Toward Eco-Design of a 5G mmWave Transmitarray Antenna Based on Life Cycle Assessment

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***Abstract*—5G is seen as one technology enabler to support the expected exponential internet data-traffic growth while digitization environmental impacts are growing. Base stations are estimated to represent the main contributor to mobile internet access network carbon footprint. In this work, life cycle assessment (LCA) of a 26 GHz transmitarray antenna is described taking into consideration the geographical location of the antenna use and providing eco-design leads to researchers, designers, LCA practitioners and industrials. Results show that energy consumption during operation is the main source of impact (between 72% and 94% for most impacts), while the material depletion is largely generated by the manufacturing process (99.3%). As a result, the eco-design must focus on product energy efficiency as well as material depletion during manufacturing. The impact of usage is highly dependent on the location due to the diverse electricity mix of countries. An eco-design solution using phase-change material (PCM) technology switches is compared to a conventional approach using GaAs p-i-n diodes. These results pave the way for reducing the impacts of transmitarray antennas and are a first step towards more sustainable solutions for millimeter wave (mmWave) networks.**

Keywords— Life cycle assessment (LCA), transmitarray, antenna, electronically steerable antenna, eco-design, 5G, mmWave, small-cell

I. Introduction

While IP traffic is exponentially growing, wireless and mobile network data is steadily increasing and expected to reach 71% of global IP traffic by 2022 [1]. 5G is expected to be the major key enabler of this transformation [2] because it offers high-capacity wireless transmission thanks to the use of millimeter-wave (mmWave) in the frequency bands from 20 to 52.6 GHz. Despite the large available bandwidth potential, mmWave signal transmissions suffer from technical challenges that could be tackled thanks to the design of electronically steerable high gain antenna [3]. Among antenna technologies that exist, transmitarray antennas are potential candidates [4]. This kind of antenna can be deployed as small-cells for 5G enhanced mobile broadband (eMBB) applications. They feature real-time beamforming capabilities in order to provide high Signal to Noise ratio (SNR), high data throughput and low electromagnetic field (EMF) exposure. Even if no power amplifier are integrated on the array elements, they are active antennas (meaning consuming power) whereas the previous mobile generations were using passive antennas (meaning no power consumption) with fixed aperture. The benefit of this added power consumption lies in the better efficiency of radio frequency (RF) power use, led by the directivity gain provided by active antennas.

Many reviewed studies pointed out the growing impact of digitization and information and communication technologies (ICT) [5], [6], [7] and [8]. According to [6] and [9], 2020 ICT carbon footprint is estimated to represent today between 2.6 to 3.6% of global carbon emissions and at least 6.4% of the world energy, with a high disparity depending on the country electricity mix. At global scale, [5], [6] and [9] agree that more than half of the ICT carbon footprint is due to ICT energy consumption in use phase and the rest is due to ICT manufacturing (embodied emissions). In 2015, mobile networks were estimated to represent more than half of global internet network carbon footprint, representing 25% of the global ICT carbon footprint [9]. Base stations have been identified as being the major contributor to power consumption of the mobile network in 2011 [10]. Ericsson and the French Haut Conseil pour le Climat warned that 5G will dramatically increase the energy demand and the digital carbon footprint unless necessary efforts are made [11], [12].

As mmWave antennas for 5G are part of the base station and may add environmental impacts to 5G global environmental footprint, we investigate potential solutions through eco-design. To the best of our knowledge, no studies provide eco-design leads for such antenna, most evaluated ICT goods being smartphones, TV and computers [13]. The goal of the proposed work is then to provide eco-design means for reducing the impacts of a transmitarray. Life cycle assessment (LCA) of a 26 GHz electronically steerable transmitarray antenna based on GaAs (gallium arsenide) p-i-n diodes is presented taking into consideration the antenna use location. Example of an eco-design solution using GeTe (germanium telluride) switches is compared to the current technology using GaAs diodes.

Main contributions of this work are:

- Provide LCA results of a transmitarray on a variety of impact categories
- Provide eco-design leads
- Demonstrate the value of eco-design in the early stages of product or technology design

The paper is organized as follows. First, LCA methodology is explained in section II detailing in particular the scope and life cycle inventory (LCI). Then the results and their interpretation are exposed section III with a focus on location influence. Section IV presents the sensitivity analysis based on three parameters. Section V is a discussion on the limits and validity of the results. At last, we will conclude in section VI.

