Bridging the Digital Divide in Tropical South America

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Paper type
Case study.

Abstract
We describe an alternative for bringing broadband telecommunications to regions with little or no fixed infrastructure, such as roads, railways or power lines, for the installation of fibre optic cables, but which possess river systems which permit the use of well-known submarine technologies. The paper describes the adoption of such an alternative in the Amazon region of Brazil, and proposes its more widespread application.
Differently from the oceans, river systems exhibit more variable behaviour due to dynamic alterations in courses, depth and flow. An example is the quantity of solid material being carried downstream, which might damage underwater cables.
In 2015, a proof of concept was demonstrated by building a 7 km stretch of cable in the Negro river near to Manaus in Brazilian Amazonia. At the time of writing a 220 km pilot project is being carried out on the Solimões (upper Amazon) river, west of Manaus. The cable-laying is complete, and some of the results of this project will be reported at TNC16.
Currently, there are regions in the world where geographical considerations have impeded or made impossible the conventional ways of building telecommunications infrastructure. We point out the benefits and difficulties of the alternative of subfluvial fibre optic cables.
Apart from describing the present-day use of long-distance subfluvial cables, we have also (re)discovered the same technology used in the same region for electrical telegraphy at the end of the 19th Century, showing there are still lessons to be learned from our forebears even in the Internet age.

Keywords
Digital divide; Access to broadband telecommunications; Lack of terrestrial infrastructure; Sub-fluvial fibre cables; Amazon basin river systems.

1. Introduction
The Amazon basin, drained by the River Amazonas (normally referred to as the Amazon in English) and its tributaries, which straddles the Equator and includes significant parts of the territories of Brazil, Bolivia, Peru, Ecuador and Colombia, has presented opportunities and challenges for human occupation since prehistoric times. The enormous rivers found here cross through dense equatorial forest, with high temperatures and heavy rainfall. River fish are plentiful, and boats are the only practical means of transport for most people and goods. This has led to the spread of population centres along the courses of the rivers.

We describe a large-scale multi-partner project aimed at providing terrestrial infrastructure for network communication in the sparsely inhabited Brazilian part of the Amazon basin. The basic technology involves the use of subfluvial optical cables laid along the beds of Amazonian rivers, providing long-distance backhaul to major population centres, in order to support broadband access for the many riverside towns in the region. Partners in this project are the Brazilian Army, federal telecommunications and energy companies, state governments and their agencies, and RNP, the Brazilian NREN. Major social benefits expected as a result of the project include the extension and improvement of the provision of government services, especially in health and education, as well as broadband Internet access, to the population at large, bridging the existing digital divide in the country. Other intended results include the provision, or the significant improvement of existing, Internet access to research and education centres. Finally, the Brazilian armed forces will gain improved communications facilities to support its capacity to preserve the security of international borders.

The article describes the context of the recent development of telecommunications networks in Brazil, especially since the Internet reached Brazil in the 1990s, by means of RNP. In this context, the Amazon basin represents the last frontier, due to the sheer difficulty of building in this region the terrestrial infrastructure required for providing broadband services to a large, scattered population in a region half the size of Europe. The solution adopted in this project, of building out this infrastructure by use of subfluvial optical cables, was only considered for the first time in 2012, the year when the regional capital of Manaus was finally connected by an electrical powerline to a hydroelectric scheme about 2000 km away. Why it took so long to consider subfluvial cables as a solution may be due to the lack of familiarity of present-day telecommunications engineers with the feats of their forebears at the end of the nineteenth century, who provided international telegraph service to Manaus by means of a subfluvial cable extending inland from the Atlantic Ocean following the Amazonas [Siemens, A., 1896].

The Amazonas is only the largest of the rivers in the Amazon basin, and its course links Manaus to the Atlantic Ocean near Belém. For this particular stretch, as mentioned, an alternative telecommunications link had already been built by 2012. A flash of insight, due to Jorge Salomão Pereira [Pereira, 2013], was to extend the concept of the subfluvial link between Belém and Manaus to several of the major tributaries of the Amazonas, including the upper part of the main river, known in Brazil as the Solimões. Pereira's plan was to extend the use of subfluvial cables to the rivers Negro, Branco and Madeira, as well.
RNP was the first organisation to propose a pilot project using this solution to provide connectivity to the town of Tefé on the Solimões, some 230 km upstream of Coari, where a gas pipeline between Manaus and Urucu, with parallel optical cable, passes under the Solimões. Thus, it would be possible to extend to Tefé the fibre connection that Coari already possesses to Manaus. The choice of Tefé is due to the location there of the Mamirauá Institute for Sustainable Development[1], an important research centre, which has been served (by satellite) by RNP since 1999.

In 2013, the authors presented an article [Grizendi and Stanton, 2013] at the UbuntuNet Connect event in Kigali, Ruanda, describing Pereira's vision, as well as the 19th Century initiative to include Manaus in the global telegraph network. The article also makes mention of a very similar proposal, which was also published that same year by communications engineers from Colombia [García Lozano, 2013], who envisaged the use of a subfluvial cable along the Solimões between Manaus and Iquitos in Peru, passing through the Colombian town of Leticia. Neither Leticia nor Iquitos has access to a terrestrial telecommunications link with the outside world.

In 2014, these proposals attracted the attention of the Brazilian Army, which is responsible for external (land border) security throughout the country, and especially in the Amazon basin, where the greatest length of this border is situated. The Army leadership was exercised by CITEx – Integrated Telematics Centre of the Army, and steps were taken to build a broad coalition of interested organisations to carry out the Amazonia Connected programme [Amazonia Conectada, 2016].

So far, apart from organising a number of meetings to disseminate information and encourage discussion of this programme, a number of practical steps have already been taken to advance its objectives. These include the demonstration of Proof of Concept (PoC), through the construction in April, 2015, of a 7 km subfluvial connection between two Army sites on the River Negro in Manaus; the oficial launch of the programme in July, 2015, with the participation of 3 ministers of the federal government and the governor of the State of Amazonas; and the preparations for the pilot project, proposed by RNP, to link Coari and Tefé. These preparations included the purchase of 240 km of cable from Nexans Norway AS, and carrying out the public tender for the laying of this cable in the first quarter of 2016, resulting in the selection of the Brazilian company, Aquamar, from Manaus. The laying of this cable was completed in April, 2016, and we envisage presentation of early results at TNC16.

In addition, the Army has also redefined the scope of the cable project, to include several more rivers in the Amazon basin. The current list now includes the tributaries Juruá and Purus, in addition to the Negro, Madeira and Solimões from the first list. The total length of these rivers, envisaged in the project, is 7,640 km, including the stretch of 1,182 km of the Upper Solimões, between Tefé and Tabatinga, next to Leticia on the Colombian border. Current plans are to complete the cabling of the Solimões by 2016, before starting on any of the other rivers. In all, it is expected that the complete project will take 3 years to carry out.

[1] http://www.mamiraua.org.br/ (available only Title in English). See also: https://en.wikipedia.org/wiki/Mamirau%C3%A1_Sustainable_Development_Reserve

It is worth mentioning that a similar project is under discussion in Peru, where a survey has been carried out to lay a subfluvial cable in the Marañon and Huallaga rivers, upstream tributaries of the Amazonas, the upstream continuation of the Solimões within Peru. This cable will connect Nauta and Yurimaguas, in the region of Loreto, enabling terrestrial connectivity to the eastern Peruvian city of Iquitos, about 400 km upstream from Tabatinga on the Brazilian border. Assuming the success of both projects, it would then be possible to link the internal telecommunications networks of the two countries by laying a subfluvial cable between Iquitos and Tabatinga, greatly improving east-west connectivity within South America.

