

Energy Efficient Technologies for 5G: Overview, Classification and Qualitative Comparison

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Abstract— *The deployment of 5G networks has led to an increase in energy consumption, which raises a significant challenge for sustainability. In this paper, we present a comparative analysis of different families of energy efficient technologies for 5G networks. We first examine energy-efficient hardware and protocols, which have been widely studied and implemented in various industries. Next, we will discuss on intelligent network management, which has gained attention in recent years due to its potential for long-term sustainability and resilience. We then explore green energy harvesting and transfer methods, including solar panels and radio frequency harvesting, and finally, we will discuss on smart grid-enabled green networks. Our work shows that a combination of various techniques from these categories can lead to significant energy savings in the long run. We demonstrate in this paper that the objectives of most of the research on energy efficiency for 5G are only for increasing performance with the same energy cost. Often, the efficient energy cost is only a side effect of the results, and not the main objectives of the research. We show in this paper the need for more research with energy efficiency as the main objectives.*

Keywords—5G, energy efficient technologies

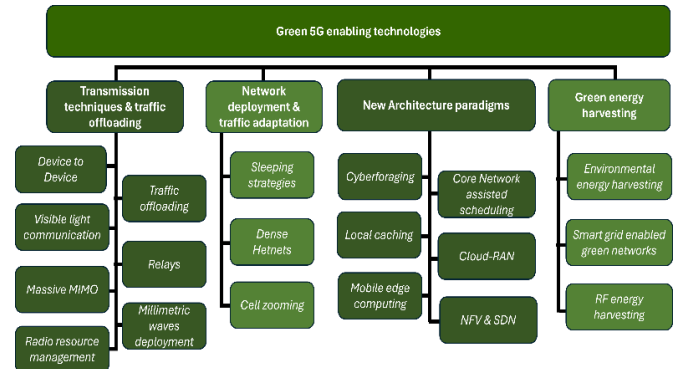
I. INTRODUCTION

As the demand for data traffic has continued to grow, the telecom industry is faced with the challenge of achieving energy sustainability, while maintaining optimal performance and user experience (UX). As a significant contributor to electricity consumption and carbon dioxide (CO₂) emissions, many stakeholders in the industry are incorporating targets to reduce their consumption and to improve their energy efficiency.

Addressing these targets necessitates leveraging technological innovations such as machine learning and sustainable energy-based technologies. Our initial objective was to identify and categorize well-known energy-efficient methods within the context of 5G, providing a comprehensive overview of the energy efficiency ecosystem. The seminal work in [1] is particularly relevant as it classifies numerous green technologies pertinent to 5G. Specifically, [1] delineates two categories for reducing energy consumption: optimizing conventional energy expenditure and exploring green energy alternatives. The first cited, subdivided into "Efficient radio access resource management" and "New architecture and deployment paradigm," addresses methods related to the access and core network parts, respectively. The second one focuses on green energy, with subsections on energy harvesting and smart grid technologies, which offer flexible energy distribution within the core network part. Building on the foundational study in [1], Williams et al. further refined this classification in [2] by incorporating additional methods and grouping the technologies into four

families: "Network deployment and dynamic adaptation," "Transmission technique and traffic offloading," "New architecture paradigms," and "Green energy harvesting and transfer". Our paper evaluates energy-efficient technologies in 5G, identifying methods to enhance energy efficiency in future mobile networks. The study has two main contributions: categorizing technologies similar to [2] with a qualitative comparison and offering guidance for improving energy efficiency in next-generation networks. As shown in Fig. 1, we classify millimeter-wave (mmWave) technology under "Transmission Techniques and Traffic Offloading" for its role in innovative data transmission, and group software-defined networking (SDN) and network function virtualization (NFV) for their focus on network functionality virtualization. The paper is organized into sections corresponding to each category, with descriptions and comparative analyses. Additionally, we provide recommendations for improving energy efficiency in 6G networks.

