - Esteios, has the simple function of serving as a repeater between the GW2 gateway (Ribeira Santa Luzia) and the data center, as there is no line of sight until LREC. The gateway on the Ponte João Gomes (GW1) is connected by optical fiber to the central.

The monitoring points are connected by point-multipoint (PtMP) links to the gateway. In turn, the gateways are interconnected by point-to-point (PtP) links to the data center. Both radio frequency links are implemented in the 5 GHz unlicensed band.

PtP backhaul links have a guaranteed throughput of 100 Mbps, enabling the real-time transmission of images and other data [16]. Point-to-multipoint links share the base station's bandwidth. Thus, the 100 Mbps are shared by the monitoring stations, making the equipment generate communication with transmission in well-defined time slots. Depending on the traffic, the link can be dynamic and be adjusted by the base station, and if one monitorization station needs more bandwidth and another not so much, the transmission window of the first one can be extended to compensate for the decrease of the other one.

After the network was operational, the network had to be redesigned to support redundancy, allowing that in the event that a link goes down, the signal is redirected to another link. The solution found by the two entities was the creation of two new point-to-point links in the same frequency band. In this way, they implemented a link between the GW4 and GW3 gateways, so that when the GW0-GW3 link goes down, the previous one goes into “action”. When the GW2-GW3 link goes down is activated an implemented link from the GW2 gateway to the GW5.

In short, the brooks monitoring network has more than 26 microwave radio links and more than 38 radio equipment Wavesys 1000, being designed to send data to LREC autonomously and free of any telecommunications service cost, without being dependent on possible breakdowns in mobile networks.

As the Região Autónoma da Madeira is not only susceptible to floods, LREC has been developing a forest fire detection system for the West of the island since 2019, known as the Subsistema de Deteção de Incêndios da RAM (SDIRAM).

SDIRAM is a project that will aim at automatic detection, by means of fully automated robots, georeferencing and analysis of the evolution of fire fronts, in real time, of forest fires, allowing the guidance of fire-fighters in combat [17].

For the fire system, the LREC team is studying point-to-point links in a band other than 5 GHz. However, it has been necessary to conduct studies on the behaviour of a link in the presence of fires, as these may suffer interference derived of the emission of pollutants from burning [18].

IV. Simulation and Analysis

In this chapter, it is intended to carry out a study on the implementation of a new network of microwave radio links, in order to implement most of the processes to be taken into account when sizing a system using microwave radio links. To this end, was made the decision to study a network that could bring practical use to the island of Madeira.

LREC is developing the fire detection system only for the West zone of the island, so the East zone will be fragile in monitorization this type of occurrence. In view of this, this flaw was taken advantage of and a microwave radio links network was studied to complement the monitorization network.

This study does not intend to carry out a in-depth analysis of the effects of fires, nor of the equipments to be used to detect them, the main focus being on the projection of a microwave radio links network in order to serve as a backhaul to the monitorization system. However, in order to design the microwave radio links, it is necessary to carry out a pre-study about the fires in the East zone, in which the municipalities of Santa Cruz, Machico and Santana are inserted, in order to make the most appropriate choice of the location to the radio stations for monitorization purposes.

A. *Wildfire Monitorization*

Apart from satellite images, fire detection can also be carried out using digital cameras and thermal sensors through camera surveillance and wireless sensors in an automatic optical recognition system, respectively.

In this context, in a simplified way, it was assumed that each station will have a 360º video surveillance camera, to allow omnidirectional coverage of the ground. The use of cameras was chosen because it is the solution most used by the entities, regardless of the type of camera.

Consequently, to meet the requirements for real-time transmission of images captured by the cameras, it was defined that each station will have to transmit data at a “round” rhythm of approximately 10 Mbps, as a system that uses the previous codec provides the compression of a video to values between 1 and 8 Mbps [19].

