Carbon Footprint of Cloud, Edge and Internet of Edges

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Abstract

In this article, we highlight the carbon footprint of data transport on Internet infrastructures by bringing together a series of studies that break down the carbon impact of digital technologies and detail the geography and routing of the Internet. The article also draws a comparison between three types of digital infrastructure where digital services are hosted either in the cloud, at the edge or in an Internet of Edges. This comparison highlights the benefits of creating short circuits for data to reduce the carbon footprint of digital communications.

1 Introduction

This paper is the first of a global study that aim at answering the following questions: What impact does the long journey of data over the Internet backbone has on the carbon footprint of communications? Could short circuits between the producer and consumer of data, as in the agri-food industry, reduce the carbon footprint of digital communications?

Today, the main digital architecture model for delivering a digital service is a globalized one. Digital services are hosted in clouds, often offshore, and data travels long distances between source, cloud and destination. By 2025, nearly half of the global datasphere will be made up of local data according to IDC [1]. To save this local data from an unnecessary long travel, synonymous with wasted resources, new types of digital architecture are emerging. These involve bringing digital services closer to the producer and consumer of data, at the edge of the network - so-called edge-based infrastructures - and connecting the edges directly and, possibly, wirelessly to each other - so-called Internet of Edges [2].

The objective of this paper is to evaluate and compare the carbon footprint per GB of providing a digital service over these three types of infrastructures - cloud-based, edge-based, and Internet of Edges - with a particular focus on the route length. We use the case of a popular digital service, videoconferencing, and adopt a simplified Life Cycle Analysis (LCA) methodology that takes into account, as far as possible, all the equipment used in a route and all the phases in the equipment's life cycle.

After introducing a few terms and definitions (Section 2), we review related work (Section 3), and define the scope of the study (Section 4). We then present the carbon footprint results by equipment (Section 5) and by type of infrastructure, with a comparison (Section 6). Finally, Section 7 presents the limitations of the study, and Section 8 concludes the study and introduce some perspective and future studies.

2 Terms and Definitions

Table 1 summarizes the major terms that are used in this study.

Table 1: Terms and Definitions

Term	Definition
Edge Computing	Edge computing is a distributed computing paradigm that brings computation and data storage closer to the sources of data.
Regional Cloud	Data centers located in the same region as the owners of data they host.
Internet of Edges	When different Edge sites are connected directly to each other via secure tunnels.
Carbon Footprint	Sum of greenhouse gas (GHG) emissions in a product system (goods or services), expressed in CO_2 equivalent (CO_2 $eq.$) and based on a life-cycle analysis with climate change as the only impact category.
Greenhouse Gas (GHG)	A greenhouse gas is a gas that absorbs and emits radiant energy at thermal infrared wavelengths, causing the greenhouse effect. The primary greenhouse gases in Earth's atmosphere are water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and ozone (O_3).
Life Cycle Analysis (LCA) methodology	Compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system over its life cycle.
A-LCA	Attributional LCA is defined by its focus on describing environmentally relevant physical flows to and from a life cycle and its subsystems.
C-LCA	Consequential LCA is defined by its aim to describe how these flows will change in response to possible decisions.
Simplified life cycle assessment (LCA)	There is no official definition of this term, but it is generally a LCA with a narrower scope, including fewer processes and/or fewer impact categories.
Product Category Rule (PCR)	Set of rules, requirements and guidelines for the preparation of environmental declarations and carbon footprint communications for one or more product categories.

3 Related Work

In this section, we review the current state of knowledge on the carbon footprints of the digital industry, on impacts due to networks and route length, and on analysis methodologies.

3.1 Carbon Footprint of the Digital Industry

In 2019, the global digital word contributed to $3.8\ \%$ of global Greenhouse Gas (GHG) emissions and $5.5\ \%$ of global electricity consumption. At the time, it comprised 4.1 billion Internet users using 35 billion endpoints (user equipment, IoT devices, and last mile networks with Internet access routers, mobile network base stations, etc.). To 2025, the number of endpoints deployed globally is expected to grow to nearly 70 billion and the carbon footprint of digital is projected to reach $2,278$ million tonnes of CO_2 equivalent which is a 3 fold increase between 2010 and 2025 [3]. In France, the digital industry represents $2.5\ \%$ of the carbon footprint and $10\ \%$ electricity consumption of the country in 2020. If nothing is done to reduce the environmental impact of digital and if usage continues to grow at the current rate, data traffic would increase sixfold, the number of equipment would rise by $65\ \%$, and the carbon footprint of digital technology in France would increase by about $45\ \%$ in 2030 compared to 2020 [4]. The same observation is made at the European level [5].

Environmental impact analysis breakdown the digital world into three tiers - users, networks, and data centers - and phases of the equipment life cycle - manufacturing, use, and end of life. Global [3] as well as regional [4] [5] studies come to a consensus that more than half of greenhouse gas emissions is due to users' equipment (terminals, laptops, IoT devices, etc.). The remainder is divided between networks and data centers (Table 2). The core of Internet networks has a limited impact whereas 'last mile' networks (e.g. Internet access routers, mobile network base stations, etc.) concentrate the bulk of the networks' carbon footprint. The French agency for ecological transition (ADEME) [1] and the French regulatory authority for electronic communications, post and press distribution (ARCEP) [2] estimate in [4] that access networks account for 75% of the total carbon footprint of fixed Internet networks and 94% of that of mobile networks in France. Manufacturing is the stage of the life cycle that contributes most to total greenhouse gas emissions of user equipment, while the use phase has the greatest impact on networks and data centers, due to their high energy consumption.

Table 2: Share of Users, Networks, and Data Centers on the Carbon Footprint of Digital

Source	Period	Perimeter	Users	Networks	Data centers
ADEME [4]	2020	France	78.7%	5.5%	15.9%
Green IT [5]	2019	Europe	65.5%	11.9%	22.5%
Green IT [3]	2019	World	66%	19%	15%

3.2 Impacts Due to Networks and Route Length

There is no clear consensus on the impact of networks on the total carbon footprint of digital. Green IT [3], a French association that brings together experts in ICT sustainability, notes the disparity of results in [6] where Internet networks contribute from $11\ \%$ to $32\ \%$ of total electricity consumption of digital in France depending on the study. Table 3 displays results from several sources of carbon footprint of transporting $1\ GB$ of data via fixed or mobile networks in France. Results varies from simple to triple depending on the study. According to [4], this large variability is due to the lack of knowledge regarding civil engineering costs, lifetime, energy consumption, and network equipment inventory. It has been agreed, however, that fixes Internet networks and more specifically fiber-optic networks have lower impact than mobile networks. The Wi-Fi Alliance [4] in their report [7] mentions that fiber-optic networks are 2.5 times as energy efficient as mobile 5G when streaming a video for one hour and 5G as much

[1] https://www.ademe.fr/en/frontpage/
[2] https://www.arcep.fr/en
[3] https://www.greenit.fr/
[4] https://www.wi-fi.org/

as 85% more energy efficient per Gigabit transmitted than previous generations. Results from French studies displayed in Table 3 confirm these findings.

Table 3: Carbon Footprint of Transporting 1 GB of Data via Fixed and Mobile Networks in France ($kg\ CO_2\ eq./GB$)

Source	Period	Fixed Networks	Mobile Networks
ADEME-ARCEP [4]	2020	9.27e−03	2.47e−02
NegaOctet [8]	2018 − 2021	4.43e−03	7.97e−03
ADEME [9]	2020	1.79e−02*	5.00e−02
FREE [10]	2020	7.72e−03*	2.43e−02

*Considering 220 $GB/subscriber/month$ [4])

The above mentioned studies bring knowledge on the carbon footprint per tier taking in account the equipment deployed within a predefined geographic area regardless to the type of digital infrastructure employed and the route length between source, server, and destination. For example, the study [4] excludes all foreign equipment associated with the use of digital services on French territory even though it is said that 55 % of traffic from data centers to French terminals came from abroad in 2019. Using that networks carbon footprint values (Table 3) to assess the GHG emissions of providing a digital service whose server is located abroad can minimize the impact of the network.

A study conducted on RENATER [5], the network dedicated to the education-research community, assesses the carbon footprint of transporting 1 GB of data on several routes of the network [11] [12]. Authors found out that traveling data from Montpellier to Orsay (700 km geographic distance) generated 1.5e−03 $kg\ CO_2\ eq./GB$ and 6.0e−4 $kg\ CO_2\ eq./GB$ for traveling data from Jussieu to Orsay (20 km geographic distance). Results shows that there is no direct correlation between the carbon footprint of a route and geographic distance between the source and the destination.