Fig. 1. Proposed Green 5G Enabling Technologies Classification



II. 1ST CATEGORY : TRANSMISSION TECHNIQUES AND TRAFFIC OFFLOADING

A. Device to Device

Device-to-Device (D2D) is a technology that is likely to be introduced by 5G. D2D aims to allow 2 devices (smartphone, car, urban element like traffic lights, drones etc.) to communicate with each other directly without going through the network, i.e., the Base Station (BS).

This technology has several objectives. First, D2D can improve performance while reducing the energy consumed. This is the case when two user equipment (UE) are close enough to each other to send information directly to each other, and thus avoid latency due to travel time in the network, improve throughput if the channels are of poor quality with the BS, and finally avoid consuming energy by passing unnecessarily through the network. D2D also aims to

integrate smart cities into the 5G network, by making vehicles, personal devices and urban infrastructure communicate, as mentioned earlier.

B. Relays

On the same basis as D2D multi-hop, the relay is an antenna that is less expensive and less powerful than a real BS and which acts as an intermediary between the devices of its cell and the BS to which it is connected. Compared to the D2D multi-hop, the relay can be installed for a long period of time. Moreover, Relays can also be more energy efficient by reducing load on the base station in densely populated areas.

C. Massive MIMO

The benefit of massive MIMO (mMIMO) is the reduction in transmission power required to achieve a given signal quality thanks to involving the use of tens or even hundreds of antennas on the transmitter and receiver to send and receive signals simultaneously. This can result in reduced power consumption for mobile devices, which can extend battery life and reduce the environmental impact of wireless communication networks. In addition, mMIMO can also reduce interference between different devices connected to the network, which in turn can reduce the power required to transmit signals and thus improve the overall energy efficiency of the network.

However, it should be noted that incorrect use of MIMO (in their standby mode for example) can also increase the energy consumption required to power the network infrastructure, which can impact the overall energy efficiency of the system.

Many technologies are based on mMIMO to improve networks energy efficiency.

- *mMIMO / Beamforming and muting.*

Beamforming directs the signal beams in space. This way, the energy can be concentrated in the direction you want to send it. The study [3] considers a BS with x antennas. The goal is to use Beamforming to direct the signal sent in one direction only. The added value of this study is the creation of an algorithm which calculates (at each interaction with the UEs) the minimum number of antennas which must remain on to transmit the message in the right direction and with sufficient power. Considering a rural macrocell (RMa) scenario (few obstacles), the BS can save up to 50% of the energy consumption (depending on the reception angle). It seems to us that this study is relevant in a RMa scenario since the traffic is not very high and the BS never saturates. Thus, the BS can switch off antennas. In an urban scenario with higher traffic density, this technology seems to be less efficient as the antennas are much more stressed.

- *mMIMO sleep mode.*

In [4], Ericson describes one of their methods to save energy that they tested at Vodafone, Portugal. First, a Machine Learning algorithm trains itself to predict traffic on a BS for several weeks. Then, this algorithm helps the BS turn off one or more of its antennas (hence the usefulness of mMIMO) dynamically, and then turn them back on at the appropriate time. Ericson reports 14% energy savings on average per BS, while maintaining all key performance indicators (KPIs). The content in [4] is also criticized in [2] because of a lack of transparency about their methodology. Indeed, the fact that Ericson do not publish its methodology

is understandable because of the market competition with other providers, but it raises the possibility of manipulation of the numbers through a lack of transparency.

- *mMIMO / adaptive deployment*

This is again a study described in the Ericson report (see Method I.C.4). This time, Ericson deploys mMIMO technology in relation to the network load. The network load can be distinguished into 3 zones: the densest environment is the urban environment, then the suburbs and finally the rural environment. According to Ericson, it is important to deploy the right number of antennas on a BS because the number of antennas would be proportional to the energy consumption. Ericson is testing this method in South Korea with the operator SK. First of all, a 64R64T ratio (64 receiving / 64 transmitting antennas) would consume 20 to 100% more than a 32R32T ratio (varies with traffic). In rural areas a 4R4T ratio is sufficient and consumes 60% less than 64R64T. In suburban areas, a 32R32T ratio is sufficient and consumes 45% less than 64R64T. In urban areas, the 64R64T ratio is required.

