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Toward Greener 5G and Beyond Radio Access Networks—A Survey

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ABSTRACT Mobile network traffic is increasing and so is the energy consumption. The Radio Access Network (RAN) part is responsible for the largest share of the mobile network energy consumption, and thus; an important consideration when expanding mobile networks to meet traffic demands. This work analyses how the energy consumption of future mobile networks can be minimised by using the right RAN architecture, share the network with other operators and implementing the most efficient energy minimising technologies in the RAN. It is explored how the different approaches can be realised in real life networks as well as the research state of the art is highlighted. Furthermore, this work provides an overview of future research directions for 6G energy saving potentials. Different energy saving contributions are evaluated by a common methodology for more realistic comparison, based on the potential energy saving of the overall mobile network consumption. Results show that implementing selected technologies and architectures, the mobile network overall energy consumption can be reduced by approximately 30%, corresponding to almost half of the RAN energy consumption. Following this, a set of guidelines towards an energy optimised mobile network is provided, proposing changes to be made initially and in the longer run for brownfield network operators as well as a target network for greenfield network operators.

INDEX TERMS Green RAN, C-RAN, vRAN, O-RAN, MOCN, MORAN, network slicing, 5G, 6G, AI.

I. INTRODUCTION

THE INFORMATION and Communications Technology (ICT) sector accounts for more than 2% of the global greenhouse gas emissions [1]. As a comparison, this level of greenhouse gas emissions is the same as used by the whole aviation sector [2]. However, today people have the opportunity of joining meetings remotely, and especially after a global pandemic where everything was moved into cyberspace, flight traffic does not grow with the same speed as the Information and Communications Technology (ICT) traffic. The required capacity of ICT sector grows when the number of users increase, or if the same amount of users consume more capacity. An important part of the ICT sector and a digitisation gamechanger are the mobile networks. Due to their still increasing popularity, the mobile networks require continuous expansion to keep up with the demands required by a number of subscribers envisioned to surpass 9 billions within the next few years [3]. To serve this large and increasing amount of subscribers, the mobile networks must not only provide coverage everywhere but also capacity enough to satisfy user demands. Hence, it is crucial for network operators to avoid the energy consumption to grow as fast as the network expansions. Thus, future greenfield installations and brownfield network expansions or updates must ensure a minimised energy consumption.

A mobile network consists of three segments: Radio Access Network (RAN), Mobile Backhaul (MBH) and core network. The RAN consists of a number of base stations serving a number of cells, in which the users of the mobile network are connected to the current base station via radio waves. The RAN is connected to the core network via the MBH. The base stations are located at cell sites. At the

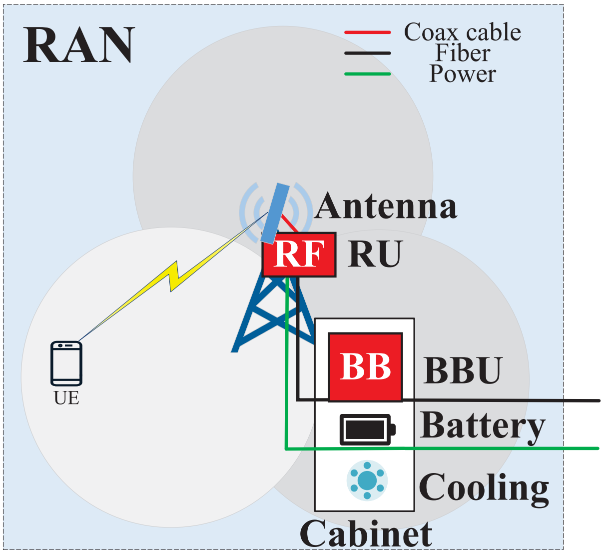

FIGURE 1. The elements of the Radio Acces Network (RAN). The figure illustrates how the antenna is connected to the Radio Unit (RU) via a coax cable, and the RU is connected to the Baseband Unit (BBU) inside the cabinet.