In an initial phase, there was a need to understand which areas were most susceptible to fires in the Eastern zone of the island, so that the choice of the location of the monitorization stations was the most coherent, allowing a greater area of visual coverage, without compromising the safety of stations in the occurrence of fires next to them. To this end, the Instituto das Florestas e Conservação da Natureza, IP-RAM, was asked for a letter of susceptibility to the occurrence of fires in Madeira (Figure 9).

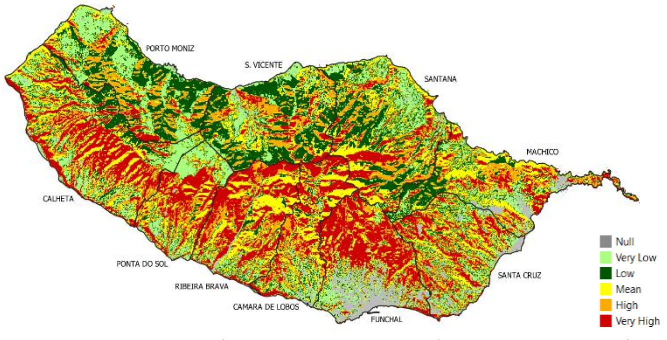


Figure 9 – Letter of susceptibility to wildfires on the island of Madeira (Provided by Instituto das Florestas e Conservação da Natureza, IP-RAM).

For the monitorization system in question, only the two highest susceptibility classes were analyzed, as it is considered that these will be sufficient to characterize the most critical areas.

The correct study of the location of the monitorization stations is an essential process, since visibility and viewshed factors must be considered, in order to minimize the shadow areas.

The Arquipélago da Madeira has several infrastructures for preventing and fighting forest fires, being one of the most essential the surveillance towers. This way, the integration of these towers in the incendiary monitorization network that is intended to be designed is an essential step.

These towers are located only on the island of Madeira, and currently there are six scattered operational towers. They are found in places with high levels, with 360º visibility to forest areas, mainly on the Southern hillside, which is the area with the highest frequency of fires and the most burnt area.

In the municipalities under study there are only two surveillance towers, one in the municipality of Machico (Pico do Suna - Figure 10), in the parish of Porto da Cruz, at an altitude of approximately 1028 meters, and another in the municipality of Santana (Boca das Voltas - São Jorge parish) at 834 m.

Figure 10 – Pico do Suna surveillance tower.

In the impossibility of these towers to visually cover the entire susceptible area to fires identified in the three town halls, there was a need to study additional locations, having as preference the choice for higher peaks in the town halls. Some of these peaks are already areas where there are radio or telecommunications stations, so the use of these infrastructures will contribute to the reduction of costs allocated to passive equipments.

In this way, the orography was analyzed along the East zone, using the features of Google Earth, in order to detect so many other existing peaks, as well as places that would provide a good viewshed in relation to the incendiary areas of greatest susceptibility identified. Emphasize that in this local selection process, care was taken not to consider areas of high fire classes, sometimes resorting to habitable locals.

After several attempts of searching the best solutions, the best alternative that was obtained was to opt for the implementation of seven stations for monitoring fires on the East coast. Of the seven stations, three would be implemented in the existing radio stations, namely in the stations of Pico do Silva, Eiroses and Pico do Areeiro and three stations would have to be fully implemented in the Pico Ruivo, Santo da Serra and Ponta de São Lourenço. In the end, it ended up resorting only to the Pico do Suna surveillance tower, as the other surveillance tower did not offer a favourable viewshed for the detection of high class fires in the Santana area.

Consequently, the viewshed of each station was obtained assuming that the viewing point was at a certain height in order to adopt the existing similarities to the functionalities of video surveillance cameras and other sensors.

The height of the three monitorization stations that would have to be implemented from the ground up was chosen to require a simple metal tower, around 5 meters. As the towers of the existing stations have much higher heights, at least 10 meters and up to 80 meters in the case of the highest tower in the region (Pico do Silva), this situation was taken advantage of, assuming higher heights, significantly favouring the covered area. In the case of the surveillance tower, it is known that the tower has a height of approximately 11 meters, so a 3 meter metal tower would be installed on the building, making a total height of 14 meters. The exact location of the projected stations, as well as the respective framing height, is detailed in the Table 2.