- *other mMIMO based methods.*

Other mMIMO based technologies such as spatial modulation and implementing Deep Learning algorithms to mMIMO may improve networks efficiency as well.

D. Radio Resource Management

Radio resource management refers to all kinds of techniques used to efficiently distribute radio resources based on interference, traffic, available resources, and other wireless communication characteristics.

E. Traffic Offloading

Traffic offloading consists of "offloading" traffic from the cellular access network to other core network access methods. The most common solution is offloading through the Wi-Fi network. The reason why traffic offloading is interesting for our topic is precisely that it requires less energy to transmit signals to your home Wi-Fi access point than to transmit signals to a base station. In general, at home, the UE is much closer to its Wi-Fi access point than to the Base Station (lower transmission power required and therefore less energy consumption of the UE).

F. Visible light communication

Visible Light Communication (VLC) uses light (visible spectrum) to transmit signals. It is designed for short-range communications, mainly indoor. VLC can definitely improve energy efficiency as it can be used as an illumination and communication source at the same time through LEDs that consume very little energy. Consequently, one may think that VLC will partially and increasingly replace Wifi. However, this may be unlikely as VLC comes with drawbacks. Since this technology is short range and does not go through obstacles, one WiFi receiver/transmitter has to be replaced by a lot of VLC receivers/transmitters to get everyone in line of sight. An Increasing number of studies on VLC's energy efficiency is expected.

G. Millimetric waves deployment

The deployment of 5G networks on millimeter wavelengths offers new opportunities to improve the energy efficiency of data transmission.

This is because using mmWaves to exchange data allows for a much larger bandwidth for users, resulting in better throughput for a small increase in instantaneous power consumption. This improvement in throughput thus allows for a reduction in total energy consumption for a given data transmission, as data is transferred more quickly.

In addition, deploying 5G at millimeter wavelengths reduces interference between users and optimizes spectrum usage, which can also contribute to better overall network energy efficiency.

- *mmWaves combined with radio access network (RAN) improvements and core improvements.*

STL partners is considering several scenarios for 5G deployment around 2030. The No 5G (no deployment of 5G techniques done), the Slow Roll Out, the Medium Roll Out and the Fast Roll Out (all 4G-LTE network is replaced by the 5G network). First result, considering the following scenario, all 5G technologies deployed by 2030 (without the mmWaves band), the network would reach 90% energy efficiency compared to 2018 LTE network. But if the 26GHz band is deployed (with mmWaves), the network would reach up to 98% energy efficiency. Second result: the different Roll Out scenarios and their environmental impacts. Between 2020 and 2030, here are the expected CO₂eq emissions. No 5G: 4750 Mt CO₂. Slow Roll out: 3880 Mt CO₂. Medium Roll out: 3100 Mt CO₂. Fast Roll out: 2590 Mt CO₂. Only the Fast Roll out scenario would reduce CO₂ emissions compared to the network in 2018.

- *Other technologies based on mmWaves*

New technologies such as Deep Learning and a combination of Machine learning and mMimo to improve hybrid coding for mmWaves seems relevant.

H. Comparative analysis

This literature review has highlighted transmission techniques and traffic management as a promising area of research for improving the energy efficiency of 5G networks. Technologies such as mMIMO and mmWaves have been the most studied in this category. Although studies on mmWaves seem promising, this method is still at an early stage of development. On the other hand, Massive MIMO is already implemented and partially deployed, offering interesting prospects for implementation with artificial intelligence (AI) and sleep strategies for antennas or base stations. In addition, the combination of mMIMO with other transmission techniques offers interesting research prospects for developing low-cost and low-installation algorithms, which could lead to significant energy savings in the next standard. However, it should be noted that some of the techniques mentioned in this category, such as VLC, D2D and mmWaves, are still at an early stage of development. Therefore, further research is needed to assess their energy efficiency and potential in a real-world (publicly available practical use case) 5G network context.