1.1 The structure of this paper

This paper describes the recent developments in network connectivity in Brazil and its neighbours, partly through the recognition of parallels with the development of electrical telegraphy in the 19th Century, both in the use of subaquatic cables, both to bridge intercontinental distances, and to pioneer the use of subfluvial cables along major rivers for integrating the remote interior of Amazonia. Section 2 describes the development of the telegraph network in Brazil, pointing out some of the parallels with the 21st Century Internet of our own times. In fact there are authors such as [Standage, 1998] who regard the "Victorian Internet" the 19th Century as contributing to more significant social and economic advances than the current equivalent. In section 3, we describe some of the current developments of 21st Century international submarine cables, which only now are achieving a global topology similar to the that of the 19th Century telegraph network. Section 4 introduces Amazonia, the greater part of the basin formed by the river Amazon and its tributaries in the heart of South America, which is densely forested and sparsely populated. There is however a significant population in this region, and the text describes some of the steps already taken to bring terrestrial broadband connectivity to the region. Section 5 discusses the formulation and partial execution of the use of subfluvial optical cables for providing broadband communications to the riverside populations in Amazonia. This is an ongoing project, which began in 2015, and so only the first tentative steps are described here. Opportunities for similar projects are also suggested.

2. Electrical telegraphy in the 19th Century

2.1 The origins of international telegraphy[2]

The use of long-distance electric signalling for communication developed after the beginning of the 19th Century, and the first commercial systems appeared in the 1830s, frequently associated with the control of the similarly new steam railway systems developed around the same time. Once land-based telegraph lines gained popularity, attention was then demanded to the possible use of this new medium for international communications, especially across seas and oceans. The technical problem was of insulation of the metallic conductor wire used to carry the signals. On land, this was normally left without insulation, and hung from poles. One of the first alternatives used for insulation was India rubber (natural rubber), but a more suitable and preferable alternative was gutta percha, a natural adhesive gum which could easily be applied to metal wires. In 1849, as proof of concept, a 2 mile (3.2 km) wire coated with gutta percha was submerged in the English Channel near Folkestone and tested successfully[3].

The first attempt to use this development commercially to connect England and France the following year was a failure, as the insulated wire did not sink to the seabed as intended. In 1851, the use of an armoured, or protected, cable was sufficient and the first working submarine cable was in business. Soon afterwards, submarine cables were also connecting England to Ireland, Belgium and the Netherlands, and crossing the narrow seas separating the islands of Denmark and on to Sweden.

[2] https://en.wikipedia.org/wiki/Electrical_telegraph
[3] https://en.wikipedia.org/wiki/Submarine_communications_cable

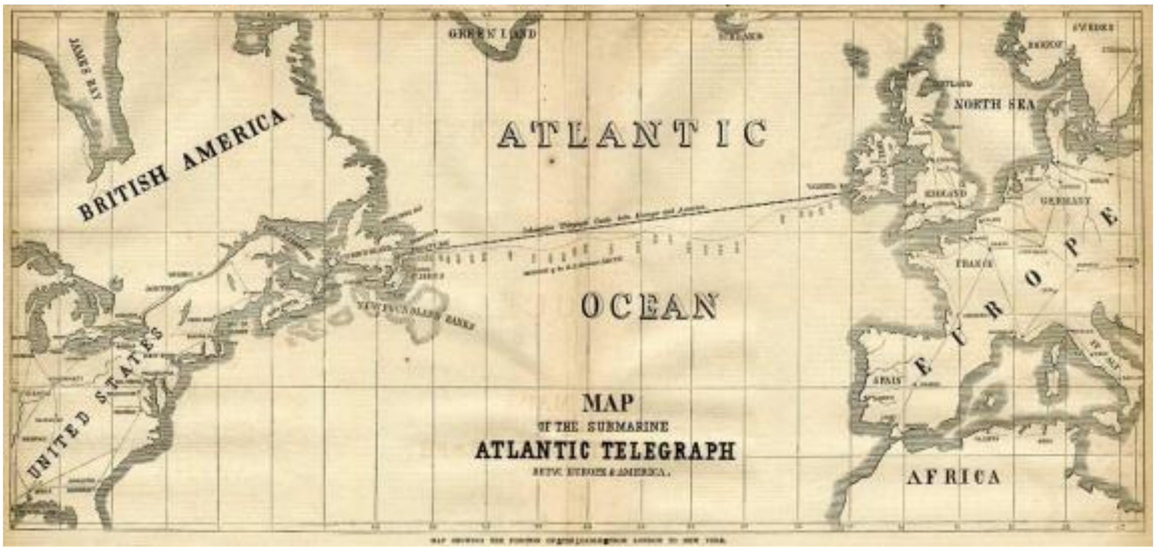


Figura 1. Route of the transatlantic cable laid in 1858[4]

However, the grand challenge of the time was to cross the North Atlantic Ocean, and the first successful attempt at this was made between Ireland and Canada in 1858 (see Figure 1). Unfortunately, for design reasons, the cable functioned for only 23 days, and another 8 years would pass before it was possible to implement a reliable transatlantic service. The successful introduction of long-distance submarine telegraphy was instrumental in shrinking the importance of distance, the major theme developed in Standage's 1998 book, "The Victorian Internet", which is discussed in section 2.3.

2.2 The origins of telegraphy in Brazil

The potential of telegraphy was quickly recognised in Brazil, and in 1852 the General Telegraph Office (RGT: Repartição Geral dos Telégrafos) was set up and given the responsibility for the use of this new technology. The first services were rendered to the state, then headed (until 1889) by the Emperor Pedro II, in recognition of the importance of speedy and accurate communications between the capital, then in Rio de Janeiro, and government departments, especially the armed forces, in far-flung provinces of this huge country. Guilherme Schüch de Capanema (b. Ouro Preto,1824 - d. Rio de Janeiro 1908), who had had a military and engineering education in his father's Austria, was appointed head of RGT, where he remained until the overthrow of Pedro II in 1889. He was made Baron Capanema in 1881.

At RGT, Capanema began building a landline telegraph network which would attain 11,000 km by 1889. One of his first projects was to provide a connection between the seat of government in Rio de Janeiro and the emperor's summer palace in Petrópolis, a little over 30 km away in the nearby mountains. A map of part of this connection, from the centre of the city of Rio de Janeiro across Guanabara Bay to the beginning of the railway line towards Petrópolis, is shown in Figure 2. It will be noted that the bay crossing includes two subaquatic stretches, totaling 15 km. The railway line was inaugurated in 1854 and the telegraph connection in 1857, a mere 6 years after the first successful submarine cable between England and France.

[4] Frank Leslie's Illustrated Newspaper, August 21, 1858 . Available at http://atlantic-cable.com/Article/1858Leslies/0821f.jpg .

(a) (b)

Figure 2: (a) The first subaquatic telegraph cable in Brazil across Guanabara Bay, Rio de Janeiro in 1857. (b) Commemorative stamp for the centenary of the RGT and its first diretor, Guilherme, Baron Capanema.

2.3 The Victorian Internet

An interesting character of the first years of the telegraph is that was a collection of separate services, not integrated between themselves. This was especially true of countries, like the USA and Brazil, initially separated by long ocean crossings from services in other countries. With time, the recognition of government and commercial advantages of international connectivity led to the establishment of new international links, most especially originating in the UK and the USA. This was a time of European empire building, and so many of the new connections were between the different seats of empire and their colonies and allies. This is particularly true of the British Empire and its allies, such as Portugal, Brazil and former Spanish colonies in South America. In the 1870s, a number of new submarine cables extended into the South Atlantic, reaching Recife, in northeastern Brazil in 1874. At around the same time new cables were built northwards and southwards along the Atlantic coast of Brazil to reach other South American countries and territories, and eventually to the Caribbean and to the USA. Other important routes connected Europe to the Middle East, Africa, Asia and Oceania. By the end of the 19th Century, global coverage of the telegraph network was almost complete, as shown in Figure 3, which depicts the extent of what has been called the Victorian Internet [Standage, 1998].