Indeed, Internet can be highly circuitous and routing distance longer than direct geographic path. The notion of routing circuitousness was at first defined by Subramanian et al. in [13] in 2002 as the degree of geographical indirectness in end-to-end path on Internet. Many researches have been carried out since to understand the Internet's geography, routing, and circuitousness. They found out that the quantity of some equipment involved in a route is not necessarily related to the distance, such as routers of the Internet network. The degree of circuitousness of Internet path relies on the geographic location of the source and destination. Internet tends to be more circuitous when data source and destination are close together than when they are far apart. [14] and [15] in 2011 set a first set of Circuitousness measurement using the Circuitousness Ratio 1.

$$\text{Circuitousness Ratio (C)} = \frac{\text{Routing Distance}(km)}{\text{Geographic Distance}(km)} \tag{1}$$

They found out that in the US, data traveled ten times the direct geographic distance between two Internet hosts located in the country. Data travels up to twice the geographic distance between two Internet hosts communicating across the Atlantic. In 2013, [16] confirms the above values using another calculation methodology and finds out that communications across the Atlantic travel 1.8 times in average the direct geographic distance. [17] in 2018, observes that the routing circuitousness of Internet is deteriorating over time.

In this paper, we aim to make a correlation between routing distance and greenhouse gas emissions.

[5]https://www.renater.fr/en/network/national-and-international/the-renater-network/

3.3 Calculation Methodology

The French government voted in 2021 the anti-waste and circular economy law (AGEC). The law imposes telecom operators to display a data consumption carbon footprint indicator on users' bill. To this end, a unified protocol for calculating the carbon footprint of French networks was created by ADEME. This effort gave birth to Product Category Rules (PCR) that are normalized methodologies based on ISO 14040 and 14044, ILCD Handbook, and ITU Series L standards adapted to the digital sector. PCR for Internet providers is described in [18] and has been since extended to digital services [19]. More PCR rules are under definition to address all categories of digital products and services.

In the meantime, the European Commission has published detailed methods for assessing the environmental impact of organizations [20] and products [21], along with recommendations [22]. The European methods associated with the above mentioned ISO standards are prescribed by Green IT to assess the environmental impact of digital [23].

National and European initiatives have in common the recourse of multi criteria impacts analysis in a life cycle perspective. They recommend assessing impacts on multiple environmental criteria such as abiotic resource depletion, Global Warming, and Tension on fresh water, taking in account all phases of products' life cycle from cradle to grave: manufacturing, use, and end of life.

Life cycle assessments are of two types. Attributional LCA (A-LCA) aims at attributing impacts retrospectively to give a "degree of responsibility". This methodology is the one used by ADEME [18, 19], ADEME and ARCEP [4], and authors of [11] to assess the impact of digital products, services, and of the overall digital industry. Consequential LCA (C-LCA) assesses a priori the evolution of impacts if assumptions are changed. This methodology is used by politics to assess the impact of new laws and regulations. Although simplified A-LCA is not a standardized methodology, it is been used by some market players including RENATER in [11] which detailed calculation methodology is provided in Table 4.

The methodology used in this study is inspired by the simplified A-LCA methodology of the study of the RENATER network. It follows as much as possible the recommendations of ADEME and Green IT to facilitate the understanding and comparability of results. However, the study differs from standard methodologies in that it focuses primarily on the comparison of three types of infrastructure. We have therefore excluded user equipment that has the same impact on all three infrastructures and makes no difference between them, although it is recommended to include user equipment when assessing the impact of a service provision. The study is limited to the effect of global warming, and aggregates heterogeneous data sets covering all or part of the product life cycle. This is due to the lack of detailed information on the components that compose the global Internet network. This study therefore provides a broad picture of the carbon footprint of the global Internet versus the edge and the Internet of Edges.

Table 4: Simplified A-LCA Formulas as per the RENATER Study

Descriptions	Formulas
Carbon Footprint of an Equipment ($kg\ CO_2\ eq./GB$)	$$= \sum_{equipement} \text{Emissions of Use} + \text{Manufacturing } (kg\ CO_2\ eq./GB) + \text{Emissions of Fiber-Optic } (kg\ CO_2\ eq./GB) \quad (2)$$

Continued on next page

Table 4 – *continued from previous page*

Descriptions	Formulas
Emissions of Use ($kg\ CO_2\ eq./GB$)	$$= \frac{\text{Electricity Consumption (kWh)} \times \text{PUE}}{\text{Traffic (GB)}} \times EF \quad (3)$$ Electricity consumption and traffic are for the same period of time (e.g. 1 hour, 1 year) EF = emission factor constant corresponding to the GHG generated by the consumption of 1 kWh of electricity in France. It corresponds to $0.108\ kg\ CO_2\ eq./kWh$ ($ELCD$ value). $PUE = 1.8$.
Emissions of Manufacturing ($kg\ CO_2\ eq./GB$)	$$= \text{Emissions of Production} + \text{Emissions of Shipping} \quad (4)$$
Emissions of Production ($kg\ CO_2\ eq./GB$)	$$= \frac{\text{Emissions of Production } (kg\ CO_2\ eq.)}{\text{Total Traffic } (GB)} \quad (5)$$
Emissions of Shipping ($kg\ CO_2\ eq./GB$)	$$= \frac{\text{Emissions of Shipping } (kg\ CO_2\ eq.)}{\text{Total Traffic } (GB)} \quad (6)$$
Total Traffic (GB)	$$= \text{Traffic on the Equipment } (GB/year) \times \text{Equipment' s Lifetime } (year) \quad (7)$$
Carbon Footprint of Fiber-Optic	$$= \frac{\text{Emission Factor } (kg\ CO_2\ eq./km) \text{ x Distance } (km)}{\text{Total Traffic } (GB)} \quad (8)$$

4 Scope of the Study

Given the lack of reliable data on other impact indicators, only impact on global warming is studied. Its unit is expressed in kg of CO_2 equivalent or $kg\ CO_2\ eq$. It takes into account the emissions of multiple Greenhouse Gases (GHG) such as carbon dioxide (CO_2), nitrous oxide (N_2O), methane (NH_4), chlorofluorocarbons ($CFCs$), etc. responsible for global warming. Wherever possible, we have included the GHG emissions emitted during all phased of product life cycle. However, end of life of the equipment is not always included due to lack of data.

4.1 Functional Unit

The study evaluates the carbon footprint in $kg\ CO_2\ eq.$ per GB of carrying out a video-conference between two fixed Internet users using several types of digital infrastructures: cloud-based, edge-based, and digital infrastructures based on the Internet of Edges (IoE). Both users are located within the European and North American regions and are fiber Internet subscribers.

4.2 System Boundaries

The system (Figure 1) includes all equipment of the digital infrastructure involved in the transmission of data over a fiber-optic network from the first routing equipment to which a sending user is connected, to the last equipment to which another receiving user is connected comprising Internet access routers, fiber-optic cables, and shelters responsible for signal amplification. The study takes into account all equipment involved in the provision of the videoconferencing service including the server hosting the videoconferencing service, and the data center housing the server. As far as possible, the study integrates all phases of the equipment's life cycle, from cradle to grave.

The system excludes impacts due to users' equipment (e.g. smartphone, laptop, desktop, etc.), software development and maintenance, and systems' supervision. It also excludes routers of the fiber-optic network, the amount of which depends on factors other than route length.