Table 2 – Location and elevation of monitoring stations for visual framing.

Station	Localization	Viewshed Height [m]
Est. Pico Silva	32°41'25.27"N, 16°52'27.63"W	**50**
Est. Pico Areeiro	32°44'11.08"N, 16°55'33.92"W	**15**
Pico Ruivo	32°45'33.03"N, 16°56'34.62"W	**5**
Est. Eiroses	32°41'14.17"N, 16°49'59.81"W	**15**
Torre Pico Suna	32°44'15.79"N, 16°51'13.61"W	**14**
Santo Serra	32°43'35.82"N, 16°48'03.08"W	**5**
Ponta São Lourenço	32°44'43.87"N, 16°42'16.70"W	**5**

From these data, the visual coverage that the set of stations will offer was simulated, using the QGIS "viewshed - visibility analysis" function, only for the municipalities under study. Figure 11 shows the respective result (in translucent green) overlaid on the mapping of incendiary susceptibility, only in the "Very High" and "High" classes, in order to be comparable with the coverage areas of the East coast of the island.

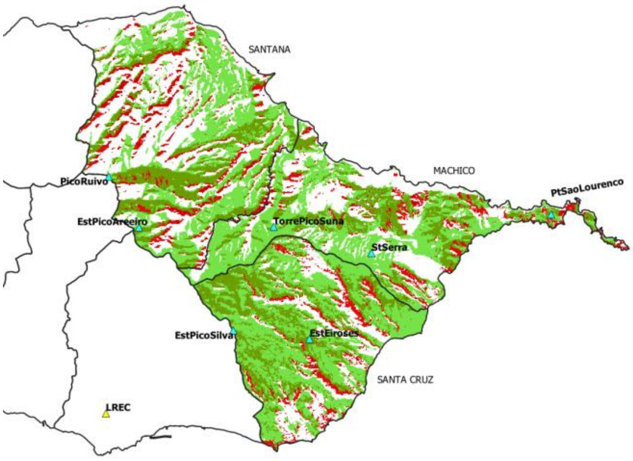


Figure 11 – Viewshed from the monitorization stations (green) and incendiary susceptibility (red).

Observing the previous figure, it is noticeable that the implementation of the monitorization stations as indicated has a good area of visual coverage, covering most of the areas more susceptible to fires.

Although a monitorization station does not have direct visibility for certain places, it does not imply that it cannot detect fires in those places. On clear days, it is possible to detect fires without direct visualization through the observation of smoke columns. However, in certain places, the smoke columns are only visible when they are already of a notable height, which only happens when the fire has some time to start developing. This way, although there is no full coverage of susceptible areas of upper classes, it can be assumed that shadow areas are not out of the monitorization range.

B. Free Banding Legislation

Under the terms of paragraph b) of no. 1 and no. 2 of article 9 of Decree-Law no. 151-A/2000, of July 20, small power stations and short range devices (SRD) are licence-free, in various applications and frequency ranges [20].

SRD stations should only operate under the “non-interference and non-protection” regime and cannot cause harmful interference in any radio communication service, including licensed services, and protection of the equipment against interference cannot be required. Another regime is the one of “non-exclusivity and sharing”.

Frequency bands license-free, with the purpose of point-to-point links, are shown in Table 3.

Table 3 – License-exempt bands applicable to microwave radio links [20].

Application	Frequency Bands	Emission Power Limits
Broadband Data Transmission	2 400 – 2 483.5 MHz	100 mW E.I.R.P.
Wireless Access Systems / Radio Local Area Network (WAS/RLAN)	5 150 – 5 350 MHz	200 mW E.I.R.P.
	5 470 – 5 725 MHz	1 W E.I.R.P.
Broadband Fixed Wireless Access (BFWA)	5 725 – 5 875 MHz	36 dBm E.I.R.P.