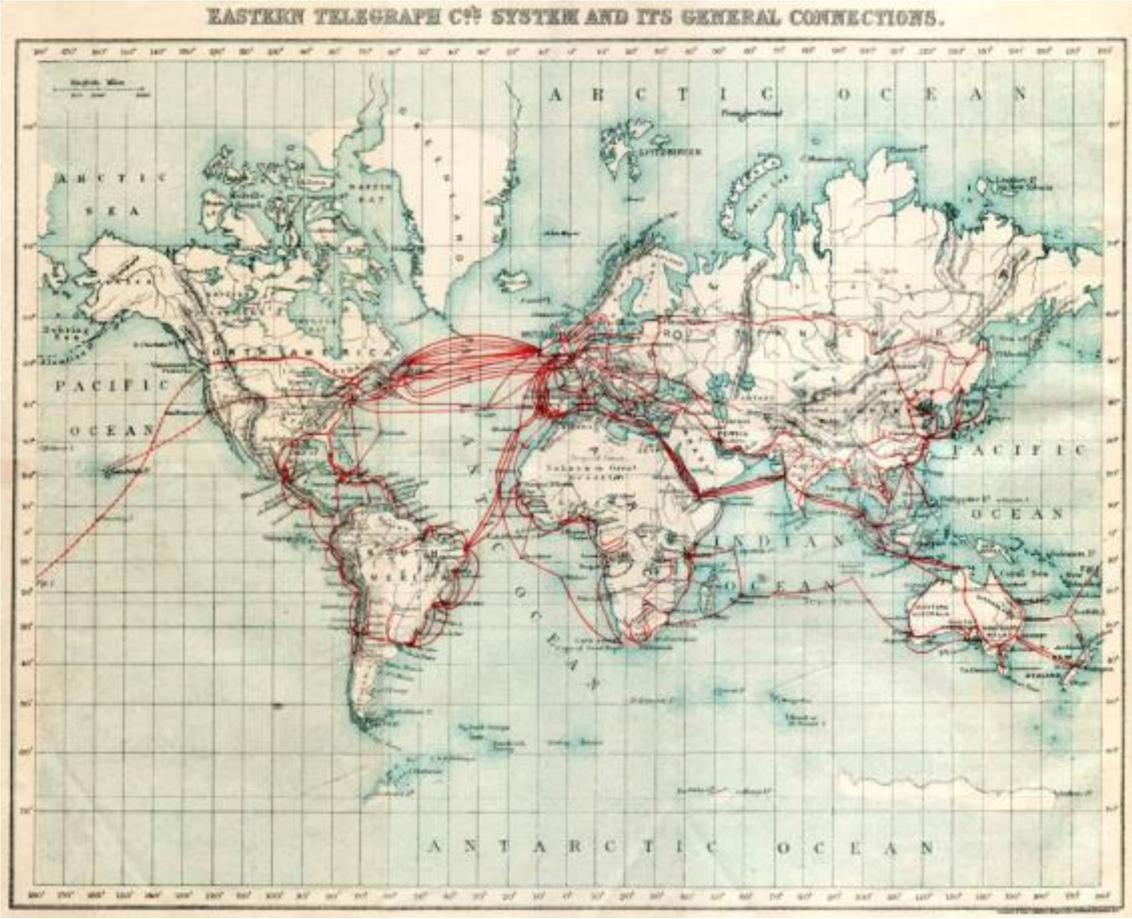


Figure 3: General connectivity of the global telegraph network in 1901.
(Available in https://i2.wp.com/atlantic-cable.com/Maps/1901EasternTelegraph.jpg)

Figure 4: Cables in South and Central America in 1901 (enlargement of Figure 3)

What is quite interesting to our eyes in the 21st Century are the great similarities between the routes on this map and those that our followed by modern submarine cables used for providing global Internet connectivity. But, more important than this, according to Standage, is the much greater impact provided by this 19th Century invention than our own of the 21st Century, mainly due to the scale of the diferences between the new invention and what had been the prior alternative. Whereas it is true that today's Internet provides better access to news, information and goods than was possible before, all of these could be made available in a matter of hours or days by other means of transmission, whereas the telegraph competed with existing land and water transport services, which, in cases of even national distances, could imply delays of days or weeks, and, in the case of intercontinental distances, much longer times than these.

Returning to Brazil, Figure 4 shows clearly that there were 3 separate cable routes between Europe and Brazil, Uruguay and Argentina, as well as overland routes from Argentina to Chile and Paraguay, and from Belém, near the mouth of the Amazon, in a westerly direction. This later route is almost certainly the cable laid by Siemens Brothers of London between Belém and Manaus in 1895-96. This cable is very interesting in several ways: firstly, the objective was to provide modern communications to the city of Manaus, then the principal world centre for the trade in natural rubber; secondly, it is by far the longest subfluvial cable of its time, and maybe even till today; thirdly, it was laid by the ocean-going CS (Cable Ship) Faraday (Figure 5), of 5000 tons, custom-designed for manoeuverability and for laying cables fore and aft, which was able comfortably to steam up the Amazon River for 1600 km in order to lay this cable. The main information we have about this initiative is the report presented by Alexander Siemens on the successful conclusion of this feat of engineering [Siemens, 1896]. Figure 6 shows a map of the cable, based on the description in this report. It seems that the cable continued in use until around 1912, by which time the rubber boom in Brazil had come to an end.

Figure 5: Siemens Brothers' cable ship CS Faraday shortly after her launch in 1874[5]

[5] Available from https://en.wikipedia.org/wiki/Siemens_Brothers

Figure 6: Route map of the Siemens Brothers' Amazon river cable built in 1895-96.

3. The Internet age and the use of submarine cables in South America

Moving to the 21st Century, maps like those of Telegeography[6] show the current and predicted states of the global infrastructure used to support telecommunications, and particularly data communications nowadays. Fundamentally today's submarine cables are similar in appearance to those of the 19th Century, although we now use optical signals transmitted along optical fibres, rather than electrical signals along metal wires. Other differences include the need for inline signal amplifiers along the cable, and the consequent need for electrical power to run these, as well as underwater Branching Units, to enable connections to intermediate destinations.
The current (as of 21 March 2016) Telegeography map of all submarine cables, both in use and proposed, touching Brazil, is shown in Figure 7 and described in Table 1.

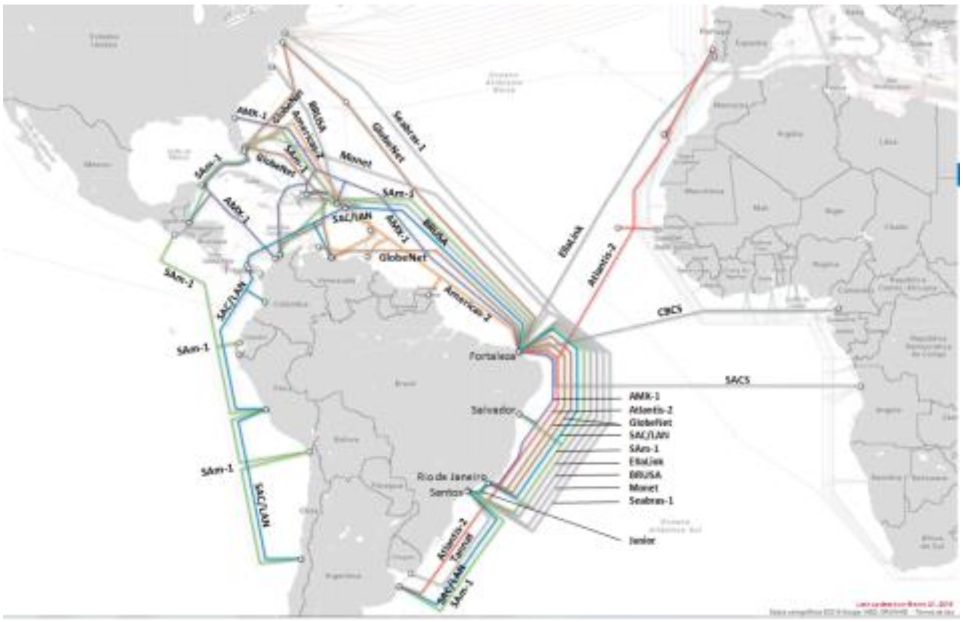


Figure 7: Annotated map of current and proposed submarine cables touching Brazil.
Available from: http://www.submarinecablemap.com/#/country/brazil [Accesse on 21/3/2016]