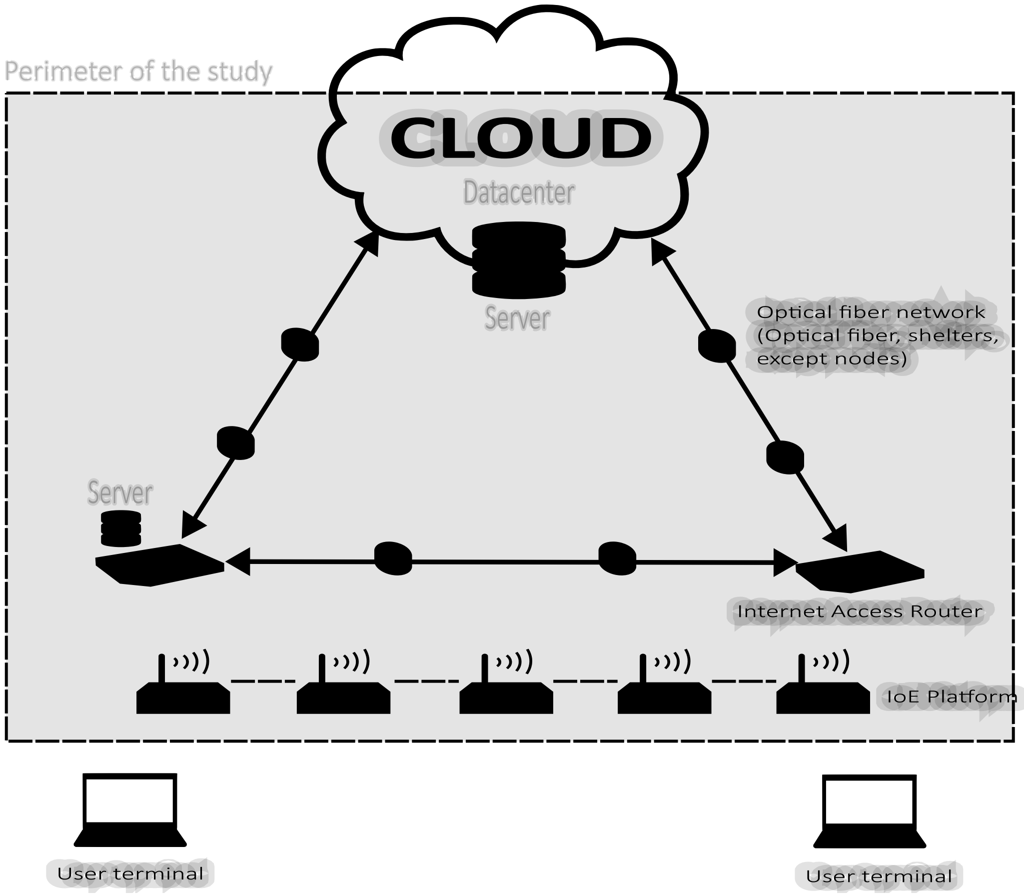

Figure 1: Perimeter of the Study

4.3 Assumptions

For the purposes of this study, we assume that the global fiber-optic network is similar to the RENATER network. It consists of fiber-optic cables, routers and shelters. Shelters are placed between two routers every 80 to 120 km (we use 120 km in this study). Average traffic per device on the RENATER network is comparable to that of global Internet routes. Thus, the carbon footprint per GB of RENATER equipment can be used in our study.

We consider that the difference between a video-conference server hosted in a data center and a server hosted at user's location (endpoint) is similar to the triangle proprieties as presenter in Figure 2.

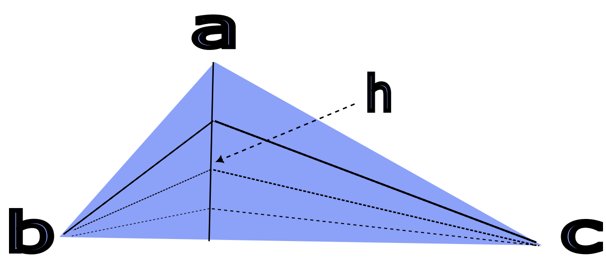

Figure 2: Triangle Side Length Rules

Figure 2 shows a triangle abc where a is seen as a cloud point and b and c as two endpoints that need to

initiate a video-conference. The video-conference server could be hosted at point a (cloud) or at b or c (edges). According to the triangle side rules (Figure 2), we have $[bc] \leq [ba] + [ac]$.
When $a \in [bc]$, the distance that the video-conference information is going to use is equal in both cases (cloud or edges).
If $a \notin [bc]$, then direct distance between the edges is shorter than going through a server in the cloud. More the height h has a bigger value more ratio between $[ba] + [ac]$ and $[bc]$ is high.

In the scenario studied, the direct route $[bc]$ can either go through the global Internet backbone network when b and c are far from each other or through a wireless multi-hop Internet of Edges (IoE) network made of IoE platforms when b and c are at vicinity (in a range of few kilometers). A wireless hop, is a wireless backhaul link between two IoE platforms with a length of 100 m. On top of the backhaul link, an IoE platform provides a wireless access point through which users connect to the Internet of Edges, with an additional 100 m of coverage. Thus, a 3 wireless hops network is composed of 4 IoE platform and provides 500 m coverage as per Figure 3 and Equation 9.

$$\text{IoE Route Length} = \text{Number of Hops x } 100\ m + (2 \text{ x } 100\ m) \tag{9}$$

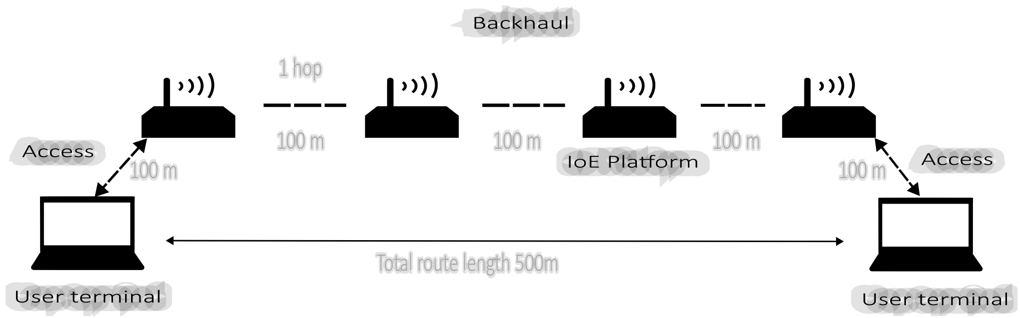

Figure 3: Three Hops IoE Network

4.4 Scenarii

In this paper we consider two scenarii:

Scenario 1 - Cloud vs Edge Digital Infrastructure: Two users located at endpoints b and c far away from each other initiate a video-conference using a service hosted on a server located in a data center at point a (Figure 2). Traffic of the video-conference goes though the route $[bac]$, called the $long\ route$, via fiber-optic networks. We repeat the scenario using a service hosted on an edge server instead. The edge server is hosted at either b or c locations. Traffic of the video-conference goes though the direct route $[bc]$, called the $short\ route$, via fiber-optic networks. We evaluate the carbon footprint ratio between $long\ route$ and $short\ route$ while varying the distance between the cloud (point a) and users (endpoints b and c). The aim is to estimate how far away from the user a cloud-based system is more attractive than an edge-based system.

Scenario 2 - Cloud vs Internet of Edges Digital Infrastructure: Two users located at endpoints b and c close to each other initiate a video-conference using a service hosted on an Internet of Edge platform (IoE platform). Traffic of the video-conference goes though the direct route $[bc]$, called the $short\ route$, via an Internet of Edges (IoE), a wireless multi-hop network created by IoE platforms. We evaluate the carbon footprint ratio between $long\ route$ calculated in $scenario$ 1 and the $short\ route$ while varying the number of wireless hops involved in the $short\ route$ $[bc]$ using the Internet of Edges. The aim is to estimate how many wireless hops it is more worthwhile to use a wireless Internet of Edges rather than cloud-based systems.

4.5 Data Set

The study builds upon a set of data coming from:

- Scientific literature with regards to global Internet network characteristics;
- Direct measurements for traceroute analysis and retrieving IoE platforms energy consumption;
- The study conducted on the RENATER network estimating the carbon footprint of transmitting a GB of data over the network [11] for the carbon footprint of fiber-optic networks;
- The report conducted by ADEME and ARCEP on the assessment of the environmental impact of digital in France [4] for multiple parameters such as energy consumption of Internet access routers, average traffic of fixed Internet line subscribers in France, etc;
- The NegaOctet database [24] which provides environmental impacts of multiple digital products and services in France;
- Online articles regarding global Internet consumption, number of km of optical fiber deployed globally, etc.

The study aggregates various information on carbon footprint of components considering all or part of the life cycle. Due to the non-homogeneous nature of this dataset, result of the study should be considered as having a high level of granularity.

4.6 Inventory of Equipment

Table 5 describes all the digital infrastructure equipment used by data as it travels the short or long routes from source to destination.