III. 2nd CATEGORY : NETWORK DEPLOYMENT AND DYNAMIC ADAPTATION

A. Sleeping strategies

Sleeping strategies are a set of methods that all have the objective of making a network element inactive during a period when the element is not in use. The most common example is the use of sleep on the UE. Our smartphones all have radio frequency (RF) circuits that allow them to catch the

radio waves that are emitted by the Base Station. In order to receive and demodulate these waves, the RF circuit must be powered during the whole reception. Thus, if the RF circuit is powered while no data is being transmitted, the energy consumed to power the RF circuit is lost. The best-known example is discontinuous reception (DRX), introduced in the LTE standard and continuously improved.

This section does not include all implementations of sleeping strategies as they are very often combined with other methods to increase energy efficiency (see other sections).

- *DRX use in handover.*

Nevertheless, we found an article tackling the question of handover energy efficiency using DRX. This implementation can only fit into this section. Indeed, Handover can sometimes be energy intensive. A handover is triggered when the RSRP (reference signal received power) of the UE received by the Base Station is below a certain threshold. Then the network decides which Base Station will take over. However, the current algorithms lack intelligence and may sometimes not select the most optimal Base Station. Thus, the handover mechanism happens again and drains the battery of UEs. In [5], Goyal and Kaushal use machine learning classification algorithms while introducing DRX to reduce energy consumption during handover (especially in the case where several handovers must be done in a row). Their final solution is a DRX algorithm that ranks UEs by handover priority. Their algorithm allows UEs to spend between 70% and 85% of the time in sleep mode during a handover (see "3.1 Power Saving Factor" [5]). In addition, the handover time can be reduced by 20% to 55% compared to the current scheme. The authors of this paper have warned that there have been no studies on DRX during handover. With the multiplication of the number of antennas that is foreseen in the 5G standard, there might be a real problem of energy consumption due to the increasing number of handovers. Real improvements are still to be expected for a less energy consuming handover.

I. Cell Zooming

Cell Zooming is a technology that aims to make the coverage radius of a cell flexible by adjusting the transmission power of the antenna. Thus, by reducing the transmission power of the antenna, the radius is reduced (zooming operation) and conversely by increasing the power (dezooming operation).

For example, in [6], a study of BS using the LTE standard showed that a cell zooming operation could be coupled with a "sleeping strategy". Indeed, the study focuses on 5 eNode Bs (eNBs) in the Kathmandu area. A previous study of the data traffic on these 5 eNBs shows that during the night, from 9pm to 8am, it is possible to switch off one of the 5 BSs, while increasing the power of the 4 others (dezooming) to make up for the lost coverage of the switched off BS. The researchers found a 20% reduction in energy consumption between 9pm and 8am, while maintaining user KPIs. This method is easy to implement. It does not require any new physical infrastructure or any new expense. All that is required is to develop an algorithm that changes the power value according to the traffic. The only difficulty here lies in the prediction of this traffic. It is necessary to keep a permanent availability within the cells, and thus not to exclude a part of the users during after a cell zooming for example.

J. Dense Hetnets

Hetnets aim to improve the energy efficiency of 5G networks using micro-, pico-, femtocells, whose use reduces transmission power. Indeed, the increasing deployment of many small cells leads to increased costs and management due to the deployment of a large number of base stations. Therefore, the paper [7] presents methods to jointly use mechanisms to associate users, and mechanisms to allocate adequate power to resources based on the flow. The use of Deep Reinforcement Learning and Deep Neural Networks seem relevant.

That's why many technologies aimed at improving energy efficiency were developed based on Hetnets.

- *Layer learning solution*

In order to improve the energy efficiency of 5G networks, a method using HetNets has been proposed. Macro base stations (MBS) are deployed where the power grid is used, while small base stations (SBS) utilize energy recovery techniques such as solar cells. The SBS also have an on/off function to save energy. The learning system is built on three layers:

Layer 1: Makes local decisions at the SBS level, using the available resources in the best way possible, and utilizes a heuristically accelerated reinforcement learning approach.