This map shows several generations of cables:

1. Pre-Internet (up to 2000): Americas 2 (to US), Atlantis 2 (to Argentina, Africa and Europe).
2. First generation Internet – usually 10G DWDM systems (2000): Globenet, SAC/LAN, SAm-1 (to US, and other Latin American countries).
3. New generation Internet – 100G DWDM systems (from 2014):
    a. to US: AMX-1 (2014), BRUSA (2018), Monet(2017) , Seabras-1 (2017).
    b. to Europe: EllaLink (2018).
    c. to Africa: CBCS (2017), SACS (2018).
    d. to Uruguay: Tannat (2018).

Some comments on the submarine cable connections:

- The pre-Internet cables are of low capacity and were designed to support voice telephone links.
- The 3 first generation Internet cables channel all international traffic through North America, turning South America into an Internet backwater, with no transit traffic.
- Three of the new generation cables, currently planned or under construction connect South America to other continents (Europa and Africa), increasing the redundancy of global connectivity. In this context, the location of the city of Fortaleza in north-east Brazil is promoted to be a uniquely favoured location, with the landing and possible interconnection there of 11 international cable systems with direct connections to Europe and Africa, as well as to North and South America.

[6] http://www.submarinecablemap.com/

Table 1: International submarine cables, in use and planned, touching Brazil

Cable name	Current Owner(S)	Year	Capaci-ty	Length (km)	Landing stations in Brazil	Other countries/territories served
Americas-2	Embratel, AT&T, Verizon, Sprint, CANTV, Tata Communications, Level 3, Centennial of Puerto Rico, Corporacion Nacional de Telecommunicaciones, Telecom Argentina, Orange, Portugal Telecom, C&W Networks, Telecom Italia Sparkle, Entel Chile	2000	7.5 Gbps	8,373	Fortaleza	Venezuela, French Guiana, USA, Martinique, Puerto Rico, Trinidad & Tobago, US Virgin Islands, Curaçao
Atlantis-2	Embratel, Deutsche Telekom, Telecom Italia Sparkle, Telecom Argentina, Telefonica, Portugal Telecom, Orange, Telefónica Larga Distancia de Puerto Rico, AT&T, Belgacom, KT, SingTel, Sprint, Tata Communications, Verizon, BT	2000	40 Gbps	8,500	Fortaleza, Rio de Janeiro (used by Embratel)	Argentina, Cape Verde, Senegal, Canary Isles (Spain), Portugal
South American Crossing (SAC) / Latin America Nautilus (LAN)	Level3, Telecom Italia Sparkle	2000	3.84 Tbps	20,000	Fortaleza, Rio de Janeiro, Santos	US Virgin Islands, Venezuela, Colombia (only Level-3), Panama, Peru, Chile, Argentina
South America 1 (SAm-1)	Telefonica	2000	1.92 Tbps	25,000	Rio de Janeiro, Salvador, Santos	Colombia, Puerto Rico (USA), USA, Guatemala, Ecuador, Peru, Chile, Argentina
GlobeNet	BTG Pactual	2000	1.36 Tbps	23,500	Fortaleza, Rio de Janeiro	Venezuela, Colombia, USA, Bermuda
America Movil-1 (AMX-1)	America Movil	2014	50 Tbps	17,800	Fortaleza, Salvador, Rio de Janeiro	Dominican Rep., Puerto Rico (USA), USA, Mexico, Guatemala, Colombia
Monet	Google, Antel, Angola Cables, Algar Telecom	2016	64 Tbps	10,556	Fortaleza, Santos	USA
Junior	Google	2017		390	Rio de Janeiro, Santos	
Seabras-1	Seaborn Networks	2017	72 Tbps	10,500	Santos	USA
Cameroun -Brazil Cable System (CBCS)	Camtel, China Unicom	2017	40 Tbps	5,900	Fortaleza	Cameroun
Tannat	Google, Antel	2018	90 Tbps	2,000	Santos	Uruguay
EllaLink	Telebras, IslaLink	2018	40 Tbps	9,501	Fortaleza, Santos	Portugal
South Atlantic Cable System (SACS)	Angola Cables	2018	40 Tbps	6,500	Fortaleza	Angola
BRUSA	Telefonica	2018		11,000	Fortaleza, Rio de Janeiro	USA, Puerto Rico

4. Amazonia

4.1 Geography

By Amazonia we refer to the region of tropical South America corresponding to the basin of the Amazon river and its tributaries, with a catchment area of 7.05 M km^2, including about 60% of the area of Brazil and smaller fractions of Bolivia, Peru, Ecuador, Colombia, Venezuela and Guyana. This corresponds to 37% of the size of South America as a whole, 69% of Europe, 72% of the USA, and 91% of Australia. The second largest river basin is of the Congo in Africa, which has a catchment area of 3.68 M km^2.

The Amazon river system has many tributaries. The longest path from source to the ocean passes through the river Apurimac, Ucayali and Amazonas, in Peru, and the Solimões, Amazonas, the Breves Narrows and the Pará river in Brazil, totalling 6,992 km, slightly longer than the Nile, at 6,853 km.[7]

Considering the size of the river discharge into the sea, the Amazon system has an average discharge of 219 M m^2/s. The second largest river, in accordance with this measure, is the Congo, with an average discharge of 41.8 M m^2/s, or less than 20% of the volume of the Amazon. In order to support this discharge, the shape of the Amazon's main channel at Obidos, its deepest point, is compared to the Mississippi river at Vicksburg, MS in the USA in Figure 8. Such a comparison may well have consequences for the laying of subfluvial cables on or within the floor of such a channel.

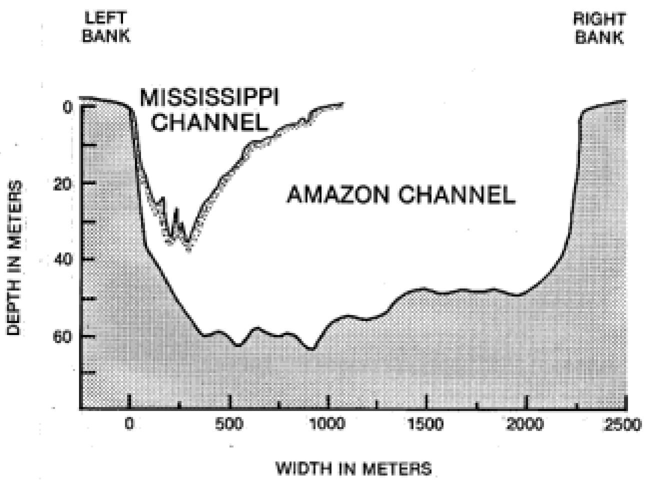


Figure 8: A comparison of the shape of the Mississippi and the Amazon at their deepest points, Vicksburg, MS, (1 km wide and 38 m deep) and Obidos, PA (2 km wide and 60 m deep).[8]

The map in Figure 9 shows some of the details of the Amazon basin, including the large number of navigable rivers, which make possible the extensive use of river transport almost as far upstream as the foothills of the Andes Cordillera, a distance of around 4.000 km from the Atlantic Ocean. Ocean-going ships ply for trade between Iquitos in Peru and the Gulf of Mexico, and large draught bulk carriers may be found on the Amazonas downstream of Manaus. In fact, over a huge area, river transport is the only practical alternative available to most of the population due to the dense equatorial rain forest and the almost entire absence of highways throughout the region. Some commercial air services operate, but to reach most communities there are few practical or affordable alternatives to fluvial transport. Needless to say, nearly all community settlements are located along the courses of the navigable rivers of the region, which also provide both a ready food supply in the form of fish.