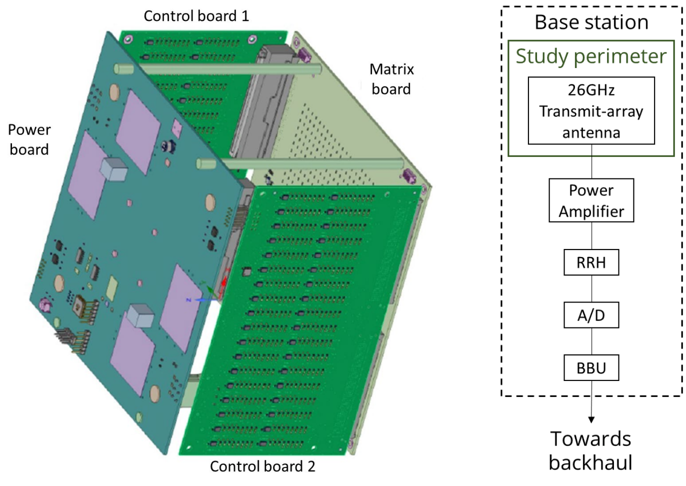
II. Methodology

A. Life Cycle Assessment (LCA) methodology

This study is based on LCA methodology complying with international standards ISO 14040 & 14044. It follows most of the European Product Environmental Footprint (PEF) method [14] and considers the L.1410 standard for LCA of ICT goods [15]. EIME software version 5.9.3 is considered to perform the life cycle impact assessment (LCIA) of the study. LCIA characterization models are from PEF method version EF3.0. The used databases are CODDE version 2020-12 and ELCD version 3.0.

B. Scope of the study

The studied system depicted in Fig. 1(a) is an electronically beam-steerable transmitarray antenna operating at 26 GHz requiring a specific antenna design. The antenna aperture (matrix board) is composed of 24×24 elements, commonly called unit cells. It consists of a printed circuit board (PCB) containing 1152 microstrip patch antennas (see [4] for more details) equally distributed on the top and bottom layers of the board. To perform the electronic beamforming, two AsGa p-i-n diodes are integrated on each patch antenna. Therefore, a unit cell is based on two microstrip patches and four p-i-n diodes. The transmission phase of each unit cell is electronically controlled (four phase states with 90° of relative phase shift) by opportunely switching the four p-i-n diodes, which are biased with two independent bias lines. Two steering logic PCBs (control board) are used. The power board supplies the energy. The boards are wired and attached with screws. In total, the system is composed of more than 5,000 components. The considered system is a prototype where product packaging is excluded. Consequences of using a prototype are discussed in section V. The antenna is a small part of a mobile base station (Fig. 1(b)), its function is to transform RF power into electromagnetic power and vice versa.



(a) (b)

Fig. 1. (a) Studied transmitarray antenna. (b) The system perimeter represents a small part of a base station. RRH: Remote Radio Head, A/D: Analog-Digital converter, BBU: Base Band Unit.

The Functional Unit (FU) is the reference unit of the study and is used for comparison between studies. It is defined as "Convert electrical energy into an electromagnetic wave at 26GHz (and the other way around) with an angular radius of +/-60° and 27dBi gain for 10 years in France". The Reference flow is one antenna.

Fig. 2 depicts the system boundaries that contains raw material acquisition, transportation of the materials, manufacturing of the components, system assembly and use stage. They represent steps A, B1.1, B1.2 and C1 from ITU L.1410 standard. Life cycle is split into manufacturing and use stages. System distribution, intermediate transportation steps, installation and end-of-life are excluded. Some scenarios were evaluated to perform sensitivity analysis to verify the consistency of these excluded stages. Most studies consider transportation to be insignificant, which seem correct as long as it is not by mean of air freight [13]. We considered a 10,000 km container ship scenario to confirm the numbers. End-of-life scenarios in France have been considered using formal recycling processes. Both led to small influencing results that validates the exclusions: respectively <1% and <2% for the complete life cycle. However, as informal ICT waste management is unknown, the end-of-life impacts are probably underestimated [13]. A 50 km passenger car scenario is used to install the antenna, resulting in a contribution of up to 10% for a particular impact category. It is thus likely that the installation phase has a significant influence, but this stage is excluded because of lack of data.