Table 5: List of Equipment Per Route and Scenario

(Nbr. of Unit)	Equipment	Scenario 1	Scenario 2
Long Route	Cloud server	1	1
	Shelter	1 every 120 km	1 every 120 km
	Fiber-optic cable	1	1
	Internet access router	2	2
Short Route	Edge server	1	
	IoE platform		1 every 100 m
	Shelters	1 every 120 km	
	Fiber-optic cable	1	
	Internet access router	2	

In $scenario$ 1, the traffic is initiated at the sending user's Internet access router and travels through the fiber-optic network to a server located in a data center, considering the $long\ route$. The traffic then travels back over the fiber-optic network to the destination user's Internet access router. The $long\ route$ therefore includes the two Internet access routers of the two users, the cloud-based server that is hosting the video-conferencing service, and equipment of the fiber-optic network (shelters and cables). If we now consider the $short\ route$, the traffic is initiated at the sending user's Internet access router, where the video-conference edge server is also located, and transits through the fiber-optic network directly to the receiving user's Internet access router. The $short\ route$ therefore includes the same equipment as the $long\ route$, with the difference that the cloud server is replaced by an edge server, and equipment on the fiber-optic network, the quantity of which varies with the routing distance.

In $scenario$ 2, the $long\ route$ is the same as in $scenario$ 1. The $short\ route$, however, uses a wireless Internet of Edges network instead of a fiber-optic network. Traffic is initiated by the IoE platform closest to the sending user, in which the videoconferencing service is embedded, and transits via a wireless multi-hop network of IoE platforms, directly to the IoE platforms closest to the receiving user. The $short\ route$ therefore includes only IoE platforms, the quantity of which varies according to the distance between the two users.

4.7 Calculation Method

The total carbon footprint of a route is the sum of the carbon footprints of the equipment used on the route.

$$\text{Total Carbon Footprint of a Route} = \sum_{equipement} \text{Carbon Footprint } (kg\ CO_2\ eq./GB) \tag{10}$$

The carbon footprint of a piece of equipment is evaluated using the formulas provided in Table 4.

Then we assess the Carbon Footprint Ratio (CF Ratio) between $long\ route$ and $short\ route$ as a function of the routing distance. To do this, we use a Route Ratio (R) based on the triangle propriety detailed in Figure 2 where R applies only to equipment whose quantity depends on routing distance (e.g. shelters). The aim is to determine how many additional pieces of these equipment are available on longer routes compare to shorter ones.

$$R = \frac{[ba] + [bc](km)}{[bc](km)} \tag{11}$$

Thus, the final Carbon Footprint Ratio equation is:

$$\text{CF Ratio} = \frac{\text{Total Carbon Footprint } LongRoute}{\text{Total Carbon Footprint } ShortRoute} \tag{12}$$

Where:

$$\begin{aligned}\text{Total Carbon Footprint } Long\ Route = {} & R \text{ x Carbon Footprint of Shelters } (kg\ CO_2\ eq./GB) \\ & + \sum_{Other\ Equipment} \text{Carbon Footprint } (kg\ CO_2\ eq./GB)\end{aligned} \tag{13}$$

When CF Ratio > 1, the $short\ route$ has lower carbon footprint than the $long\ route$.
When CF Ratio < 1, the $short\ route$ has higher carbon footprint than the $long\ route$.

To define the range of routing distances to take into account in the study, we compare values from the literature with real life measurements. ADEME in [25] estimates that average travel of any digital thing on Internet is $15,000\ km$ in 2019. We compare this information with direct measurement using traceroute between a Paris-based user and popular videoconferencing services such as Jitsimeet [6], Zoom [7],

[6] https://meet.jit.si/
[7] https://zoom.us/

and Teams [8]. Results lead to servers based on the east and west coasts of the USA. The geographic distance between Paris and San Francisco (the most remote server location in our study) is $9,000\ km$ one way and $18,000\ km$ round trip. To convert geographic distance into routing distance we use the Circuitousness Ratio (C) as defined in Section 3. If we consider a Circuitousness Ratio of 1.8 with Formula 1, the routing distance for a communications between a user located in Paris and a server in San Francisco would be $16,200\ km$. In the case of a video-conference between two users located at equal distance from the server, this routing distance is multiplied by two and reaches $32,400\ km$. In this paper, we study distances up to a maximum of $40,000\ km$.

5 Carbon Footprint of Digital Infrastructure Equipment

A digital infrastructure is made up of equipment such as Internet access routers, fiber-optic Internet network equipment (fiber-optic cables, network routers, and shelters), and servers hosting digital services. In this section we details the carbon footprint of each type of equipment considered in the study.

5.1 Internet Access Router

A Internet access router is the most peripheral equipment of the fixed Internet network located close to the user. To assess the carbon footprint of a Internet access router we use the data provided in [4]. The study tells that total carbon footprint of fixed Internet networks in France is $9.27\text{e}{-}03\ kg\ CO_2\ eq./GB$ in 2020 out of which Internet access routers represent $45\ \%$ of the impact. Hence, the total carbon footprint of an Internet access router per GB can be estimated at $4.17\text{e}{-}03\ kg\ CO_2\ eq./GB$. This estimate includes all the steps of the product life cycle from cradle to grave.

Based on the energy consumption, traffic and lifetime data provided in [4] and using the formula provided in [11], we deduce from the above result the carbon footprint per phase of the equipment's life cycle. There are $30,652,000$ fixed Internet subscribers in France consuming $220\ GB$ of data per month in 2020. Each subscriber is equipped with an Internet access router consuming in average $90\ kWh/year$ with a 10 year lifetime. The carbon Footprint of use can be estimated at $3.68\text{e}{-}03\ kg\ CO_2\ eq./GB$ using Formula 3. The carbon footprint of the other stages (manufacturing and end of life) is obtained by subtracting the carbon footprint of use from the total, which gives $4.93\text{e}{-}04\ kg\ CO_2\ eq./GB$ (see Table 6).

Table 6: Carbon Footprint of Internet Access Router

$kg\ CO_2\ eq./GB$	Use	Manufacturing	End of Life	Total
Internet access router	3.68e−03	4.93e−04		4.17e−03

5.2 Optical Fiber

Due to the very low energy consumption of fiber optic cable, we will not take into account the emissions associated with the use of this equipment. The lack of data concerning the cable's end-of-life prevents us from assessing the carbon footprint of this phase. Thus, the carbon footprint of fiber-optic cable only includes the manufacturing phase, which also includes cable installation.

In [11], the emission factor for the manufacturing of ACOME's 96-core optical fiber cables is $1,269.6\ kg\ CO_2\ eq./km$ with $25\ years$ lifetime. In 2020 [26], $5\ bn\ km$ of fiber-optic cable were deployed worldwide for a global

[8]https://www.microsoft.com/en/microsoft-teams/group-chat-software

Internet traffic of 59 ZB [1]. Using the calculation methodology presented in Table 4, we obtain a carbon footprint per GB of a fiber-optic cable of 4.31e−03$kg\ CO_2\ eq./GB$.

In the context of RENATER, the network comprises $12,000\ km$ of fiber-optic cables transferring 490,000,000 GB of traffic per year using a single pair of fibers on a 96-wire cable. [11] therefore divided the ACOME emission factor by 48 to obtain the impact of the fiber pair and obtained a carbon footprint of 2.59e−05 $kg\ CO_2\ eq./GB$.

The ratio between the carbon emissions of the overall fiber-optic network and those of the RENATER network is much higher than the divisor that autors of [11] have used to assess the impact of RENATER's optical fiber pair (Table 7). This means that using RENATER's value would be optimistic. However, for reasons of data consistency and to limit the use of extrapolation, for this study, we use a cloud optimistic scenario in which the RENATER fiber-optic network emission factor applies.

Table 7: Carbon Footprint of Optical Fiber Cable

$kg\ CO_2\ eq./GB$	Use	Manufacturing	End of Life	Total
Global Internet Network	N/A	4.31e−03	N/A	4.31e−03
RENATER Network	N/A	2.59e−05	N/A	2.59e−05
Ratio Global/RENATER		166.15		

5.3 Shelters

Shelters are network components that host optical transport equipment for amplifying optical light signals. In [11], authors assess the carbon footprint of 10 shelters of the RENATER network with direct measurement of traffic, energy consumption and by using manufacturers' LCA products information. Table 8 shows the results detailing the carbon footprint of each shelter and the average.

Table 8: Carbon Footprint of RENATER's Shelters

ID	Carbon Footprint ($kg\ CO_2\ eq./GB$)
Shelter 1	3.36e−05
Shelter 2	3.16e−05
Shelter 3	3.16e−05
Shelter 4	2.54e−05
Shelter 5	2.54e−05
Shelter 6	2.54e−05
Shelter 7	1.85e−05
Shelter 8	1.85e−05
Shelter 9	1.85e−05
Shelter 10	1.85e−05
Average	2.47e−05

The study tells there is one shelter every 80 km to 120 km of fiber-optic cable. In this study we use a cloud optimistic scenario where there is one shelter every 120 km with an average carbon footprint per shelter of 2.47e−05 $kg\ CO_2\ eq./GB$. This value takes into account all phases of the product life cycle, with the exception of the shelter's end of life (Table 9).