[7] All these statistics are based on https://en.wikipedia.org/wiki/List_of_rivers_by_length
[8] http://disc.sci.gsfc.nasa.gov/geomorphology/GEO_4/GEO_PLATE_F-22.shtml

Figure 9: Phyical geography map of the Amazon river basin[9]

4.2 Telecommunications in Brazilian Amazonia

For many years, terrestrial radio communications within Brazilian Amazonia were the option of choice, for reasons of cost and flexibility. Long distance communications would be provided by tall transmission towers, well above the forest canopy. Currently satellite communication provides the best alternative for long distance data and voice communication

Privatised in 1997-8, national telecommunications service provision is dominated by four large companies: Vivo (owned by Telefónica from Spain), Claro/Embratel (owned by América Móvil from Mexico), TIM (owned by Telecom Itália from Italy) and Oi (Brazilian). There is a fifth and smaller company with national coverage, Telebras, which is state-owned, and was created to provide an alternative service provider for areas with poor coverage. Additionally there are a number of regional companies, as well as the presence of some large international companies, such as Level-3 and NTT.

The nationwide provider networks are present in all 26 states and the Federal District (home to the federal capital, Brasília), and have similar topologies, which are heavily influenced by population density and terrestrial communications infrastructure (power lines, railway lines and highways). Figure 9 shows the geographical distribution of population density, as measured in the Census carried out in 2000. It can be seen that most of the lowly populated areas are to the north and west of the country, which generally corresponds to the Amazon river basin.

This uneven population distribution greatly influences the geographical coverage of the telecommunications infrastructure of the service providers, whose long-distance routes in Amazonia are very recent and limited in number (see Figure 10), affecting, as a result, the coverage of RNP's network as shown in Figure 11.

[9] https://www.tes.com/lessons/iKxPOoIVdlPVpg/amazon-rainforest

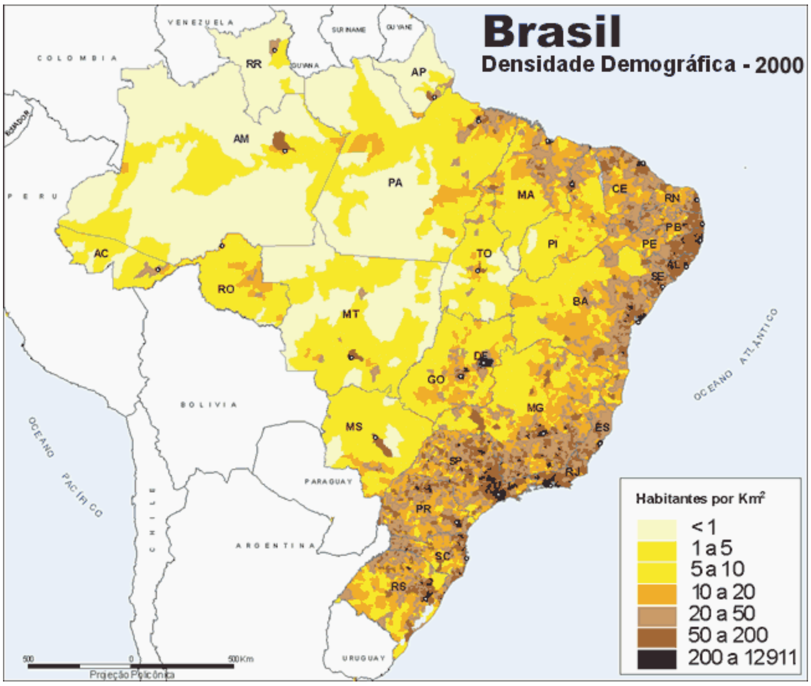


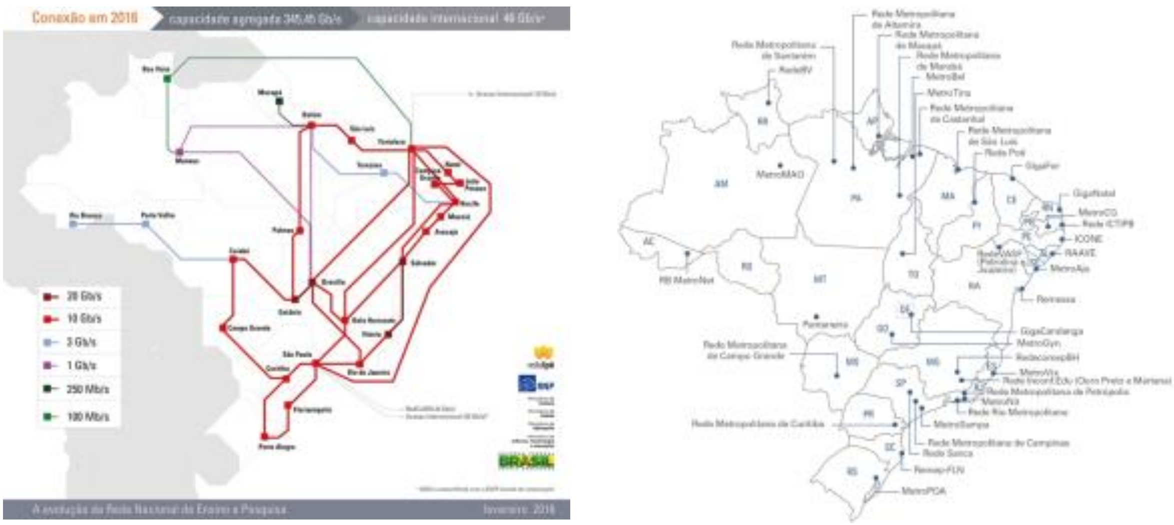
Figure 9: Population density in Brazil in 2000.

Figure 10: Existing Fibre Optic (FO) routes in Brazilian Amazonia.

Currently, the following long-distance optical routes have been deployed in the Brazilian Amazon region (see Figure 11):

- Porto Velho (Rondonia state) – Manaus (Amazonas state): optical cable owned by telecom operator Embratel, aerial, using utility poles, constructed along the federal highway, BR 319, which crosses an area of dense tropical rainforest between these state capitals. This was the first optical route which crossed the Amazon River system, using subfluvial cables at Manaus, linking the north bank of the Amazon to the national optical infrastructure [Azevedo 2010]
- Tucuruí – Belém – Marabá – Santarém – Itaituba: OPGW owned by the state-owned electricity generating company, Eletronorte, using its own power transmission lines, used to connect large-scale hydroelectric generating facilities at Tucuruí, in Pará state to population centres in Pará and Amazonas states;

- Tucuruí – Macapá – Manaus: OPGW owned by mobile telecom operator TIM (Telecom Italia Mobile), using electric power transmission lines of Isolux-Corsán to connect large-scale hydroelectric generating facilities at Tucuruí and, in future, Belo Monte, both in Pará state, to population centres in Macapá, Amapá state, and Manaus (see Figure 9) [Doile 2010]. This was only the second optical route to link the north bank of the Amazon to the national optical infrastructure;
- Manaus – Coarí – Urucu: optical cable owned by Petrobras, Brazil's state-owned oil and gas company, deployed along a gas pipeline from the production centre at Urucu (Amazonas state) to the state capital, Manaus [Petrobras 2009]. This provides another optical route crossing the Amazon River System – however it only currently reaches Urucu;
- Manaus – Boa Vista: optical cable owned by telecom operator Oi deployed underground along the federal highway, BR 174, which crosses indigenous reservations state between these two capitals. A second OPGW cable links Boa Vista to the border with Venezuela, where it connects to the Venezuelan national network run by CANTV.
- Macapá – Oiapoque, optical cable owned by telecom operator Oi, deployed underground along the federal highway, BR 156, through a non-populated area, connecting Macapá to the border with French Guiana (still to be completed).