Layer 2: Makes decisions at the MBS level and is composed of a multilayer feedback neural network responsible for the energy factor mechanism. Data collected on the service function chains (SFC) are used to predict performance.

Layer 3: No description is provided in [7]

According to article [7], this approach has yielded promising results in terms of managing radio resources for self-organized networks and energy efficiency, but no quantitative data is provided.

- *User association and power allocation through Deep Learning*

The theoretical (at the moment) method combines user association and power allocation, which can be achieved using Deep Reinforcement Learning (DRL) and Deep Neural Networks (DNN). The predictive performance of this approach is promising as it should show better spectral efficiency and load balancing between base stations, leading to improved user association and congestion avoidance. However, no quantitative improvement is mentioned in the article [7]. The use of deep learning algorithms enables effective resource management and power allocation, resulting in increased energy efficiency.

- *CNN for resource allocation*

A Convolutional neural network (CNN) is constructed and utilized to allocate power and resources based on the quality of service for each user. This approach subdivides the power allocation problem into a sequence of classification and regression tasks, which reduces the problem complexity and improves energy efficiency. The expected and potential performance of this approach is promising as it should demonstrate better spectral efficiency and load balancing between base stations, enabling better user association and congestion avoidance. However, no quantitative improvement is mentioned in the article [7]. The use of deep learning and machine learning algorithms allows for effective and efficient resource management and power allocation, leading to increased energy efficiency.

K. Comparative analysis

Although quantitative data are still missing to compare all these technologies, it appears that each of them plays a significant role in optimizing energy efficiency in access networks for 5G networks.

Looking at the complexity of these technologies, Dense HetNets require additional infrastructure deployment (e.g., pico/femto cells), while Cell Zooming and Sleeping Strategies are software-based solutions.

However, it is challenging to compare these technologies as they are interdependent. Therefore, our comparative study of this category reveals both, the potential and the necessity, of an intelligent combination of different experimental technologies belonging to this category, in order to improve already advanced and performing technologies such as sleeping strategies, cell zooming, and mMIMO.

In particular, Sleeping Strategies have been the most widely used technology (even before 5G) in this category, making it the most critical technology. Therefore, further research in this family, particularly in Sleeping Strategies and possible combinations, is crucial for building an eco-friendly mobile network.

III. 3RD CATEGORY : NEW ARCHITECTURE PARADIGMS

A. Cyberforaging

Cyber Foraging is a technique used to offload some of the UE's complex computational tasks on nearby powerful servers to save the UE's battery. The UE's battery creates a bottleneck when it comes to compute heavy tasks. So, it is more power efficient to use available resources on more powerful machines nearby.

B. Local Caching

Local caching allows frequently accessed content to be stored at the edge of the network. For instance, an image or video on social media that is extremely popular is to be downloaded by a large proportion of users. If this type of content is stored closer to the user, data transmission across the network can be reduced, and so the energy consumption will be.

C. Mobile Edge Computing

Mobile Edge Computing (MEC) is a technology that enables computing resources and services to be hosted close to the end-network. This architecture reduces the centralization of data computing, thus reducing data transmission over the network. MEC also allows for the distribution of computing resources across the edge network, which can lead to lower energy consumption.

D. Core network assisted scheduling

This technology allows the network to be more involved in resource management. Especially when it comes to energy savings, the network would be able to optimize scheduling — based on traffic load, channel status, and other network conditions — to reduce excessive amounts of data to be transmitted, thus reducing energy consumption, especially on mobile devices.

E. Cloud-RAN

Cloud-RAN or Centralized-RAN (CRAN) refers to a new architecture that aims to centralize the processing of radio

signals, thus reducing the power consumption of individual base stations. The base stations are connected via fiber optic links to a centralized processing unit. This means the base stations would no longer be capable of computing on their own. Base stations would become transmitter and receiver elements, reducing the cost of maintenance and installation. However, this technique will also introduce a lot more transmitter / receiver elements on the RAN side as 5G eventually will use mm Wave - signals using that frequency are short range. Therefore, CRAN could potentially increase energy consumption if no work is done on optimizing individual transmitter / receiver elements energy efficiency.