Table 9: Carbon Footprint of Shelters

$kg\ CO_2\ eq./GB$	Use	Manufacturing	End of Life	Total
Shelter	2.47e−05		N/A	2.47e−05

5.4 Internet of Edge Platform

The Internet of Edge platform (IoE platform) is an electronic device half the size of an Internet access router. It connects to neighboring IoE platforms to form a wireless mesh network, and embeds servers to deliver digital services to its users. The digital infrastructure created by IoE platforms, known as the Internet of Edges, replaces cloud-based and edge-based infrastructure, by routing integrated digital application traffic peer-to-peer, from source to destination, bypassing other digital infrastructures.

To assess the carbon emissions of an IoE platform, we assume that the manufacturing, end of life and total lifespan of the product are identical to those of an Internet access router, and that only the energy consumption and traffic volume per product change.

The carbon footprint of manufacturing and end of life of an IoE platform can therefore be estimated at $4.93\text{e}{-04}\ kg\ CO_2\ eq./GB$, the same as for an Internet access router. The carbon emission linked to the use of an IoE platform is calculated using Equation 3 and the following traffic and energy consumption metrics. The IoE platform features $7\ W$ energy consumption 24/7, which represents an energy consumption of $61.32\ kWh$ per year. PUE value is 0. The volume of traffic transferred by an IoE platform is more important than a regular Internet access router as it transfers the vicinity traffic of neighboring users. The average traffic of the IoE platform can be estimated as follow:

- High hypothesis: we estimate at $100\ MB/s$ the data consumption during 12 hours per day, representing a traffic of $1,576,800\ GB$ per year.
- Low hypothesis: the average Internet consumption of a fix Internet user in France is $220\ GB$. According to [1] 40% of Internet traffic could be handled locally ($88\ GB$). An IoE platform may transfer the traffic of 30 neighboring IoE platforms. Total traffic of an IoE platform could be $220\ GB$ + ($88\ GB$ x 30) = $2,860\ GB$ per month and $34,320\ GB$ per year.
- Medium hypothesis: we take the average between the high and low hypothesis leading to $805,560\ GB$ per year.

Based on the above mentioned traffic, energy consumption, and PUE values assumptions, and using Equation 3, the carbon footprint of an IoE platform is $8.22\text{e}{-06}\ kg\ CO_2\ eq./GB$. The total carbon Footprint of an IoE platform, taking in account all phases of the product life cycle, is $5.01\text{e}{-04}\ kg\ CO_2\ eq./GB$ (Table 10).

Table 10: IoE Platform Carbon Footprint

$kg\ CO_2\ eq./GB$	Use	Manufacturing	End of Life	Total
IoE Platform	8.22e−06	4.93e−04		5.01e−04

5.5 Cloud and Edge Servers

In this section, we evaluate the carbon footprint of a video-conference server located in a cloud or at the edge. We therefore compare the specifications of a Jitsimeet video-conference server and an IoE platform with the products of our data set. The aim is to identify the data set that best fits our case study.

Specifications of IoE platforms [27] and Jitsimeet server small organization [28] are detailed in Table 11. We add on the table the specifications of servers of the RENATER network studied in [11] and those studied by the NegaOctet consortium [24] and indicate their respective carbon footprints in Table 12.

Table 11: Servers Specifications

Source	Processor (Nbr. core)	vCPU (=core x 8)	RAM (GB)	Disc (GB)
Jitsimeet	4	32	4	20
IoE Platform	2	16	0.512	
RENATER servers	1.2	9.52	67.68	175
NegaOcted (medium VM)	1	8	32	nc
NegaOcted (large VM)	6	48	192	nc

Table 12: Servers' Carbon Footprint

Source	Carbon Footprint
RENATER	5.42e−06 $kg\ CO_2\ eq./GB$
NegaOcted (medium VM)	3.80e+01 $kg\ CO_2\ eq./year$
NegaOcted (large VM)	1.80e+02 $kg\ CO_2\ eq./year$

According to Table 11, NegaOctet's large VM is oversized in processor capacity, CPU, and RAM. Their medium VM is undersized in processor and CPU while RAM is oversized. RENATER VMs' processor capacity and CPU are undersized while their are oversized in RAM and Disc. On the one hand, RENATER's data is based on the product references of 10 servers hosting 800 VM to obtain an approximate value for 2 VM. Although, Negaoctet's functional unit, that is expressed in $kg\ CO_2\ eq./year$, would need to be converted in $kg\ CO_2\ eq./GB$ with assumption of yearly traffic as per the formulas in Table 4.

Because the above described dataset is not specific to our use case and to avoid too many extrapolations. we take RENATER's data as reference for the cloud-based server (Table 13). For the edge server's carbon footprint we consider the emissions of the cloud server to which we remove the PUE value and apply a penalty of 80% due to the lack of optimization of edge server compared to cloud one. These values take into account all phases of the product life cycle with the exception of end-of-life.

Table 13: Cloud and Edge Servers Carbon Footprint

$kg\ CO_2\ eq./GB$	Use	Manufacturing	End of Life	Total
Cloud Server	5.42e−06	6.64e−09	N/A	5.42e−06
Edge Server	5.42e−06	1, 20e−08	N/A	5.43e−06

6 Results

Depending on whether it's based on the cloud, the edge or the Internet of Edges, a digital infrastructure will take the data on longer or shorter routes. These routes involve various types of equipment, the quantity of some of which increases with distance. The carbon footprint of a route is the sum of the carbon footprint of all the equipment used on the route. The following section gives the carbon footprint results of the routes created by each type of digital architecture, and compares them according to the scenarios defined in the scope of the study.

6.1 Scenario 1 : Cloud vs Edge Digital Infrastructure

The $scenario$ 1 assesses and compares the carbon footprints per GB of the routes created by a cloud-based video-conference system, the $long\ route$, with those created by an edge-based system, the $short\ route$.

6.1.1 Carbon Footprint of Cloud-Based Digital Infrastructure

Figure 4 shows the total carbon footprint of the $long\ route$ created by a cloud-based video-conference system (route $[bac]$ on Figure 2), with regards to the routing distance. It shows that the total carbon footprint of transmitting 1 GB of data between two users over fiber-optic network and a cloud server increases linearly from 8.37e−03 to 1.65e−02 $kg\ CO_2\ eq./GB$ for routing distances varying from 1 km to $40,000\ km$.

Given the Internet routing circuitousness and the triangle proprieties, two users carrying out a video conference using a cloud server located 33 km away from both of them (geographic distance between cloud and user) will generate a total route length of 120 km using Formula 14 with a Circuitousness Ratio (C) of 1.8. This digital infrastructure will generate 8.40 $g\ CO_2\ eq.$ per GB transferred.

$$\text{Routing Distance } (km) = \text{Geographic Distance Cloud to User } (km) \text{ x } C \text{ x } 2 \quad (14)$$

The same video-conference performed with a cloud re-located $11,000\ km$ away from both users (nearly $40.000\ km$ routing distance) is going to generate 16.5 $g\ CO_2\ eq./GB$. Considering now a case study where two users located in Paris are carrying out a video-conference using a server based in San-Francisco. San Francisco being $9,000\ km$ away from Paris, the routing distance of this communication will be $32,400\ km$ and generate a carbon footprint of 15.00 $g\ CO_2\ eq.$ per GB transferred.