(a) (b)

Figure 11: Network maps of RNP – (a) national backbone, (b) location of the 40 metropolitan networks. (Note the sparse coverage in the sparsely populated north and west of the country.)

The most recent crossing, at Jurupari, PA, is quite spectacular, involving a 2.13 km span between two 290 m tall transmission towers, only marginally shorter than the Eiffel Tower in Paris. As this stretch of the Amazon river is navigable by ocean shipping, the minimum clearance above the high water level is 72 m. (Figures 12 to 14).

Figure 12: Jurupari crossing looking eastwards (downstream) (Courtesy of Isolux-Corsán)

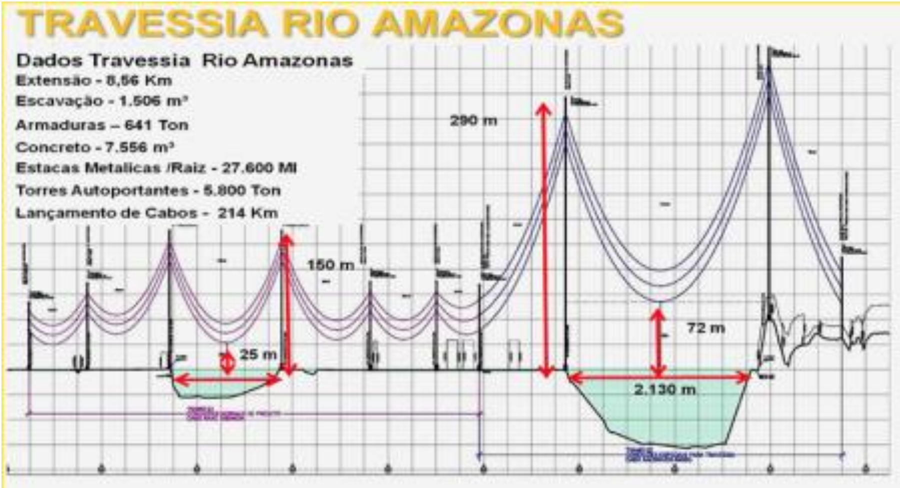


Figure 13: Jurupari crossing: engineering details (Courtesy of Isolux-Corsán)

Figure 14: Jurupari crossing looking southwards. (Courtesy of Isolux-Corsán)

1. 5. A project to deploy optical cable in the Amazon region

In many parts of the world, there are still regions of difficult access by land and of low population density. Some of these regions have, in the rivers that traverse them, a common solution to meet diverse society needs.

One of them is the Amazon region of Northern Brazil and some neighbouring countries, where there are few roads serving the main cities and where the population lives mainly along the banks of the great rivers that cross it.

The Amazon Rivers project was first described in [Grizendi and Stanton, 2013] and is summarized here. It began as a Final Undergraduate Project, under the orientation of the first author of this paper, presented at the National Institute for Telecommunications – Inatel [Vitor 2012]. This student project was concerned initially with providing a fibre connection across the mouth of the River Amazon, and then upriver to Santarém (Pará state).

Since 2013, RNP instigated the Brazilian government, and particularly the Communications Ministry, to undertake the much more ambitious project, of deployment of optical cables along the courses of its major rivers – such as the rivers Amazon, Negro and Solimões.

This proposal for the deployment of such subfluvial optical routes in the Amazon region was launched as a challenge to improve telecommunications infrastructure in the region, improving the availability of both broadband and communications in general, considering that the rivers in this region provide the main means of transport and where, along their banks, most of its population lives.

The main benefits expected from this project were:

- to create in the Amazon region a telecommunications infrastructure that will accelerate regional integration and development and contribute to the robustness of systems of national defence and policing;
- to establish a solid foundation for the development of research and education networks in the region;
- to contribute to the technological and industrial development of Brazil with global scale and competitiveness.

Besides the ease of reaching and meeting the needs of the riverside populations of these rivers, a cable route along the riverbed damages the environment far less than the construction of a road, that cuts through the tropical rainforest and ends up causing significant environmental damage.

The project was elaborated together with Padtec (www.padtec.com.br), a Brazilian manufacturer of optical systems, seeking close alignment with the intentions of the Brazilian government with respect to its National Broadband Plan. Figure 15 shows the proposed project, with the total length of cables estimated at 7,784 km and comprising six routes, as follows

A. Belém – Macapa – Manaus: 2,030 km, (mostly) along the River Amazon (marked in red);
B. Manaus – Iauareté (border with Colombia), 1,384 km, along the River Negro, (green);
C. Panacarica – Pacaraíma (border with Venezuela), 744 km, along the River Branco (yellow);
D. Manaus – Tabatinga (border with Peru and Colombia), 1,696 km, along the River Solimões, (orange);
E. Itacoatiara – Porto Velho, 1,115 km, along the River Madeira (blue);
F. Macapá – Oiapoque (border with French Guiana), 815 km, along the Atlantic coast (violet).

Figure 15 - The six routes in the complete project

(drawn using Google Earth, courtesy of Padtec)

Table 2 shows the population and the number of university and research institution campi (RNP clients) that could be served by this project.

Table 2 – Population and numbers of campi served by the project (courtesy Padtec)

State	Pará	Amazonas	Amapá	Rondônia	Roraima	TOTAL
Total population near to routes	3,198,418	2,997,309	633,919	443,058	342,344	7,615,048
Total population along the routes	2,947,076	2,872,946	562,219	443,058	342,344	7,167,643
% population served on routes	92%	96%	89%	100%	100%	94%
Cities	22	33	7	1	5	68
Total number of cities along the routes	13	26	5	1	5	50
% cities along the routes	59%	79%	71%	100%	100%	74%
Total number of RNP clients along routes	13	12	3	0	1	29

(Population count courtesy of Teleatlas 2013)

6. The Amazonia Connected Project

The Amazon Rivers project has caught the attention of several ministries of the federal government, as well as of the governments of the states of Amazonas and Pará. In addition to the Ministry of Science, Technology and Innovation (MCTI), which helps to maintain RNP, and the Ministry of Communications (MC), the proposal has been enthusiastically adopted by the Ministry of Defence (MD), through the Brazilian Army, which maintains a significant presence in Amazonia, securing very long land borders with 7 neighbouring countries. Starting in November, 2014, an alliance was established through a Memorandum of Understanding (MoU), involving these ministries and state governments, as well as a number of state and federal agencies and institutions listed below.

Federal ministries: MCTI, MC, MD.
Federal agencies: Telebras (MC); Eletrobras, through its subsidiary Eletronorte (Ministry of Mines and Energy - MME); Chico Mendes Institute for the Conservation of Biodiversity (Ministry of the Environment - MMA); National Water Agency (MMA).
State goverments and agencies: Government of Amazonas (AM); State Court of AM; State Prosecution Service (AM)Institute of Environmental Protection (AM); State university (AM); IT company (AM); IT company of Pará state (PA).
Social Organisation: RNP (MCTI).