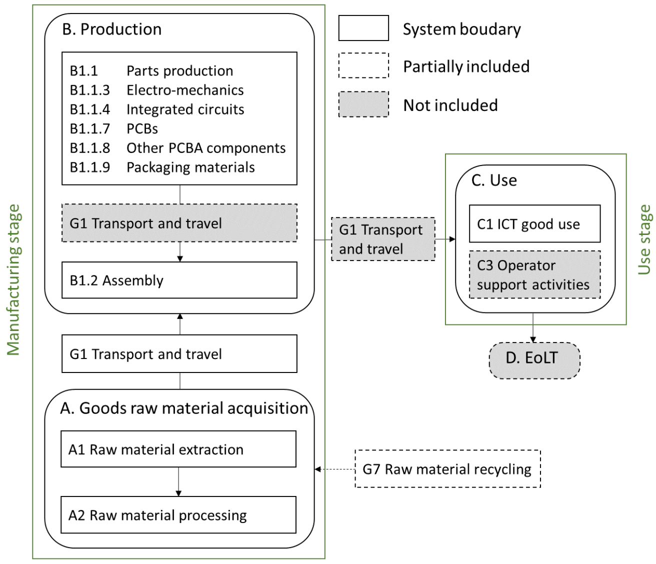


Fig. 2. System boundaries according to ITU L.1410 standard [15].

C. Impact categories

A limited selection of impact categories is taken into account as described into table I. This selection is based on suggestions from [16] and ADEME French environmental agency Product Category Rules (PCR) on digital services [17].

D. Life cycle inventory

Both primary (directly coming from measurements or manufacturer) and secondary data (generic data or hypothesis) are used. Main sources of primary data come from specifications and bill-of-materials. Secondary data are mainly coming from CODDE electronics database and a few data originate from ELCD database. Such LCI databases provide aggregated data representing a range of technology at a certain time and specific geographic location. Data collection efforts are put for key components: either primary data or adapted secondary data were used to best fit the actual situation.

The synthetized LCI is provided in table II. Literature informs us that integrated circuits (ICs), PCB and gold must be of prior attention for manufacturing [13], such secondary data are adjusted accordingly for a selection of parameters. Details are provided below in II.D.1) and II.D.2).

TABLE I. LIST OF IMPACT CATEGORIES

Acronym	Impact category	Unit	ILCD Level[a]
ADPe	Resource use, minerals and metals	kg SB eq.	III
CTUe	Ecotoxicity, freshwater	CTUe	III
CTUh-c	Human toxicity, cancer	CTUh	III
CTUh-nc	Human toxicity, non-cancer	CTUh	III
GWP	Climate change	kg CO2 eq.	I
IR	Ionising radiation, human health	kg U235 eq.	II
WU	Water use	m3 eq.	III

[a]ILCD level represents methods quality, there are classified as level I: recommended and satisfactory, level II: recommended but in need of some improvements, level III: recommended but to be applied with caution.

TABLE II. ANTENNA SYNTHETIZED BILL OF MATERIALS

Part	Mass (g)	Area (cm²)	Nbr[a]
Power board			***1***
ICs	1.2	-	8
Others (resistors, capacitors etc.)	242.7	-	64
PCB	-	324	1
Command board			***2***
ICs	4.9	-	653
Others (resistors, capacitors etc.)	91.2	-	674
PCB	-	198	1
Matrix board			***1***
ICs	0.5	-	2306
Others (resistors, capacitors etc.)	15.9	-	16
PCB	-	324	1
Total	***726.0***		***5056***

[a]Nbr: number of items based on one board. PCB surface is used for modeling.