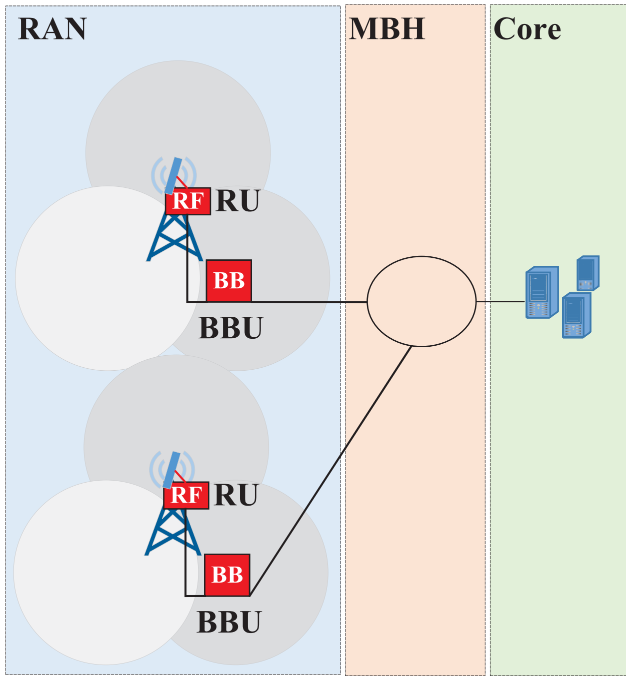

FIGURE 2. The distributed RAN architecture where the base station functions are divided into a Radio Unit (RU) and a Baseband Unit (BBU). The BBU is connected to the core network via the Mobile Backhaul (MBH) network.

cell site, radio waves transmitted by a User Entity (UE) is received by an antenna and sent to a Radio Unit (RU) via a coaxial cable. The RU handles the Radio Frequency (RF) functional part of the conversion from radio waves to bits. The RU then transfers the user data over a fiber connection to the Baseband Unit (BBU) which handles the remaining Baseband (BB) functions. A part from the BBU and RU, a cell site consists of a cabinet, that holds the BBU and backup power sources, with power supply and cooling which can be from air conditioning. A cell site installation is illustrated in Fig. 1. The current installation type used by many operators today is the so-called distributed RAN architecture. This architecture refers to the RU and BBU both being installed at the cell site, close to the users. The distributed RAN architecture as well as the three network segments RAN, MBH and core network are illustrated in Fig. 2. The figure illustrates only one cell served by one RU and BBU. However, in reality many RUs and BBUs are installed at each cell site. The number of RUs and BBUs will depend on the number of frequency bands and sectors served at the current cell site.

User mobility makes an un-equal distribution of the traffic in the network and only 20% of the base stations in the RAN carry 80% of the total traffic [4]. This leaves many opportunities to improve the energy consumption of the RAN. This paper focuses on energy minimisation potential in Radio Access Technologies (RATs) from 4G and beyond. Hence, as RATs become more and more energy efficient when technology emerges, equipment from older generations of mobile networks become much more energy consuming in comparison. Therefore, it is necessary to decommission previous RATs and focus on new ones with a lower energy consumption and a much higher utilisation of resources.

This survey investigates solutions for future mobile networks to minimise the energy consumption, with a focus on architectures, network sharing opportunities and the technological evolution, by creating a common foundation of the energy savings impact. In the remainder of this paper, Section II presents state of the art in academia and industry as well as our contributions. Section III models the energy consumption, which will be used for the remainder of the work as a common comparison template. Section IV presents architectural energy optimisation opportunities of the mobile network. Section V presents the technological evolution that will minimise energy consumption in the future and Section VI examines how the network can be shared between different operators. Section VII discusses the impact of the savings presented throughout this survey and provides a set of deployment guidelines and directions for brownfield and greenfield network operators. Finally the conclusion closes this survey.

Please be aware of attached list of acronyms, placed right after the conclusion and acknowledgement on page 25.

II. RELATED WORK

Several surveys have previously looked into minimising the energy consumption of mobile networks. The work in [5] presents suggestions to improve and monitor the energy efficiency in 5G and beyond mobile networks and highlights previous projects focusing on energy efficiency. In [6], the authors provide a review and analysis of channel capacity, offline and online transmission schemes, and power optimisation from an information theory perspective. The survey

TABLE 1. Summary of existing surveys contribution areas compared to the contribution areas of this current work.