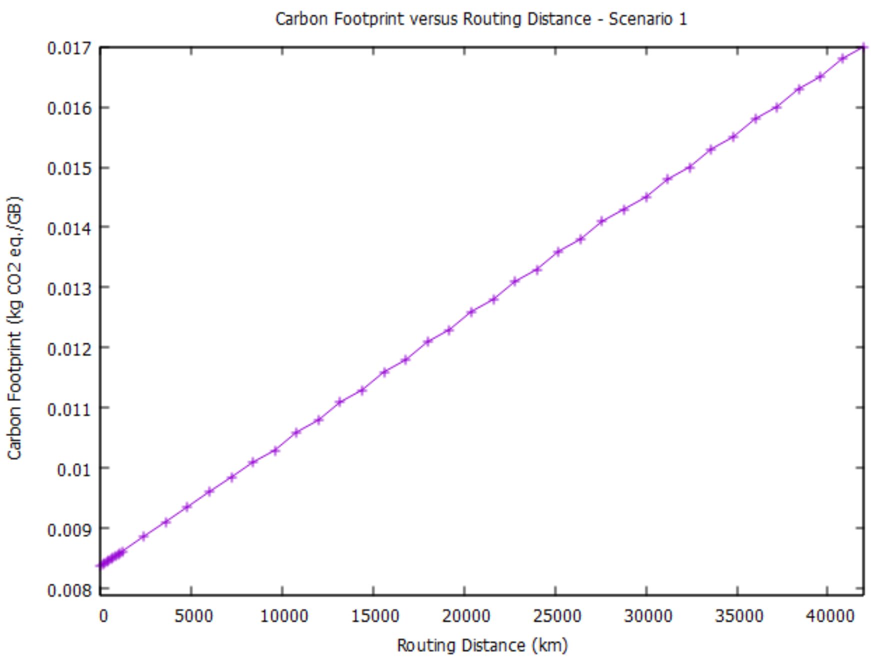

Figure 4: Carbon Footprint of a Cloud-Based Video-Conference System as a Function of Routing Distance of the $Long\ Route$

Figure 5 shows the share of each type of equipment in the total carbon footprint of the $long\ route$. We can see that the share of Internet access routers decreases with the routing distance in favor of shelters, while the impact of the cloud server and optical fiber is negligible. For a video-conference between two users in Paris using a server based in California, Internet access routers and shelters contribute respectively 55 % and 44.5 % to the total carbon footprint of the route, and are equal when the route length reaches $40,000\ km$.

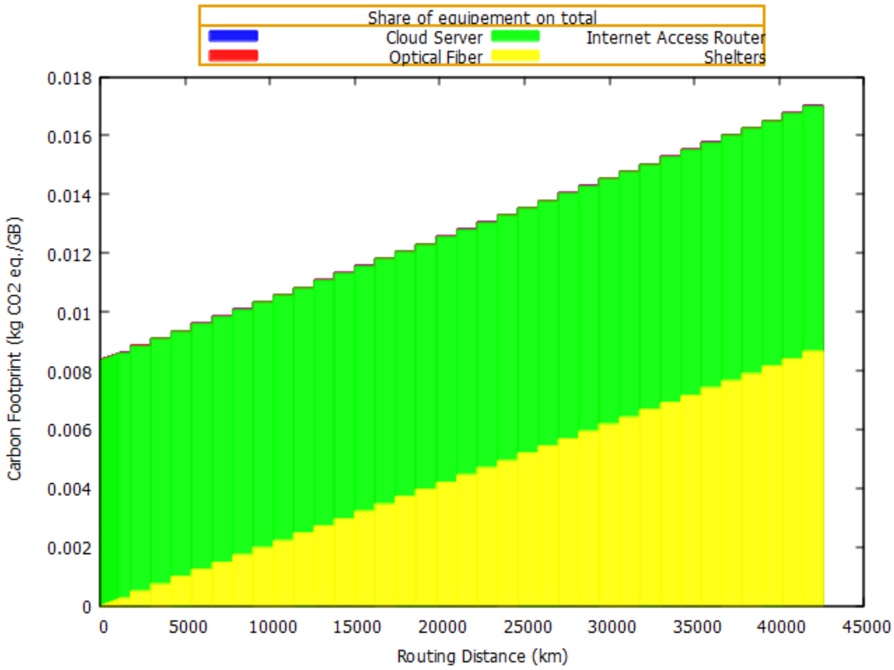

Figure 5: Share of Equipment on the Total Carbon Footprint of the $Long\ Route$

6.1.2 Comparison with Edge-Based Digital Infrastructure

We now compare the carbon footprint of the $long\ route$ with an alternative, called the $short\ route$, that consist in the direct route between users bypassing the cloud, using an edge server instead. Results of the carbon footprint ratio ($CF\ Ratio$) between the $long\ route$ and the $short\ route$ using Formula 12 is provided in Figure 6 according to a route ratio (R) between the length of $long\ routes$ and the length of $short\ routes$ obtained with Formula 11.

We can see that the carbon footprint ratio is always nearly equal or > 1. This means that the carbon footprint of the $long\ route$ is always greater than that of the $short\ route$ except when the length of the two routes is equal ($R = 1$). The carbon footprint of the $long\ route$ is then slightly lower ($CF\ Ratio = 0.99$) due to the penalty applied to the carbon footprint of the edge server, assuming it is less optimized than the cloud one.

The carbon footprint ratio increases with the route ratio - as we move the cloud server further away from users. Video-conferencing between two users apart of $120\ km$ using a cloud-based system with a routing distance twice as long as the direct route between the users ($R = 2 = 240\ km$ route length) will have a carbon footprint ratio of 1.006. This means that users generate 0.6 % more greenhouse gases by using a cloud-based system which sever is located $66\ km$ away from them (Geographical distance between

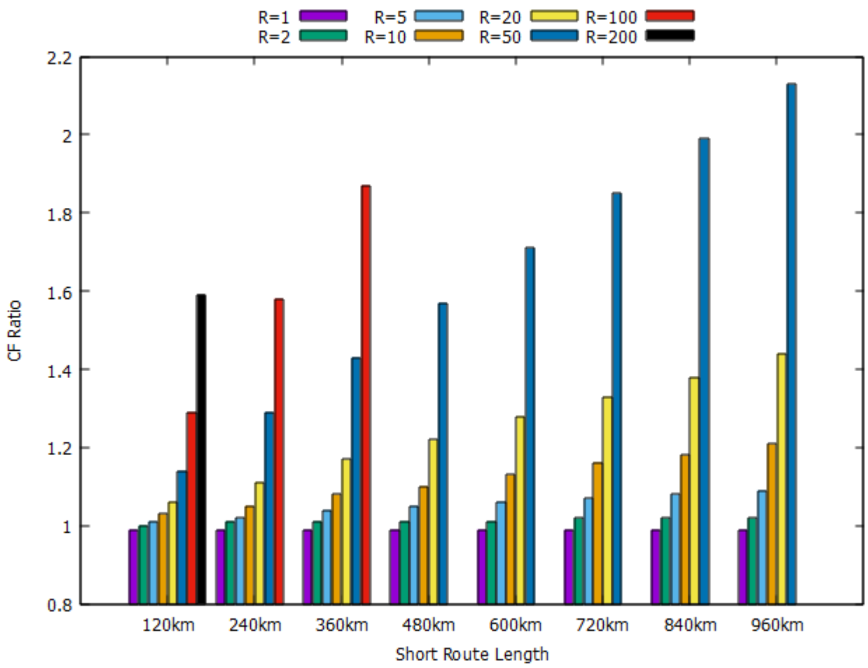

Figure 6: Results of Carbon Footprint Ratio ($CF\ Ratio$) as a Function of the Route Ratio (R) and the $Short\ Route$ Length

cloud and user) than if they used an edge-based system. Relocating the cloud server to a route length 100 times longer than the direct route ($12,000\ km$ routing distance) will increase the carbon footprint ratio to 1.3. This means that users will produce 30% more greenhouse gases using a cloud servers located $3,300\ km$ away from them than when using an edge-based system. Moving the cloud server even farther at $10,000\ km$ ($36,000\ km$ route length, $R = 300$) will raise the carbon footprint ratio to 1.88. Thus, the two users using a far away cloud-based system will generate $88\ \%$ more greenhouse gases than if using an edge-based system. In the scope of our study, limited to a routing distance of $40,000\ km$, the maximum overhead of the cloud relative to the edge is 1.99. This occurs when two users $840\ km$ apart hold a video-conference using a cloud-based system with a routing distance 50 times longer than the direct route between users.

This threshold can be explained by the impact of Internet access routers. We saw earlier that Internet access routers accounted for $50\ \%$ to $99\ \%$ of the total impact of the route, depending on its length. The other half of the impact is mainly due to shelters, the quantity of which varies according to distance. This means that using an edge-based system reduces the impact associated with the long journey of data to the cloud, but does not reduce the non-compressible impact of Internet access routers.

6.1.3 Nearby Users Case Study

Figure 7 analyses the carbon footprint ratio with regards to the geographic distance between users and the cloud server when the two users are $1\ km$ apart.