Systems operating in the 5250-5350 MHz band and in the 5470-5725 MHz band must use Transmitted Power Control (TPC), otherwise the maximum allowed medium power of E.I.R.P. and the corresponding maximum power density value for the E.I.R.P. average should be reduced by 3 dB. The equipment, in both bands, can only have integrated or dedicated antennas [20].

The 5725-5875 MHz frequency band, known as the 5.8 GHz band, is licence-free from radio licensing; however, it is subject to prior registration of stations with ANACOM.

C. Free Band Solutions

Following the developed projects by LREC, previously studied, an attempt was made to design the backhaul network by microwave radio links on unlicensed bands, so that the project wraps less annual costs, increasing its viability.

Of the four frequency bands present in Table 3, the use of the 2.4 GHz band was excluded, as it is in a very congested phase, which would bring problems of interference in practice. Consequently, it was found that the unlicensed frequency bands most attractive to the project, correspond to the 5470-5725 MHz band and the 5725-5875 MHz band, as the maximum allowed power is much higher than the others, accommodating the needs of links a few kilometres. In the simulations carried out in Feixer, the previous bands were adjusted to 5.4 GHz and 5.8 GHz frequencies, respectively.

With the locations of the stations defined, the verification of the best routes to interconnect the monitorization stations to the data center at LREC began. In the impossibility to interconnecting each station to the LREC using microwave radio links, it was decided to use the monitorization stations themselves as a gateway to the links, resulting in point-to-point links. The choice intended to minimize the distances of the links, always checking the unobstructed line of sight.

The initial solution requires seven microwave radio links to cover the monitorization network, with all links represented in the Figure 12.

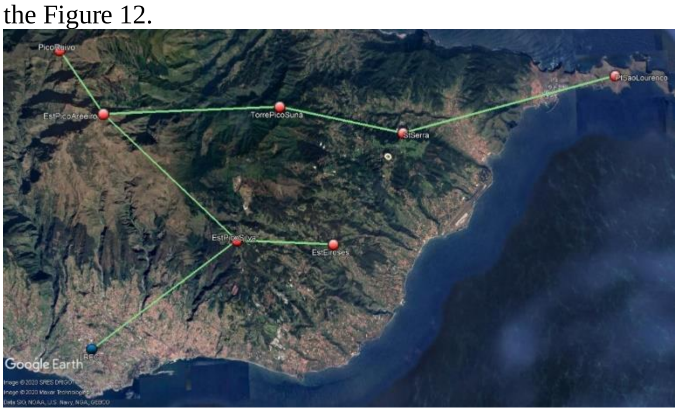


Figure 12 – Mapping of the proposed initial solution.

As most links are in “series”, the capacity required in each link will have to increase with each jump made, in order to aggregate the information from the monitorization stations. Therefore, the link to LREC must have a minimum capacity of 70 Mbps, while the anticipated 10 Mbps will be sufficient for the link StSerra-PtSaoLourenco or for EstPicoAreeiro-PicoRuivo or for EstPicoSilva-EstEiroses. The TorrePicoSuna-StSerra link requires a throughput of 20 Mbps to satisfy the aggregation of data from the Santo da Serra and Ponta de São Lourenço stations, and successively for the remaining links.

In the Feixer simulator, the assignment of the binary rhythm for the link is dependent on the rhythms of the plesiochronous digital hierarchies and the synchronous digital hierarchies, therefore, the binary rhythms that live up to the needs of this project are 34, 140 and 155 Mbps.

Consequently, for the LREC-EstPicoSilva and EstPicoSilva-EstPicoAreeiro links attempts were made to simulate the links with a 140 Mbps channel while the remaining links were simulated with a 34 Mbps rhythm.

In the shortest links from the network, was chosen to use the 5.4 GHz frequency, while in the links that require more power, that is, the longer ones, the 5.8 GHz band was used, not using the network all in the same band, avoiding high levels of interference at stations. To help minimize feedback interference, was tried, whenever possible, not to place the station's transmitting and receiving antenna on the same level.