Contribution areas of this work	Other green RAN surveys contribution areas
Timely – published in 2020 or later	[6], [8], [9], [12], [14], [16], [17], [18], [19], [20], [21], [22], [23], [24], [25]
Cloud-RAN	[5], [7], [8], [9], [10], [11], [12], [13], [14], [15], [17], [21], [22]
Open RAN	[20], [21], [22]
Virtual RAN	[5], [7], [8], [10] , [13], [18], [21]
Network sharing	
Network slicing	[7], [8], [13]
Sleep modes	[23], [24]
Power amplifier improvements	[24]
Artificial Intelligence	[5], [7], [8], [20], [23], [25], [26]
Renewable energy	[5], [22]
Energy harvesting	[6], [7], [12], [17], [26]
B5G and 6G energy saving directions	[27], [16], [17], [18], [19]
A critical review of litterature	
Energy savings overview and comparison	[24]
Overview of research projects	[5], [8], [21], [28]

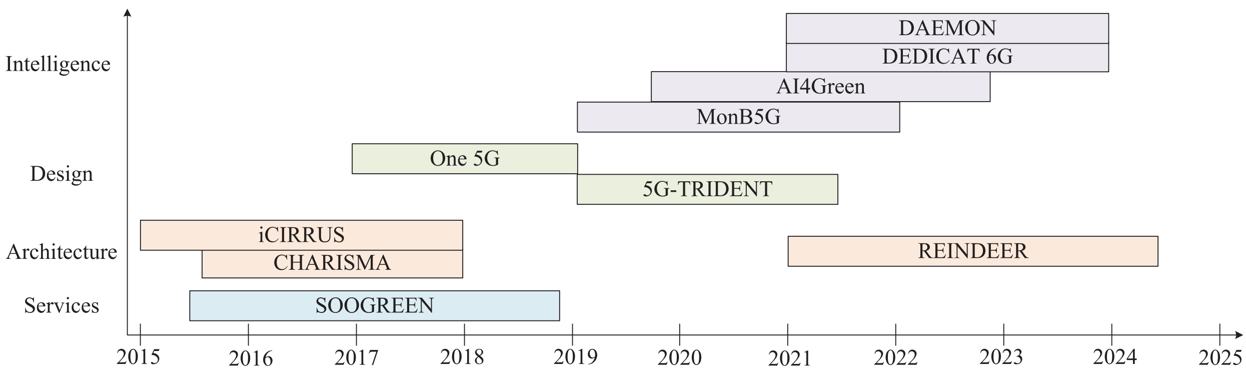

FIGURE 3. Research projects involved in activities aiming to reduce mobile network energy consumption. The x axis shows the years the project have run or is expected to run, the y axis shows the area of contribution.

in [7] considers the interaction between energy harvesting technologies and software based optimisation. The work in [8] also investigates how softwarisation can improve the energy effectiveness as well as the potential of adaptive network sharing with a focus on Cloud RAN (C-RAN) architecture. Table 1 compares existing surveys in the area of energy efficient mobile networks and green RAN to the contribution areas of this current survey.

As illustrated in Table 1, the C-RAN mobile network architecture, which has for several years been a vital part of surveys on energy reductions in mobile networks, is widely examined for examples in recent work: [5], [7], [8], [9]. However, the work in [10], [11], [12], [13], [14] addresses the C-RAN architecture particularly. More specifically, authors in [10] survey the benefits proposed in the case of C-RAN, for example minimised interference, delay and improved energy consumption. The literature survey in [12] highlights benefits and limitations of C-RAN as well as discusses potential enhancement techniques. The survey in [13] compares different network architectures with various amounts of shared resources. In [15], different functional constellations of the C-RAN architecture are surveyed.

A. GREEN NETWORKING RESEARCH PROJECTS

During the past years, energy reduction in mobile networks has received tremendous focus from the industry. Selected research projects are listed in this section, their timeline and areas of contribution are illustrated in Fig. 3.