1) Manufacturing stage

The manufacturing stage is composed of material acquisition (A), component manufacturing (B1.1) and assembling (B1.2). Primary data from antenna design are: specifications, system composition and component references. PCB manufacturer provided metal deposition thickness and finishing manufacturing process. Transportations related to the material extraction stage are included into the CODDE database. The assembling phase (B1.2) is exclusively associated to the soldering process. Some secondary data are adjusted with primary data in order to better fit the antenna: PCB finishing gold mass, ICs gold content and mass of the components. The rest of components and manufacturing processes are based on secondary data provided by CODDE database. No details are provided about raw material transportation. It is unknown if processes and components are using virgin or recycled materials. The manufacturing yield is unknown and not taken into account.

According to [18], material composition of transistors and diodes have a high impact on the LCA results, especially gold content. That is why a simple “material approach” is considered when primary and secondary data are not available or not satisfying (this approach excludes manufacturing processes (B)). It considers the material declaration of a product as the main source of LCI information. Example of product declaration is IPC-1752B standard. As a result, only the extraction (A1), processing (A2) and transportation (G1) of the material are considered. The databases used for material approach LCI are CODDE and ELCD. Only three sets of components were modelled this way (DC-DC 30W, DC-DC 1W and terminal assemblies).

Manufacturing location is mainly considered in China where the current major worldwide producers are located. In CODDE database some datasets are available only for Europe, which minimizes their impacts. Concerned datasets are connectors, capacitors and PCB manufacturing.

a) Mass of components: we weighted most contributing components (especially ICs) with a micrometric balance (precision up to 0.1mg). EIME provides generic masses for a list of packaged components that was used as secondary data for the remaining components. Most of measured masses were found close to the EIME list except for microprocessor STM32 (packaging LQFP64) which measured mass was 347µg against 960µg.

b) GaAs PIN Diode: there are more than 2,000 diodes out of 5,000 components, thus requiring special attention. The diode mass was measured to 213µg. The available dataset is a generic GaAs IC, which is not entirely satisfying. Gold content was thus adjusted to the minimum known gold mass provided by the Macom MA4AGP907 datasheet.

c) DC/DC converters 30W and 1W: a material approach with manufacturer IPC-1752 declaration was considered.

d) Mass of solders: the solder mass defines the impact of the process. Components are soldered to the PCBs with a 95.5% Sn, 3.8% Ag, 0.5% Cu solder paste. Processing differs between through hole and SMD (surface-mounted device) components. EIME also provides a table of solder mass for standard SMD components and packaged components. Most of the system solders were missing and estimated through a linear correlation between solder surfaces and masses.

e) PCBs: CODDE database provides datasets for PCBs depending on the number of layers and pre-impregnated material. A solder mask and a NiAu finishing are added. The gold finishing dataset was reduced by a 20-fold factor to represent the real amount of gold used. The nickel coating is based on CODDE nickel production dataset and an industrial coating processing.

2) Use stage

Use stage only accounts for one active consumption mode. Global electricity mix from ELCD database is considered. We have directly measured the system electricity consumption to 19.92W, representing 175kWh/year. Emergency diesel generator are out of the scope of the study but would be worth considering as their contribution seems not negligible [9].

III. Results & Interpretation

A. General results

Fig. 3 presents the main LCA results for the antenna assuming 10 years lifetime period over its complete life cycle in France. The use stage is the largest contributor for 5 of the 7 impact categories (see table I for acronyms definition): IR (94%), WU (88.7%), CTUe (87.6%), GWP (77.5%) and CTUh-nc (72%). The manufacturing stage is nearly the only contributor to the ADPe (99.3%) and contributes 63.6% to the CTUh-c. The major contribution of the use stage was expected as the product is turned on 24/7 for 10 years. Regarding GWP impact, 62.6 kg CO2e are necessary to manufacture the antenna and 217.0 kg CO2e for the 10-years use stage leading to a total amount of 280 kg CO2e over its complete life cycle.

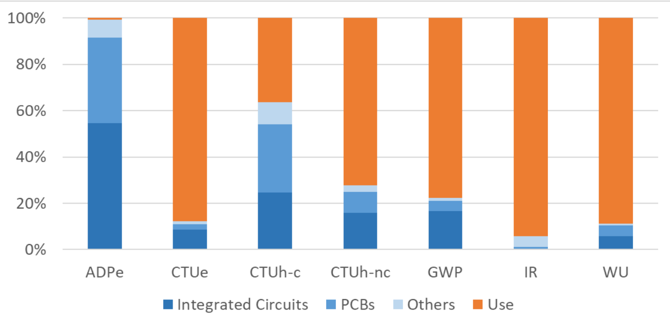


Fig. 3. LCA results of the transmitarray antenna. 100% represents the complete life cycle (manufacturing + use). “Others” category is composed of connectors, solders, resistors and capacitors.