In this project, it was assumed that in the free bands, the systems will have TPC implementation, to avoid a reduction in the emission power.

The size of the used channels for the simulation in the 5 GHz band was 20 MHz or 40 MHz, following the 802.11n standard, or even the 802.11.ac standard. This last standard also allowed the use of channels with higher bandwidth, however its use was avoided to minimize interference between channels.

At the level of supplementary attenuation, only attenuation by clouds or fog was evaluated. It is known that the models of attenuation of rain already take into account the attenuation of clouds. However, due to the high altitude of the region's high points, there are clouds below these points, even on days without precipitation. Furthermore, since this is a tropical region, fog often occurs, even if it isn’t winter. That said, both attenuations caused by fog and clouds were calculated. For links above about 1,000 meters, where clouds are already occurring, the worst attenuation result between clouds and fog was chosen. Below that altitude, it was defined that there will only be fog.

In this way, the main parameters of the project to be fulfilled were:

- ✓ Respect the quality and reliability standards, according to ITU-R recommendations, seeking for the minimum possible cost;
- ✓ Link capacity: 1x34 Mbps ou 1x140 Mbps;
- ✓ Transmission frequency: “5.4 GHz” or “5.8 GHz” band;
- ✓ Maximum transmitter power:

$$P_{emax\,[dBm]} = E.I.R.P._{[dBm]} - G_{antenna\,[dBi]} + L_{cable\,[dB]} \quad (1)$$

- ✓ Noise factor of the receiver:

$$F_{[dB]} = 7 + 0.1 * f_{[GHz]} \quad (2)$$

- ✓ Minimum safety margin closer to 3 dB.

Therefore, after several analyzes to the best solution for each link, Table 4 summarizes the implementation characteristics found, respecting the parameters previously described.

Table 4 – Characteristics of the initial solution using free bands.

Links	**Frequency [GHz]**	**Antennas Gain [dBi]**	**Capacity [Mbps]**	**Bandwidth [MHz]**	**Modulation**	**Safety Margin [dB]**
LREC - EstPicoSilva	5.8	45.7	140	40	16 QAM	3.1
EstPicoSilva - EstPicoAreeiro	5.8	36.2	140	40	16 QAM	2.9
EstPicoSilva - EstEiroses	5.4	21.6	34	20	4 QAM	3.2
EstPicoAreeiro - PicoRuivo	5.4	21.6	34	20	4 QAM	8.8
EstPicoAreeiro - TorrePicoSuma	5.8	22.2	34	20	4 QAM	3.2
TorrePicoSuma - StSerra	5.4	27.6	34	20	4 QAM	3.8
StSerra - PtSaoLourenco	5.8	36.2	34	20	4 QAM	3.2

The StSerra-PtSaoLourenco link, even with low speed, required antennas of 5 inches (1.5 meters), as this represents the longest link in the network, about nine kilometres. Despite this size of the antennas, it was considered that their implementation will be valid on the network. Above this diameter, it is already considered impossible to use these antennas for the purposes of this network, thus avoiding the need for reinforced towers.

The links that required the highest transmission rate were the ones that caused the most problems, because in addition to this factor, they were one of the longest links, making it necessary to use antennas with a relatively large dimension for this type of project. However, as you can see in the previous table, the link to the LREC requires huge antennas (4.5 meters). This makes it impossible to accept the validity of this link with these characteristics, as in addition to the fact that there are no antennas on the market for these bands of this size, its application would be impractical far above the ground.

A valid solution for this link would be to use an active repeater on the Terreiro da Luta. However, the implementation of an active repeater would generate an increased cost, since equipment as energy supply units, and a new shelter would be necessary to implement a station.

Thus, a new study was carried out, departing, however, from the initially defined objective, evaluating the link in question using bands that require licensing.

D. Licensed Band Solution

The study was carried out for the frequencies available by the national communications authority in the band between 1 and 20 GHz. The plans for available frequencies and the respective spacing between channels (b_{orf}) were extracted from ANACOM's document [21].