- SOOGREEN: The "Service-oriented optimization of Green mobile networks", SooGreen project, investigated how to reduce the energy consumption of services in light of the traffic evolution and exploit new network architectures [29]. Results include energy optimisations powered by smart grid [30], hybrid C-RAN [31], and base station On/Off switching proposals [32].
- CHARISMA: The "Converged Heterogeneous Advanced 5G Cloud-RAN Architecture for Intelligent and Secure Media Access", CHARISMA project, investigated an intelligent, hierarchical routing and para-virtualised architecture, uniting the concepts of devolved offload decisions with shortest path nearest to end-users and an end-to-end security service chain [33].
- iCIRRUS: The "intelligent Converged network consolIdating Radio and optical access aRound USer

equipment", iCIRRUS project, proposed an intelligent C-RAN solution bringing together optical fibre technology, low-cost but highly flexible Ethernet networking and wireless resource management [34]. Results showed resource allocation and energy minimisation in C-RAN [35], [36], [37], [38], [39] and energy efficient scheduling [40].
- 5G-TRIDENT: The "5G Technologies for Reconfigurable and efficient raDio accEss iNfrastrucTure and mobile devices", 5G-TRIDENT project, investigated design and implementation aspects of 5G, with special emphasis on reconfigurability as well as cost- and energy-efficiency enhancement [41].
- One 5G: The "E2E-aware Optimizations and advancements for the Network Edge of 5G New Radio", one 5G project, investigated 5G extensions and provided a larger study on massive MIMO (mMIMO) targeting an optimised antenna design and a reduction of complexity and energy consumption [42].
- MonB5G: The MonB5G project, develops a hierarchical, fault-tolerant, automated data driven network management system that is incorporating security and energy efficiency as key features, for orchestrating a massive number of parallel network slices and more diverse service types using zero touch adaptive networking [43]. Results include energy optimisations for 6G [44] and increased infrastructure resource efficiency [45].
- DAEMON: The "Network intelligence for aDAptive and sElf-Learning MObile Networks", DAEMON project, investigates the use of network intelligence to deliver extremely high performance, reduce the energy footprint and provide extremely reliable networks [46]. Results include automated energy savings [47], [48], [49].
- DEDICAT 6G: The "Dynamic coverage Extension and Distributed Intelligence for human Centric Applications with assured security, privacy, and Trust: from 5G to 6G", DEDICAT 6G project, develops a smart connectivity platform using artificial intelligence and blockchain techniques with the aims to improve resource utilisation, reduce latency, response time, and energy consumption as well as cost reductions and reinforcement of security, privacy, and trust [50].
- REINDEER: The "REsilient INteractive applications through hyper Diversity in Energy Efficient RadioWeaves", REINDEER project, develops a smart connectivity platform as energy-efficient, smart, scalable and secure connectivity infrastructure, and topologies for zero-outage and efficient and secure deployment, bringing the intelligence closer to the user [51]. The particular "RadioWeaves" distributed infrastructure used, has shown improvements in quality of service and energy efficiency, compared to conventional collocated Multiple Input Multiple Output (MIMO) systems [52]. Recent efforts in the RadioWeaves technology include the work in [53].
- AI4Green: The "Artificial Intelligence for Green Networks", AI4Green project works toward comprehensive, sophisticated and energy-efficient algorithms to solve the challenges faced in network design, deployment, and management [54]. The main goal of the AI4Green project is to achieve an improvement of about 30-40% of the end-to-end energy efficiency compared to current networks [54]. Results in the area on energy reduction contributions include: [5], [55], [56].

B. STATUS IN INDUSTRIAL ALLIANCES

Greener mobile networks receive tremendous attention from the industry. GSM Association (GSMA) is engaging the mobile industry towards climate action, and provides several yearly analysis on how the mobile industry is progressing towards the ambition to be net zero [57]. The O-RAN alliance addressed a set of energy efficiency goals and targets to support sustainable Open RAN deployments in their technical priorities of release 2 [58]. Next Generation Mobile Networks (NGMN) released in 2021 a whitepaper concerning green future networks [4]. Furthermore, the Next G Alliance have established a working group, referred to as Green G, which was launched in 2021 [59]. 3rd Generation Partnership Project (3GPP) is also working actively towards reduced energy consumption in mobile networks and have released a technical specification for energy efficiency of 5G [60].