Fig. 4 details the manufacturing stage split into integrated circuits (ICs), printed circuit boards (PCBs) and “Others” composed of connectors, solders, resistors and capacitors. ICs are the main contributors to the manufacturing stage for the GWP (74%), CTUe (71%), CTUh-nc (57%), ADPe (55%), and WU (51%). PCBs contributes to 58% for CTUh-c, and 42% for WU. Regarding manufacturing stage, gold is the major contributor to ADPe (84%). It is present into ICs (50%) and onto PCB surface finishing (30%).

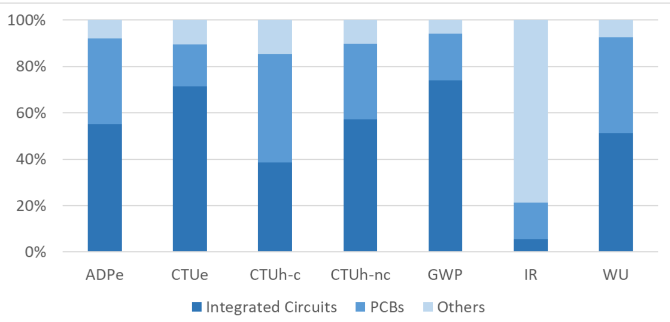


Fig. 4. LCA results of the transmitarray antenna. 100% represents the complete manufacturing stage. “Others” category is composed of connectors, solders, resistors and capacitors.

B. Country scenarios

Geographic location is known to have a strong influence on the quantification of the impacts due to country electricity mix. Fig. 5 depicts antenna life cycle impacts with different use stage location. Impacts range from a 7-fold increase (GWP and CTUh-c in China) to 13-fold decrease (IR in Brazil). ADPe impacts are unchanged because the use stage contribution is marginal. The 10-year use phase leads to 280 kg CO2 eq. in France against 1,850 kg CO2 eq. in China.

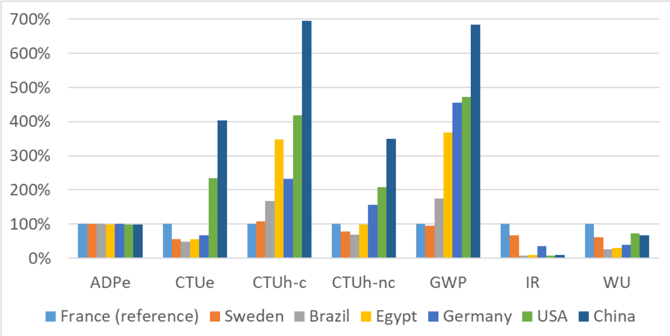


Fig. 5. Comparison of LCA results of the transmitarray antenna over its life cycle depending on use stage location.

C. Sensitivity analysis

Our sensitivity analysis focuses on three parameters:

i. Gold contained into the PCBs gold finishing,

ii. Number of GaAs diodes,

iii. Antenna lifespan.

(i) Gold represents the main impact of ADPe (84%) which is of interest when considering the reduction of manufacturing impacts. We focused on PCBs finishing gold thickness, which is directly related to its mass. It ranges from 0.05µm to 0.23µm reflecting the technological offer of the manufacturers. It represents about 30% of the ADPe. (ii) The number of GaAs diodes represents the prototype status of the product, as it is considered that the performances of an industrial antenna will be adjusted with a new design. The larger the matrix, the better the antenna gain and the larger the number of components. As a result, the number of GaAs diodes is directly related to the number of ICs, to the PCBs surface and to the electricity consumption that is greatly reduced. With a gain ranging from 23dBi to 30dBi, it leads to an antenna aperture ranging from 16x16 to 36x36 unit cells. (iii) Antenna lifespan ranging from 5 to 15 years is also studied to analyze the impact of failure.