We can see that as soon as the cloud server is located $56\ km$ away from the users and more (geographic distance between cloud and user) the advantage of the edge become obvious. Two nearby users $1\ km$ apart using a cloud server located $140\ km$ away (geographic distance) to carry out a video-conference

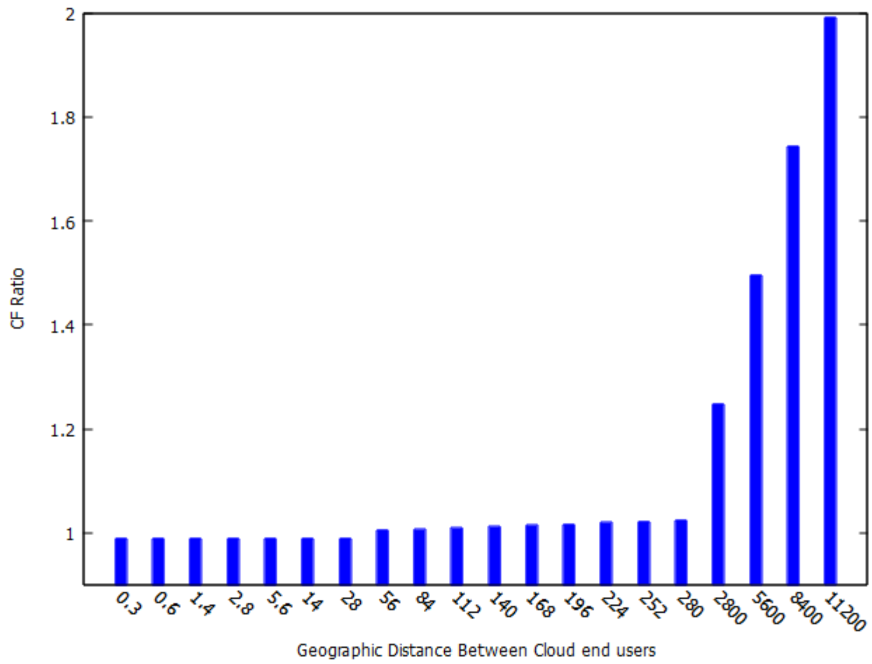

Figure 7: Results of Carbon Footprint Ratio ($CF\ Ratio$) as a Function of the Geographic Distance Between Cloud and Users when Users are 1 km Apart

will generate 1.2 % more greenhouse gases than using an edge-based system. Moving the cloud server further away, to $8,400$ km (next to popular videoconferencing servers in our measurements) will generate 74.4 % more greenhouse gases than an edge-based system.

6.1.4 Scenario 1 Conclusion

To conclude on the first scenario, the total carbon footprint of a route between two Internet host increases with the routing distance. Internet access routers account for the majority of the total impact of the route but the share decreases with the route length down to 50 % in favor of other equipment, the quantity of which varies with distance (e.g. shelters). Detours to cloud servers for videoconferencing increase the length of the itinerary and therefore the carbon footprint per GB transferred. Switching to an edge-based system reduces route length and therefore the carbon footprint per GB transferred. The study unveils that using edge-based systems to carry out a video-conference between two users is always almost equal to or better than using a cloud-based system in terms of carbon footprint, regardless of the location of the cloud. Edge-based systems become considerably better than cloud-based systems, further we move the cloud server 56 km or more away from the users. If two nearby users, 1 km apart, set up a video-conference using a cloud server located $8,400$ km away, like some popular videoconferencing services, they will produce 74.4 % more greenhouse gases than if they used an edge-based system instead. Within the scope of the study, which is limited to a maximum routing distance of $40,000$ km in the European and North American Regions, the carbon footprint of edge systems is at best half that of cloud systems due to the incomprehensible impact of Internet access routers.

6.2 Scenario 2: : Cloud vs Internet of Edges Digital Infrastructure

The $scenario$ 2 assesses and compares the carbon footprints per GB of the routes created by a video-conference system based on the Internet of Edges, the $short\ route$, with those created by a cloud-based system, the $long\ route$.

6.2.1 Carbon Footprint of a Digital Infrastructure Based on the Internet of Edges

Figure 8 shows the total carbon footprint of the $short\ route$ (route $[bc]$ on Figure 2), when the route passes over a wireless multi-hops Internet of Edges (IoE) network. The carbon footprint is represented with regards to the number of wireless hop on the route. We can see that the carbon footprint of the $short\ route$ via an IoE increases linearly with the number of wireless hop. This is because each additional wireless hop is an additional IoE platform on the route. Thus, the carbon impact of IoE is of $1.00\text{e}{-3}\ kg\ CO_2\ eq./GB$ for a 1 hop network and $1.80\text{e}{-2}\ kg\ CO_2\ eq./GB$ for a 35 wireless hops network.

Two nearby users, located $1\ km$ apart, taking part to a video-conference, will use a 8 wireless hops IoE network to communicate (Formula 9) and generate $4.51\ g\ CO_2\ eq.$ per GB transferred. A cloud-based system, by way of comparison, would generate at best $8.37\ g\ CO_2\ eq.$ per GB (Figure 5), or $85.6\ \%$ more greenhouse gases emissions than the Internet of Edges. This is only possible if there is a direct route through the Internet's fiber optic backbone between the two users and the cloud server is located on this route.

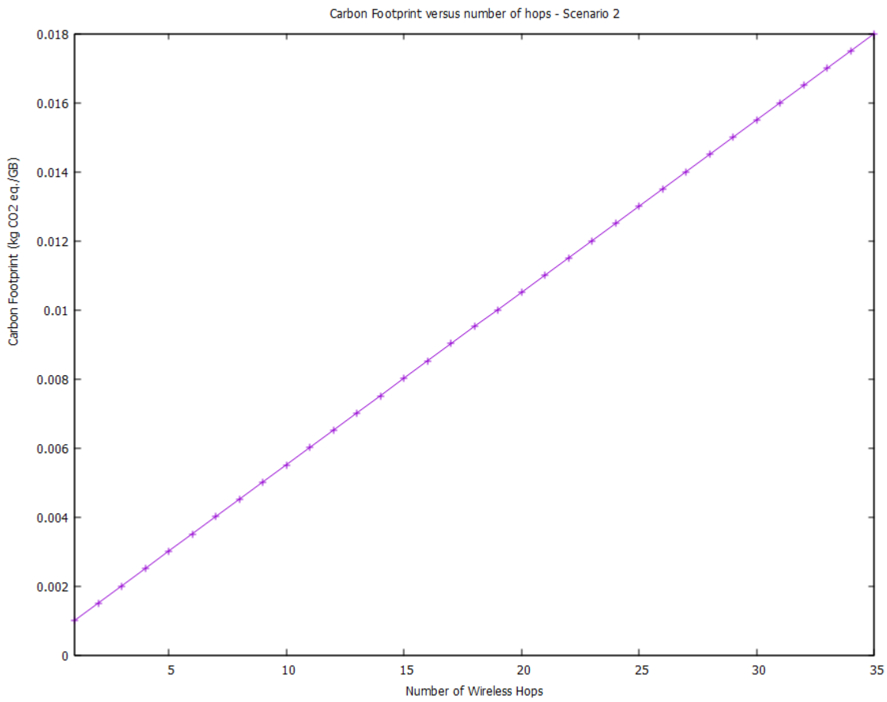

Figure 8: Carbon Footprint of $Short\ Route$ using IoE as a Function of the Number of Wireless Hops

6.2.2 Comparison with Cloud-Based Digital Infrastructure

We now compare the carbon footprint of the $short\ route$ using the Internet of Edges (IoE) with the $long\ route$ using an cloud server instead. Figure 9 gives the carbon footprint ratio ($CF\ Ratio$) between the $long\ route$ passing through clouds and the $short\ route$ using a wireless multi-hops Internet of Edges network while varying the length of the $long\ route$ and the number of wireless hops of the $short\ route$.

We can see that when the cloud is located at 1 to 133 km away from its users, into a regional cloud, and generates a routing distance up to 480 km between two users, the carbon footprint of their communications will equal that of a 15 wireless hops IoE network ($CF\ Ratio \geq 1$). With 15 wireless hops, IoE connects users located 1.7 km apart. This means that users located up to 1.7 km apart are better off using an Internet of Edges rather than a regional cloud system to achieve a video-conference with a lower carbon footprint. In the 0 to 1.7 km range, carbon footprint per GB of the Internet of Edges is up to 8.45 times lower than that of regional cloud systems ($1 \leq CF\ Ratio \leq 8.45$).

The cloud is now further away, 6,000 km from the users and generates a routing distance of 21,600 km between two users. This would be the case if two user located in France were to organize a video-conference using a cloud system based on the east coast of the United States. The carbon footprint of these transatlantic communications will equal that of a 24 wireless hops IoE network with a range of 2.6 km ($CFRatio \geq 1$) . Users in that radius communicating with an IoE will generate a carbon footprint per GB up to 12.8 times lower than if they were using an cloud-based systems located on the east coast of the United States ($1 \leq CF\ Ratio \leq 12.8$).