The fees for the use of frequencies were determined using the simulator available on the ANACOM website, for a distance of 7.655 km, corresponding to the distance of the LREC-EstPicoSilva link. In the simulator it was defined that only one bidirectional channel co-channel was intended.

In this case, the criteria of the previous solutions were maintained, however, the maximum power of the emitter started to be determined by:

$$P_{emax\,[W]} = {}^{6}\!/\!_{f^{1.2}_{[GHz]}} \quad (3)$$

After all the results were obtained from the simulations, a filter was made, selecting the cases that had the best safety margin and that offered the lowest cost of implementation, as well as an annual fee, for each frequency band. Thus, the following cases were obtained described in Table 5.

Table 5 – Favourable cases for the implementation of the LREC-EstPicoSilva link, using licensed bands.

Frequency [GHz]	**Bandwidth [MHz]**	**Antennas Gain [dBi]**	**Modulation**	**Safety Margin [dB]**	**Annual Rate [€]**
6	29.65	32.0	64 QAM	8.2	2 695.65
7	28	33.4	64 QAM	7.6	2 545.64
8	28	34.5	64 QAM	6.6	2 545.64
11	28	37.3	64 QAM	3.1	2 545.64
13	28	41.3	64 QAM	6.4	1 181.41
	56	38.8	8 PSK	9.9	2 362.82
15	56	40.0	8 PSK	6.7	2 362.82
18	55	44.1	8 PSK	3.8	1 179.34

Thus, it was concluded that the best solution achieved in this study of licensed bands corresponds to the transfer of data over a link at the frequency of 18 GHz, with a bandwidth for the transmission of 55 MHz and using 8 PSK modulation, verifying this way, that even though initially investing in the project for larger antennas, the 18 GHz band presented a solution that allowed to reduce the annual rates to half of the value.

Since all the solutions presented so far are not the best possible solution, we then proceeded to the study of a feasible solution, which proves to have less associated costs.

E. *Final Proposal - Redundancy Solution*

A plausible solution to comply with the link clauses, without requiring licensed bands or repeaters, is the use of several channels of relatively low speed and not the use of a single channel of high speed.

Besides that, this solution started from the reformulation of the solution presented initial, where the network scheme initially suggested had a weak availability in monitorization. When a link fails, all monitorization data that “passed” through it was compromised, constituting a high risk, for example, if the LREC-EstPicoSilva link failed, the entire monitorization network would be compromised.

Thus, it was proposed that the backhaul network should have redundancy in the microwave radio links. Due to the scheme that the initial solution presented, it was found that the network implementation in a architecture ring would be the one that would be most advantageous and the one that best suited, allowing total redundancy in all links. The ring structure of the network is observable in the Figure 13.

Figure 13 – Mapping of the final proposed solution with redundancy.

To achieve this redundancy, it was necessary to implement two active repeaters, one in the Pico do Areeiro area (RepPicoAreeiro – 32°43'39.29"N, 16°56'34.62"W) and the other one between the Eiroses and Ponta de São Lourenço stations , located at the Pico do Facho radio station in Machico (RepPicoFacho – 32°43'27.08"N, 16°45'32.44"W).

Although it is possible to obtain an unobstructed line of sight between the EstEiroses and PtSaoLourenco stations, it was not possible to use a direct link, due to its long length for this type of bands, using an active repeater in Pico do Facho. In this case, the structure of the existing station was used to place the repeater. The respective RepPicoFacho-PtSaoLourenco link was, unlike all others, classified as a coastal route, due to the presence of the sea in most of the link.

As the links from the North coast could already pass through the Pico Ruivo station and, later, through the adjacent repeater, the EstPicoSilva-EstPicoAreeiro link initially designed would no longer make sense, since it was removed in this solution.

Another advantage, by making the network redundant, was the possibility of “load relief” in the LREC-EstPicoSilva link, since it will be possible to define that the monitorization data of the stations in the North are directed natively through RepPicoAreeiro. South coast data can be transmitted directly to LREC through the LREC-EstPicoSilva link, allowing a balance in the distribution of information. Then, in the event of a link failure, data is transmitted in the other direction of the ring network.