Table III presents the sensitivity analysis of the three parameters for the complete antenna life cycle. Red color indicates an increase of impact while green indicates a decrease. It is to be noted that changing the number of diodes changes the FU as the antenna performances are changed. Other parameters variation is performed with a constant FU. We note that PCB gold finishing has influence only on ADPe. Considering the total antenna gold content would probably lead to more than a 2-fold influence ratio increase for ADPe impact as PCB gold finishing only concerns 36% of gold ADPe impact. Using recycled gold as input material is not considered, but can lead to significant ADPe impact reduction according to

[19]. Number of GaAs diodes strongly influences all impact categories, underlying the need for a precise dimensioning of the system. Lifespan reduction has a strong influence on ADPe and CTUh-c outlining the need to design time-proof products.

TABLE III. SENSITIVITY ANALYSIS ON 3 PARAMETERS

		ADPe	CTUe	CTUh-c	CTUh-nc	GWP	IR	WU
gold tk[a] (µm)	0.23	145%	100%	108%	108%	100%	100%	104%
	0.092	100%	100%	100%	100%	100%	100%	100%
	0.05	86%	100%	98%	98%	100%	100%	99%
Number of diodes[b]	36x36x4	186%	206%	198%	202%	206%	201%	205%
	24x24x4	100%	100%	100%	100%	100%	100%	100%
	16x16x4	62%	53%	57%	55%	53%	55%	53%
lifespan (years)	15	67%	96%	79%	91%	93%	98%	96%
	10	100%	100%	100%	100%	100%	100%	100%
	5	199%	112%	164%	128%	122%	106%	111%

[a]Gold finishing thickness. [b]Antenna aperture is multiplied by 4 to obtain the total number of diodes. Nb of diodes variation alters the FU. Others parameters do not alter the FU.

IV. ECO-DESIGN

From the LCA results and sensitivity analysis, several alternatives have emerged to reduce the antenna environmental impact. They are listed below.

i. Reducing use stage electricity consumption

ii. Reducing gold content and alternatively increasing the recycled gold share

iii. Increasing the lifespan

iv. Avoiding system over-dimensioning

Different technical solutions can be envisaged for the previous suggested eco-design routes. In this work we will focus on one eco-design solution aiming at (i). GeTe is a phase-change material (PCM) that consumes energy only when changing its phase, turning the switch on or off. GeTe switches technology thus brings drastic energy reduction during the use stage compared to GaAs diodes requiring constant power consumption. The drawback is that it can only perform a limited number of switchings. Thereafter the application considered is a backhaul link or Fixed Wireless Access (FWA) link that does not require real-time beamforming reconfiguration. It is a high-speed wireless data transmission link between two fixed and aligned antennas. It can be exploited to replace optical fiber in remote or difficult-to-access areas. Electronic beamforming can be used to realign antennas that lost alignment due to meteorological events, or to introduce flexibility in the network by allowing reconfiguration from one point to another. Considering these application cases, GaAs diodes based antenna is compared to another design based on CEA-Leti GeTe switches technology operated at 26GHz in the same way as [20]. Both antennas are compared to the same function described by the FU. Only antennas are compared while the rest of the system remain unchanged.

The only difference between the two designs relies on the soldered GaAs diodes, which are replaced with integrated GeTe switches. The antenna consumption is adjusted accordingly but the rest of the design is unchanged. One GeTe switch consumes 400mW during a 1µs commutation. Considering a hourly realignment the GeTe antenna design consumes an average of 874nW during a 10 year lifespan or 7.7 mWh/year. The GeTe switches modelling is limited to a material and energy approach because no manufacturing data are today available as the technology is still under development. Germanium LCIA data were provided by Umicore [21] considering Ge as a zinc co-product, they also offer an alternative and cleaner production from recycling. Tellurium LCIA is from ecoinvent. Fig. 6 illustrates the comparison between both technologies; the use stage impacts disappears completely for the GeTe based antenna. Part of the manufacturing stage is reduced for GeTe design, but this is mainly due to the lack of data about production stage. We note a minor reduction on ADPe that cannot be considered as representative.