F. NFV and SDN

The method used to reduce the energy consumption of 5G networks is to virtualize network services through Network Function Virtualization (NFV). This minimizes the use of dedicated physical hardware. One of the biggest advantages of NFV is its energy efficiency. It is possible to reduce energy consumption by up to 30% with its implementation in the 5G architecture.

That's why many methods are based on NFV to improve energy efficiency.

- *NFV and Long Short-Term Memory (LSTM)*

According to [7], using an LSTM recurrent neural network (RNN) to predict resource demand in an NFV environment. The data collected on chain service functions (SFC) is used to predict performance. The complexity and performance of the model depend on the quality of the input data. Thus, the initial costs of building and implementing the model, and the need for regular monitoring and updating of the data are necessary to maintain good performance.

- *Optimized path prediction with AI model*

This method proposed in [7] aims to reduce energy consumption in 5G networks by minimizing the energy consumption of switches, ports, and active links, and determining the optimal path for data. The proposed approach uses a hybrid solution of energy-efficient routing that employs supervised and reinforcement learning to improve network energy efficiency. The first step involves reducing the number of features considered for optimization using principal component analysis (PCA). The second step utilizes reinforcement learning (Q learning) or another prediction method to dynamically route data through repeated path selection until the optimal path to the destination is found. According to [7], the proposed technique is energy-efficient and maintains network performance. However, the complexity of resources and development depends on the complexity of the features, such as the number of parameters retained in PCA.

- *Optimization with MILP algorithm*

A simulation in [8] has been conducted on a virtualized network (NFV) using the CRAN architecture. The researchers insisted on the importance of decoupling radio units and computing units. In this architecture, the computing part is not attached to a single base station as in the traditional architecture. The computing units are virtual machines (VM) linked to base stations. The researchers developed a mixed integer linear programming (MILP) algorithm that computes the minimum number of virtual machines to enable, based on localization of the network elements, travel time in the network and traffic load. A virtualized network using CRAN

architecture could potentially save up to 38% energy consumption compared to a non-virtualized network without CRAN architecture.

G. Comparative analysis

We found a lot of resources on NFV, but not on the other methods that are simply applications of NFV. Methods III.A, III.B and III.C use servers to offload computational tasks from the UE, but overall, we do not know if they are energy efficient. Methods III.E and III.F bring major changes on the network, but they could increase energy consumption if not studied enough (only one study shows that NFV can be energy efficient).

IV. 4TH CATEGORY : GREEN ENERGY HARVESTING AND TRANSFER

A. Environmental energy harvesting

This method consists of using renewable energies to power the various equipment making up the network. For example, in a country with a lot of sunshine, one can imagine installing a sufficient number of solar panels on a Base Station to make it self-sufficient in energy. Studies on the subject compare the different energy collection/storage equipment and/or carry out simulations/measurements to demonstrate that these renewable energies can meet the needs of a Base Station. There are two objectives to this method: replacing fossil fuels with renewable energies, but also to ensuring that each Base Station has its own independent power source in case of a problem on the power grid (increasing resilience).

- *Solar panels powering: BS & UE*

In [9], solar panels are shown as the solution to cope with the increasing number of BS and UE (a major challenge of 5G is to manage the growing number of equipment). These two components are the main part of the access network which is the network part that needs the most energy optimization. Thus, 2 types of solar panels for the UE are compared: one that is placed on the shell of the phone (small, low capacity, not expensive) and another that is deployed along the backpack to provide more surface areas for capture (high capacity, model with or without battery, more expensive). "Green energy project", also mentioned, aims to power a BS only with solar energy. Solar panels for the UE can keep your device alive if you are outdoors and the sun is strong enough. Charging time varies between 1h30 and 8h, price varies between 14\$ (shell model) and 70\$ (high end backpack model). The "green energy project", in Thailand, has succeeded in reducing the consumption of conventional energy but not yet to supply 100% of the BS studied with renewable energy. This project wants to build a long-term network of solar panels and especially to implement a new battery system to use energy when the weather or the night does not allow it. One difficulty appears when you want to power equipment only with solar panels, because this energy is not available all the time. For the countries located at the poles, this implementation can even be useless because during a whole part of the year there is almost no sun. Moreover, if there is sunshine, it is necessary to be able to store this energy to reuse it later, which entails an additional cost for the purchase and replacement of batteries.