Consequently, all the links studied in the solution initially presented in the free band, had to be reformulated, because the sizing of the links had to be carried out taking into account the redundancy in the backhaul network. Thus, the links that required the lowest speeds, already had to be prepared to support a much higher speed, the maximum speed (100 Mbps) defined for this fire monitorization network.

Thus, instead of the 140 Mbps channel, three 34 Mbps channels were used, totalling a throughput of approximately 102 Mbps, satisfying the initial defined condition of 100 Mbps. As seen in the initial solution, the use of 34 Mbps channels, satisfies the compliance of the clauses more easily than of higher speed channels.

In this final proposal, all the parameters of the solutions were maintained in the free bands previously portrayed, however, the link capacity changed to 3x34 Mbps or 1x140 Mbps.

Therefore, the characterization of the links for the final proposal of this work, for the network that serves as a backhaul to the fire monitorization system on the East coast, must follow the parameters set out in Table 6. In turn, the respective results obtained are also described in the same table.

Table 6 – Characteristics of the final proposal with redundancy.

Links	**Frequency [GHz]**	**Antennas Gain [dBi]**	**Capacity [Mbps]**	**Bandwidth [MHz]**	**Modulation**	**Safety Margin [dB]**
LREC - EstPicoSilva	5.8	31.7	34	20	4 QAM	3.1
EstPicoSilva - EstEiroses	5.4	21.6	34	20	4 QAM	3.2
EstEiroses - RepPicoFacho	5.8	32.7	34	20	4 QAM	3.0
RepPicoFacho - PtSaoLourenco	5.4	31.1	34	20	4 QAM	3.7
LREC - RepPicoAreeiro	5.8	34.2	34	20	4 QAM	3.3
RepPicoAreeiro - PicoRuivo	5.4	27.6	140	40	16 QAM	4.5
PicoRuivo - EstPicoAreeiro	5.4	21.6	140	40	16 QAM	3.1
EstPicoAreeiro - TorrePicoSuma	5.8	22.2	34	20	4 QAM	3.2
TorrePicoSuma - StSerra	5.4	27.6	34	20	4 QAM	3.8
StSerra - PtSaoLourenco	5.8	36.2	34	20	4 QAM	3.2

V. CONCLUSION

Currently, microwave radio links are essentially a competitive backhaul alternative to optical fibers for mobile networks. Despite the growth of optical fibers, microwave links manage to have a greater volume of installation, and it is estimated that by 2023, 40% of stations worldwide will be connected by microwave links. When choosing the backhaul network, it is important to consider several factors, namely those related to costs such as the Total Cost of Ownership, which is generally lower than that practiced in optical fibers, and this factor can be a great advantage in certain situations.

The reality of these communication systems varies depending on the country under analysis and can be used a lot or not. In the Arquipélago da Madeira, there were, in 2019, just over half of the number of licensed links in 2009, with a clear disuse of these links in the last few years. The distribution of these links has undergone major changes among the entities that held them from the moment they began to give priority to optical fibers, however, there are still microwave radio links of different frequencies to be used.

For all of the above and taking into account the high susceptibility of some types of telecommunications systems to catastrophic events, it was wanted, according to the areas of greatest susceptibility to burn, to create a telecommunications network by microwave radio links in order to complement the lack of fire monitorization in the Eastern zone of the island. After studying several alternatives, a final solution was reached, which essentially came from the initially designed radio network, but with a major improvement in the network's integrity. This is because it was possible to redesign the network to have redundancy, in this case in a ring, using two active repeaters. It is noticeable that this solution would be more expensive than the initial solution, however, at least the availability of the monitorization network is safeguarded in case of a point-to-point link "getting lost".

The redundancy was performed only at the level of the backhaul radio link network, since the monitorization systems were not studied or their redundancy.