In July, 2015, the Amazonia Connected Project (A-C) was officially launched in Manaus by the three ministers involved in the presence of the governor of AM. By this time the objectives of the Amazon Rivers project had been altered, to concentrate attention on the rivers of Western Amazonia which could provide telecommunications infrastructure through the use of subfluvial cables. The new configuration is shown in Figure 16 and in Table 3. Initially, the total cost had been estimated at around US$ 300M for laying over 7,600 km of cable, plus the necessary connection equipment, but real experience has shown that this estimate was unduly pessimistic.

Table 3: Initial configuration of the Amazonia Connected project

River	From	To	Distance (km)
Negro	Manaus	S. Gabriel da Cachoeira	1,000
Solimões	Coari	Tabatinga	1,182

Purus	Beruri	Boca do Acre	2,091
Juruá	Fonte Boa	Guajará	2,200
Madeira	Manaus	Porto Velho	1,170
TOTAL			7,643

Figure 16: River routes of the Amazonia Connected project

Even before this formal event in July 2015, the Army had already carried out a Proof of Concept (PoC) for the use of a subfluvial cable, consisting of the deployment of 6,800 m of cable between two Army installations in the city of Manaus, as shown in Figure 17, where the subfluvial section provides redundancy to connections to these Army installations (shown in yellow) which were already separately connected to RNP's MetroMAO metropolitan network in this city (shown in green).

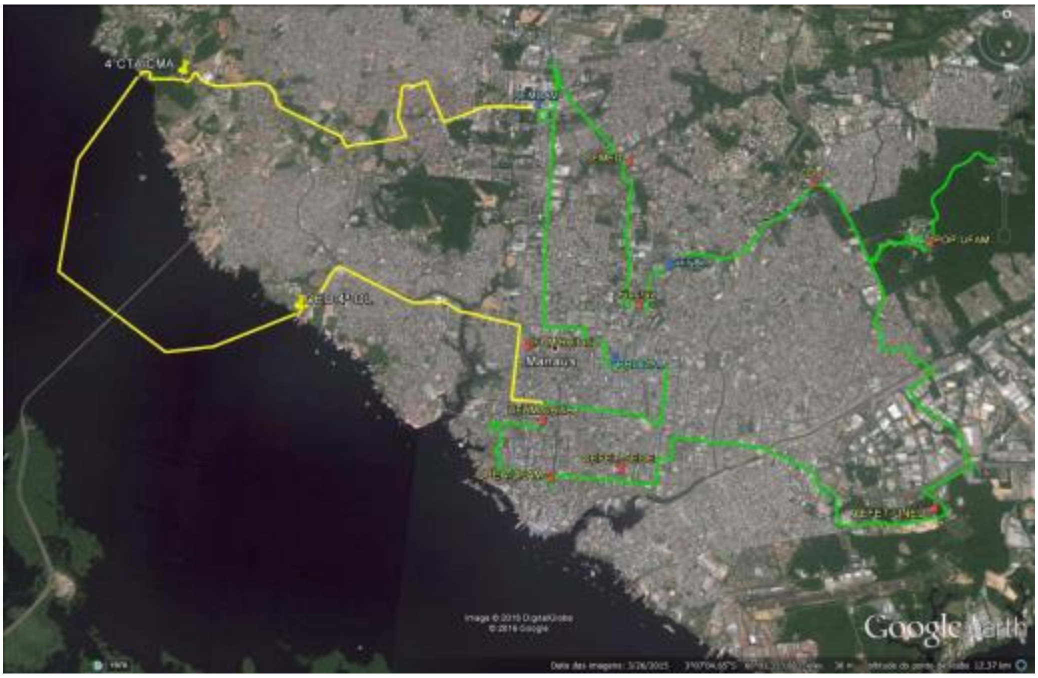


Figure 16: The 6,800 m subfluvial cable deployed in the Negro river in Manaus

The Army also took the decision carry out the pilot project proposed in [Grizendi and Stanton, 2013] which was to launch an initial 240 km subfluvial cable between Coari and Tefé as the first section of the cabling of the Solimões river. This was originally proposed in order to provide a broadband connection to the Mamirauá Institute for Sustainable Development, an internationally recognised centre for research into the sustainable management of the flooded forest region of the mid-Solimões, just upstream from Tefé. This would replace the existing satellite link.

Tefé, which has an urban population of around 50,000, is also is the home to a number of other potential clients of RNP's network, including campi of the Federal University of Amazonas (IFAM), the State University of Amazonas (UEA) and the state-run Centre for Technological Education of Amazonas (CETAM), as well as the local offices of the federal Open University of Brazil (OAB) and the federal Chico Mendes Institute for the Conservation of Biodiversity (ICMBIO), and RNP is currently studying the deployment of another owned metropolitan network to serve this community, once the new subfluvial link is activated. Such a network will probably also be shared by agencies of the state and federal governments to provide other services, especially in the fields od health and education. There is also commercial interest in providing mobile broadband services to this community, and it is expected that

The A-C pilot project was confirmed in the middle of 2015, and the Army reserved the necessary financial resources for acquiring the cable, supplied by the Norwegian company, Lexans[10], and the optical equipment, from Padtec[11], as well as contracting the engineering firm Aquamar[12], from Manaus, to lay the cable. Figure 17 shows a map of the pilot. The cable was successfully laid between March and April, 2016, and is expected to be inaugurated in May. In Figure 18, photographs illustrate the scale and the detail of the cable laying process. We intend to report on its initial utilisation at TNC2016.

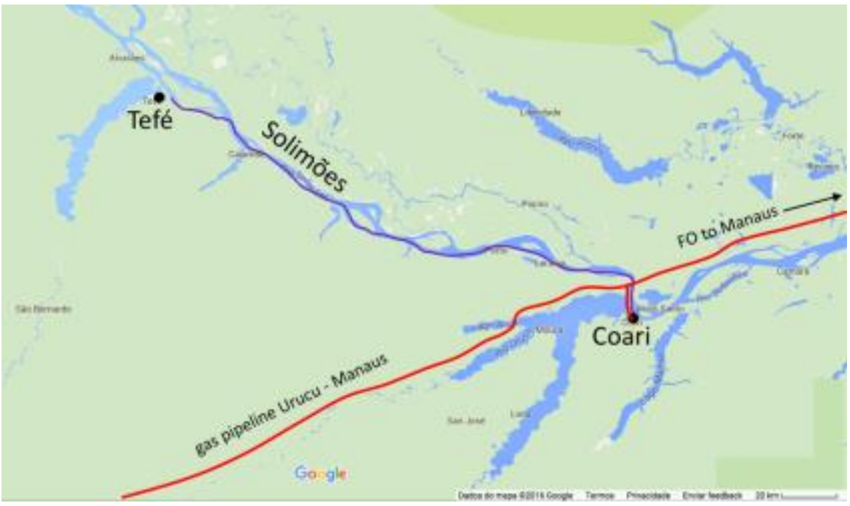


Figure 17: The pilot project linking Cori to Tefé along the Solimões.

[10] http://www.nexans.com/
[11] http://www.padtec.com.br/en/
[12] http://site.aquamarmergulho.com.br/index_eua.html

Figure 18: Prow and stern of the barge used to lay the pilot project cable from Coari to Tefé

Figure 19: Laying the cable: The reel of cable on the deck, and the launching of the cable at the stern.

2. 7. Related projects and studies

In 2013 a parallel proposal for deploying optical subfluvial cables in the Amazon region was published in [Garcia, 2013]. The author, an engineer from Colombia, also aimed to reduce the digital divide, separating Amazon region inhabitants with only satellite communications from their compatriots in the more populous parts of Colombia, and proposed this to be done in collaboration with neighbouring Amazon countries: Brazil, Ecuador and Peru. His proposal was to build a subfluvial cable from Manaus up the River Solimões as far as Leticia (Colombia) and Iquitos (Peru), and thence connect them, by terrestrial international links, to Colombia and Peru, respectively. He assumed that Manaus would be connected terrestrially by way of Venezuela (as it finally was in 2013). Garcia's proposal is illustrated in Figure 20.