B. Radio Frequency Energy Harvesting

Radio Frequency (RF) harvesting is a form of wireless power transfer. The RF receiver scans the environment for signals and transforms the received signals into electricity. The scanned signals do not provide enough energy to power a system, but it can help power an internet-of-things (IoT) transmitter, or any other low power communicating systems.

C. Smart grid enabled green networks

The idea behind the smart grid is to allow energy production and trading available through the network. It is even more relevant when combined with energy harvesting : when BSs produce their own energy and make it available for the network.

D. Comparative analysis

Whilst RF energy harvesting doesn't seem efficient on a large scale (only IoT for now), we strongly believe further research must be conducted on the Smart Grid and on Environmental Energy Harvesting. Those two methods have the potential to be efficient on a large scale and applicable for most of the network.

V. METRICS FOR 5G GREEN NETWORKS

To facilitate the evaluation and comparison of green metrics, establishing of metrics is imperative. However, the large diversity of metrics presents a challenge, as each provides distinct information with its own advantages and disadvantages. Indeed, Green metrics target different KPIs and quality of service (QoS), and their relevance varies based on characteristics like computational complexity and optimization implementation. This diversity necessitates a combination of metrics to achieve accurate and relevant energy efficiency evaluations.

In his unpublished lecture PDF document about "5G networks and beyond" at the Complex Networks and Telecommunication 2018 summer school, Dr. Calvanese Strinati categorized green metrics into four levels: country, corporate, facility, and equipment. Based on this knowledge, we propose classifying green metrics into two categories: "equipment level" and "system level." This distinction is crucial because enhancing energy efficiency at the component level is a good start but may be negatively balanced by the rebound effect at the system level. Therefore, a comprehensive approach that combines metrics from both those categories to evaluate the aforementioned methods sounds relevant as the strengths of certain metrics can mitigate the weaknesses of others, despite some inevitable redundancy in the information provided.

VI. CONCLUSION AND FUTURE WORK

In conclusion, while there is no single solution to reduce energy consumption in 5G networks, a combination of various techniques from the different categories can lead to significant energy savings in the long run. It is essential for the industry to keep researching and implementing sustainable practices to ensure the long-term sustainability of the 5G network.

Among these categories, energy-efficient hardware and protocols are the most documented methods, as they have been widely studied and implemented in various industries. Transmission techniques, network deployment and dynamic

adaptation techniques (1st and 2nd categories) definitely have the potential to be energy efficient.

At the same time, we found very few studies on the energy efficiency of new network paradigms (3rd category). We cannot clearly state whether the new architecture of the network (cloud, virtualization) can help reduce energy. We strongly encourage research on energy efficiency of the new architecture, as this category is likely to bring the most important changes in the networks for 5G. 6G will focus even more on network virtualization and the use of AI, and for now there are not enough green technologies introduced in 6G. While AI seems to be the only solution studied for greener technology, we need improvement in the physical layer as well.

It is important to note that none of these methods (from 1st, 2nd and 3rd categories) is primarily designed for energy efficiency. Indeed, Research on energy efficiency for 5G has been going on for many years now, but most of this research was dedicated to improving battery life, user experience (UX) and performance. Therefore, we encourage research that prioritizes reducing energy consumption over improving performance while maintaining or increasing energy usage. Green energy harvesting (4th category) gathers the only methods that focus on reducing energy consumption or using green energy. We found few studies on this topic, consequently we strongly encourage more research on this field. It is extremely important to anticipate the energy issues of the next decades. Considering the political situation, the growing unavailability of fossil resources, we need mobile networks that run on greener energy, and that use less energy.

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