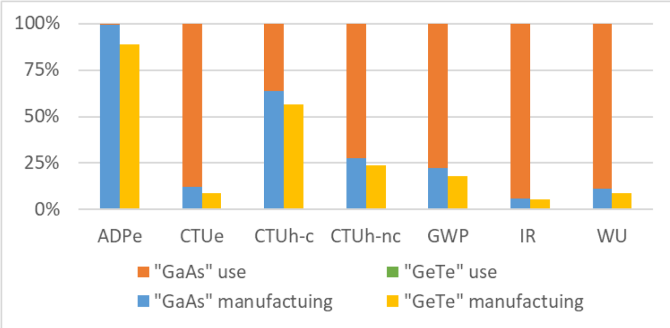


Fig. 6. Comparison between the GaAs diode technology and the GeTe switch technology over the antenna life cycle for a specific backhaul application case.

V. DISCUSSIONS

In this section, we discuss the limits and validity of the proposed study.

- The first limit is the use of a non-industrialized prototype that brings uncertainties and data gaps. The final industrial system could be largely different if it turns into an ASIC (application-specific integrated circuit). The sensitivity analysis based on the number of diodes illustrates the strong influence that can have such scale effect.
- Second is the lack of available or up-to-date data. This is inherent to this study (first limit) but also to the ICT sector that is rapidly changing [13]. It leads to the use of secondary and generic data, hypothesis and exclusions bringing uncertainties and shadow zones. This was expected as data-access is a source of concerns when realizing LCA studies [13]. For instance, missing components had to be modelled with an imprecise material approach. However, using secondary data can be time-saving and is enough to draw eco-design routes.
- Third, the use of ELCD database for electricity mix brings uncertainties as it is superseded.
- Last, some limits are inherent to the analysis possibilities offered by the LCA software and associated database.

While the presence of the previous limits, the main results and eco-design leads are in accordance with the literature [13], gold and lifespan are also found to be a sensitive parameter in [22], importance of gold recycling is highlighted by [19]. Moreover, sensitivity analysis has exhibited that most life cycle stage exclusions were consistent except for installation stage. We are thus confident with the reliance of the eco-design results.

However, capitalizing on absolute LCA results should be done considering the sensitivity of the system dimensioning as 5G small-cells may turn to have different size. In addition, eco-design leads at the antenna scale are not guaranteed at the network scale. Dimensioning of the transmitarray has influence on its power consumption, but also its gain and signal range. Thus, network grid and transmitarray antenna dimensioning depend on each other's. Getting lower network environmental impacts might require a larger transmitarray antenna with larger impacts. This could be a question of network architecture: should we use a centralized or distributed network? This reflection could also lead to consider another kind of antenna architecture, like phased-array antennas.

VI. Conclusions

This study details the first LCA of a transmitarray antenna, highlighting the electricity consumption during the use phase as the main contributor to most impacts (between 72% and 94%). The material depletion is also an important factor to consider with impacts mainly generated by the manufacturing phase (99.3%). This motivates to investigate new antenna design taking into consideration both energy consumption and manufacturing stage. Our results highlight a strong dependency with parameters such as the location of the antenna, the system dimensioning, the lifespan and the quantity of gold content. Those parameters can be directly used as eco-design perspectives for the industrials, researchers and eco-designers. A low-energy technology is evaluated showing the great potential of phase change material (PCM) in a particular case, turning average energy consumption from 19.92W down to 874nW. The results are underlying again the need to take into consideration the manufacturing phase in order to address the diversity of impacts, including here resource depletion. This demonstrates the relevance of performing eco-design at the early stage of technology design, as it allows quantifying the relevance of ideas and exposes their limits, thus guiding the next innovation challenge to be addressed through eco-design. As antennas are part of a global telecommunication system, the whole network should therefore be addressed in next studies with the help of involved parties to consider the full complexity of the system. Performing this LCA is certainly a first step towards more sustainable solutions for mmWave networks.

Acknowledgment

The authors would like to thank Elise Monnier, Ernesto Quisbert-Trujillo, Eric Mercier, and Peggy Zwolinski for the fruitful discussions we had during the redaction of this article. We also gratefully acknowledge Umicore who provided valuable LCIA data on germanium. CEA-Leti is a Carnot institute. This work was supported by the French ANR via Carnot funding.

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