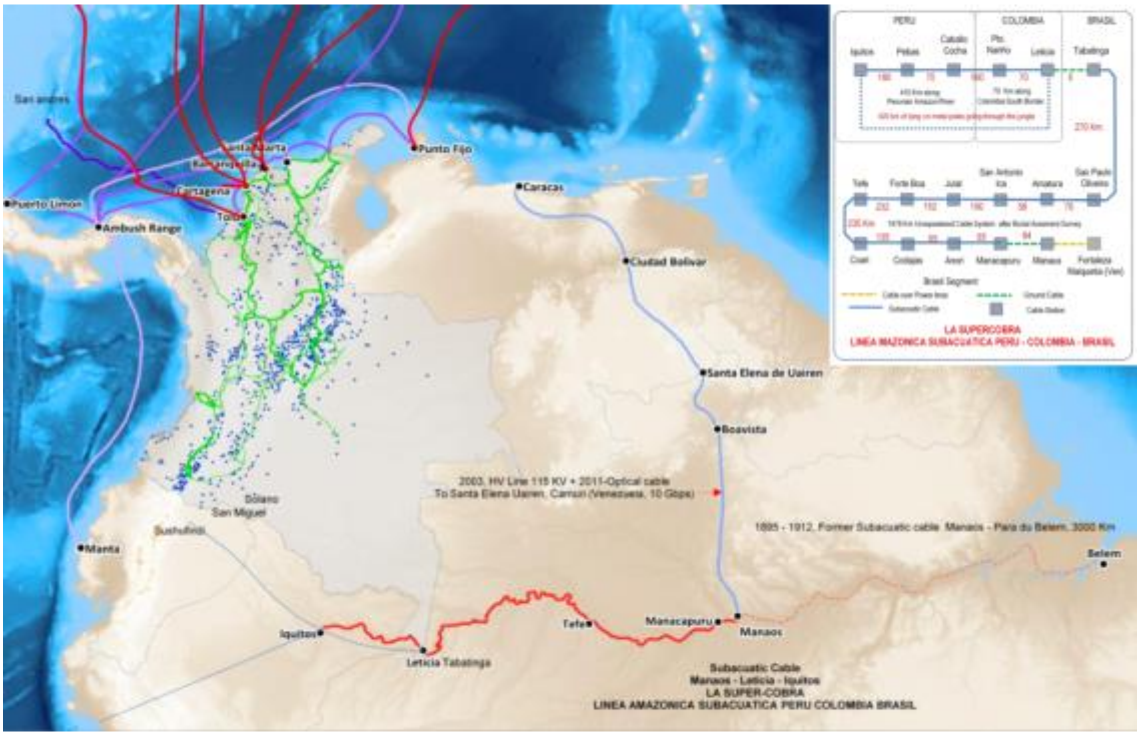


Figure 20: Proposal by [Garcia, 2013] to provide terrestrial connectivity to Iquitos and Leticia

Supposing the success of the Amazonia Connected project in building such a cable upstream from Manaus as far as the Colombian border at the twin towns of Tabatinga (Brazil) and Leticia (Colombia), Garcia's proposal only requires a cable from Tabatinga to Iquitos, a river distance of only 420 km.

Upstream from Iquitos, several of the tributaries of the main river are navigable for several hundred kilometres, and one interesting fluvial port is Yurimaguas on the Huallaga river, a tributary of the Marañón, which itself joins the Ucayali, to form the Peruvian Amazonas just upstream of Iquitos. The Peruvian Amazonas becomes the Solimões at the Brazilian border.

There is interest in Peru in providing terrestrial communications to Iquitos, the largest town in Peruvian Amazonia. It seems that there are those in Peru who are thinking of a solution linking Iquitos to Yurimaguas, a distance of about 550 km by river, and around 400 km in a direct line. The direct line could be used for radio communications with a number of tall repeater towers along the route. Alternatively, a subfluvial cable could be used, and it seems that a survey of this alternative has already been carried out. It is not yet clear what is the preferred solution, nor how it will be built.

Figure 21 shows the possible interconnection between Brazil and the Pacific coast by means of subfluvial cables through the Amazon basic, and use of a new highway recently completed between Yurimaguas and the port of Paita. Within Amazonia, the proposal takes advantage of an 98 km highway between Iquitos and Paita. Among the advantages of this proposal is the provision of an entirely new East-West telecommunications crossing of Amazonia, which increases the redundancy of the general South American communications network, as well as providing broadband connectivity to communities living along the rivers mentioned.

Figure 21: A proposed crossing of Peruvian Amazonia (inset map of the IIRSA North highway[13])

8. Conclusion

The article has gone to some length, firstly to demonstrate the debt we owe and rarely acknowledge to the pioneers of underwater communication cables from the mid-19th Century. The main part of the article deals with the current rapid expansion of the global submarine fibre optic network, especially in the South Atlantic Ocean, where new cables crossing between South America, Africa and Europe will soon change significantly the global topology of today's Internet.

[13] IIRSA: IIRSA = Integration of the Regional Infrastructure of South America https://pt.wikipedia.org/wiki/Iniciativa_para_a_Integração_da_Infraestrutura_Regional_Sul-Americana

The other main emphasis is on the application of submarine cable technology to large rivers, such as those in the Amazon region of South America, where dense tropical forest makes for low population densities and minimal land transport systems. In their place fluvial transport is often the only alternative, at least for the very great majority of the population.

We have seen that subfluvial cables were already used in the Amazon from the end of the 19th Century. The current article describes a current initiative to adopt this approach for bringing broadband telecommunications to the region by the use of fibre optic subfluvial cables. This is being carried out in Brazil by a coalition formed by the Armed Forces, the national government, state governments from the region and some utility companies. The original proposal for such a solution originated with the authors, both from RNP, the Brazilian NREN, which is also a member of this coalition. The first cables have already been laid, but there is much still to do, not least to learn how to solve potential problems with this kind of infrastructure.

We also suggest the extension of the proposal for use in Colombia and Peru, Amazonian neighbours of Brazil. In addition to Amazonia, we dare to suggest that this solution may be applicable to other, probably tropical, parts of the world, with large rivers (or lakes) and dense forests, such as may be found in Africa and Southeast Asia.

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Eduardo Grizendi is Director of Engineering and Operations at RNP. Since 1990 he has taught at Instituto Nacional de Telecomunicações (Inatel), in Santa Rita do Sapucaí, Minas Gerais, Brazil. He holds a Master of Science in Telecommunication Systems from Inatel and a MBA in Business from Fundação Getúlio Vargas (FGV). He graduated in Electronic Engineering at Instituto Tecnológico de Aeronáutica (ITA). He has worked in the field of telecommunications since 1978, initially in R&D institutions, and afterwards in telecommunications carriers and consulting services.

Michael Stanton is Director of Research and Development at RNP, the Brazilian national research and education network. After a PhD in mathematics at Cambridge University in 1971, he has taught at several universities in Brazil, since 1994 as professor of computer networking at the Universidade Federal Fluminense (UFF) in Niterói, Rio de Janeiro state, until his retirement in 2014. Between 1986 and 1993, he helped to kick-start research and education networking in Brazil, including the setting-up and running of both a regional network in Rio de Janeiro state (Rede-Rio) and RNP. He returned to RNP in 2001, with responsibility for R&D and RNP involvement in new networking and large-scale collaboration projects. Since 2012, Michael's new international activities have included representing RNP on the Global CEO Forum's Global Network Architecture (GNA) group, engaged in the design of the architecture of the future academic Internet, and joining the Council of the Research Data Alliance in 2014.