Contrary to the initial solution in the free band, even though the same speed is needed in the entire redundant network, this time it was possible to obtain better results. This was due to the use of several lower speed channels instead of a single much higher speed channel, with the exception of the two shorter links. On the other hand, the choice of radio equipment will take into account the requirement to achieve the emission of several channels.

In short, the use of free bandwidth in this project, according to the final proposed solution, made it possible to meet the imposed requirements, and, even in the long run, brings great advantages in terms of costs, so it is essential to respect the limitations imposed by the controlling authority, in order to minimize the interference that they may cause, avoiding the cession of these links by the authority.

REFERENCES

[1] C. Salema, Feixes Hertzianos, 3ª ed., IST Press, 2011.

[2] ANACOM, "Medidas de Proteção e Resiliência de Infraestruturas de Comunicações Eletrónicas - Relatório do Grupo de Trabalho dos Incêndios Florestais," 2018.

[3] ANACOM, "Incêndios Florestais - Medidas de Proteção e Resiliência de Infraestruturas de Comunicações Eletrónicas," 2017.

[4] J. Donovan, "It's Time for You to Understand Microwave Backhaul Infrastructure," CommScope, October 2016. [Online].

[5] Ericsson , "Ericsson Microwave Outlook," Sweden, 2018.

[6] Ericsson, "Trends And Needs In The Microwave Industry - Ericsson Microwave Outlook," Sweden, 2017.

[7] Microwave Link, "Current Trends in Microwave Backhaul," February 2018. [Online]. Available: https://www.microwave-link.com/microwave/current-trends-in-microwave-backhaul/. [Accessed in September 2019].

[8] Huawei Technologies, "Huawei Microwave & mm-Wave Whitepaper," 2016.

[9] Ericsson, "Ericsson Microwave Outlook," Sweden, 2019.

[10] P. Nava, "IMT Backhaul (including High Altitude Platform Stations)," Saint Petersburg, 2018.

[11] R. Lombardi, N. Zein, M. Frecassetti e P. Agabio, "Evolution of Fixed Services for wireless backhaul of IMT 2020 / 5G," Geneva, 2019.

[12] Huawei Technologies, "Multiple-Input Multiple-Output (MIMO) Technology," 2019.

[13] CableFree, "XPIC – Cross Polarization Interference Cancellation," [Online]. Available: https://www.cablefree.net/wirelesstechnology/microwave/xpic-cross-polarization-interference-cancellation/. [Accessed in December 2019].

[14] Laboratório Regional de Engenharia Civil, "Projeto MonitorizaRibeiras," [Online]. Available: http://www.lrec.pt/?m=5. [Accessed in February 2020].

[15] Laboratório Regional de Engenharia Civil, "Sistema de Comunicações," [Online]. Available: http://www.lrec.pt/?m=5&s=1. [Accessed in February 2020].

[16] Wavecom, "Case Study - Monitorização das Ribeiras da Madeira," 2015.

[17] F. J. Cardoso, "Sistema de Alerta," *Diário de Notícias Madeira*, pp. 8-9, 3 July 2019.

[18] Laboratório Regional de Engenharia Civil, "Aspetos Tecnológicos sobre a Prevenção de Riscos Naturais (casos práticos do SAARAM e SDIFRAM)," 2019.

[19] F. Pereira, "Multi-application Video Coding: Targeting HD Resolution," Audiovisual Communication, 2019/2020.

[20] ANACOM, "Isenção De Licença De Estação," 2020.

[21] ANACOM, "Faixas de frequências superiores a 1 GHz - Redes de Ligações Ponto-Ponto e Redes de Ligações Ponto-Multiponto," 2019.

[22] ANACOM, *Simulador Taxa 1.4.1 - SFFH Faixas Superiores a 1GHz - LPP*.

[23] J. Donovan, "It's Time for You to Understand Microwave Backhaul Infrastructure," CommScope, October 2016. [Online]. Available: https://www.commscope.com/Blog/Its-Time-for-You-to-Understand-Microwave-Backhaul-Infrastructure/. [Accessed in September 2019].