If the cloud is relocated 9,000 km away from users, on the west coast of the United States, generating a routing distance of 32,400 km between two users, the carbon footprint of their communications will equal that of a 29 wireless hops IoE network. A 29 wireless hops network connects users in a range of 3.1 km. Communications between users located in the 0 to 3.1 km range will have a carbon footprint up to 15 times lower than using a cloud-based systems located on the west coast of the United States ($1 \leq CF\ Ratio \leq 15$).

Withing the scope of this study, IoE emit up to 16.74 times less greenhouse gases than cloud-based system. This happens when two users located $\leq 300\ m$ from each are carrying out a video-conference using a cloud-based located 11,000 km away from users generating a 40,000 km route that is the upper limit of this study. The maximum Internet of Edges range beyond which it is more worthwhile to use a cloud-based system in terms of carbon footprint is 32 wireless hops or 3.4 km range. In an IoE network of this size, the carbon footprint is equal to that of a cloud-based system located 11,000 km from its users, or 40,000 km of routing distance.

6.2.3 Scenario 2 Conclusion

The aim is the second scenario was to estimate how many wireless hops it is more worthwhile to use an Internet of Edges rather than cloud-based systems. The study reveals that up to 15 wireless hops and 1.7 km range, it is always more advantageous to use an Internet of Edges than any cloud-based system in terms of carbon footprint, regardless of cloud location. The largest IoE network beyond which it is more worthwhile to use a cloud-based system in terms of carbon footprint is 32 wireless hops or 3.4 km range. In the meantime, we observe that the carbon footprint of the Internet of Edges is up to 8.45 times lower than regional cloud systems, up to 15 times lower than cloud-based systems when relocated across the Atlantic, and 16.74 times lower than the farthest cloud location studied.

7 Limit of the Study

Several factors mean that the carbon footprint of Internet core network is underestimated. The study excludes impacts due to network routers even though they contribute to a large portion of the carbon footprint of a route - 4 times the share of shelters in the study of the RENATER network [11]. Impacts due to the end of life of most equipment are missing such as optical fiber and shelters. Distance between shelters has been set at 120 km, the longest distance in [11]. We use the smallest carbon footprint value

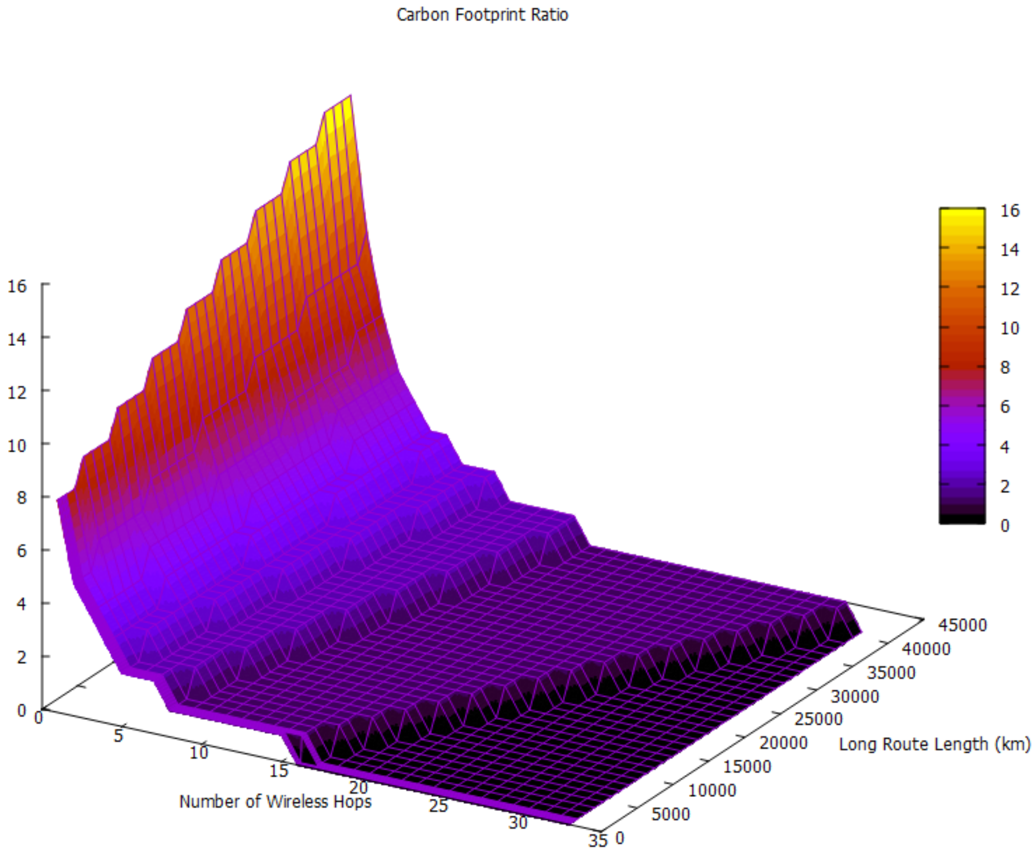

Figure 9: Carbon Footprint Ratio Between the $Long\ Route$ to Cloud and the $Short\ Route$ using IoE as a Function of the $Long\ Route$ Length and the Number of Wireless Hops of the $Short\ Route$

for optical fiber proposed by [11] rather than the large value of the Global Internet Network (166 times smaller). Data center efficiency was assumed to be total, whereas in reality it is around $20\ \%$. Other factors mean that the carbon footprint of the edge is overestimated. A penalty of $80\ \%$ was applied to the edge server considering it was less optimized than the cloud one. The Internet of Edges has been studied as an additional device to be deployed next to users, which is the least favorable scenario in terms of carbon footprint. The study compares the Internet of Edges to the fixed Internet made of optical fiber that is the least energy consuming Internet network - 2.5 times as energy efficient as mobile 5G when streaming a video for one hour and 5G as much as 85% more energy efficient per Gigabit transmitted than previous generations [7]. Further studies could compare the impact of the Internet of Edges to mobile networks. We could also examine the impact of the Internet of Edges as software integrated directly into end-devices rather than as an additional device. Last but not least, the study takes into consideration a maximum routes length of $40,000\ km$ through the European and North American regions. Today, many digital services are provided by companies located in the Asia-Pacific region, resulting in longer routes with a higher circuitousness ratio.

8 Conclusion

In this study, we have estimated and compared the carbon footprint of transferring 1 GB of data between two users performing a video-conference via three types of digital infrastructures: cloud-based, edge-based, and an infrastructure based on the Internet of Edges. To do this, we have implemented a simplified LCA methodology that takes into account, as far as possible, all the equipment involved in a route from a transmitting user to a receiving user through clouds, edges and Internet of Edges and all phases of the equipment life cycle, from cradle to grave.

Results highlight the importance of route length on the total carbon impact of providing a digital service. The longer the route, the more equipment is used, increasing the carbon footprint of communications. In our study, the share of network equipment, the quantity of which varies according to the length of the route (excluding Internet access routers), can represent up to 50% of the total impact per GB of a communication. This should be seen in the light of the fact that the carbon footprint of routes across the Internet backbone is underestimated, and that the maximum route length is limited to transatlantic communications, thus avoiding longer routes through, for example, the Asia-Pacific region.

The study reveals the undeniable advantages of using alternative digital infrastructures such as the edge and the Internet of the Edge. These infrastructures reduce the length of the route between two Internet hosts, and therefore the carbon footprint per GB transferred. In our study, the use of an edge system can halve the carbon footprint per GB of videoconferencing compared with cloud-based systems. The even shorter circuits created by the Internet of Edges, which bypasses the Internet's core networks, emit up to 16.74 times less greenhouse gases than a cloud-based system when users are at vicinity, within a radius of 3.4 km.

The study uses the videoconferencing service as a reference. However, all Internet services are using the same cloud model where large data centers are hosting the servers of those services. By generalizing our study, we could conclude that mini-data centers on the edge and direct communications via the Internet of Edges are promising solutions for reducing the impact of digital services on our environment.

The study provides a better understanding of the role of digital infrastructure on the carbon footprint of digital service provision, which can help to design system that deliver low-carbon digital services. The study also shows that the Internet of Edges is a credible alternative for delivering vicinity traffic with low carbon impact. To complete our study, we could compare the impact of the Internet of Edges to energy consuming mobile networks and examine the Internet of Edges as software integrated directly into end-devices rather than as an additional device.

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