C. OUR CONTRIBUTIONS

This current work presents an overview of methods for minimising the energy consumption in mobile networks with three major focus areas: Network architectures, network sharing and technology evolution. Thus, this paper analyses and compares the potential of current and future energy consumption minimisation techniques, with a critical review of existing literature and presents a methodology for a common comparison of the energy saving potential in different solutions. Furthermore, this paper provides guidelines for deployment and expansions of future mobile networks in a more energy efficient manner. As illustrated in Table 1, this combination of energy reducing parameters has not been seen before, as well as the critical literature review and the guidelines add a so far unseen dimension to the paper. Hence, the contributions of this paper are not only an overview of current research directions and their impact but also an overview of how proposed changes can be realised in future mobile networks. Hence, our contributions include:

- A critical review and analysis of existing literature in the area of network architectures, network sharing opportunities and technological evolution. Proposing a common comparison platform, to evaluate the energy minimisation impact of different proposals. Furthermore the energy savings are examined in perspective of possible Customer Experience (CEX) impacts.

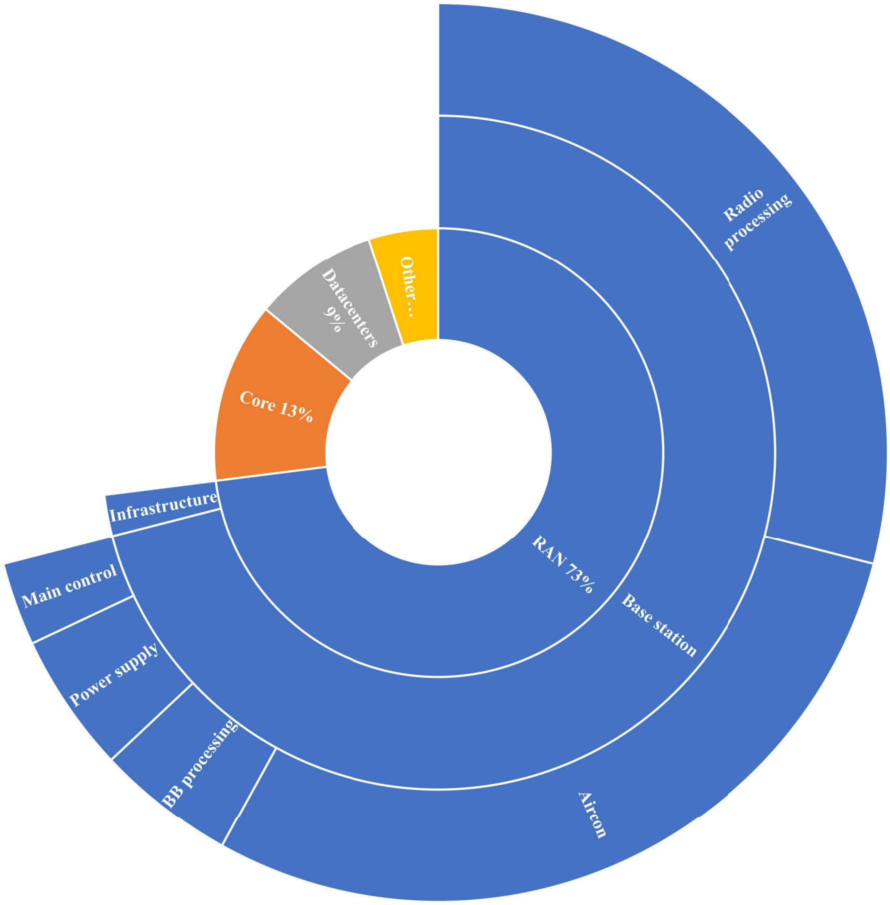

FIGURE 4. The energy consumption of the mobile network in the inner circle, showing 73% energy consumption in the RAN, coloured in blue. The share of the core network is coloured in orange, the share of datacentres is grey and the share of other operations is coloured in yellow. The middle circle shows the share of the RAN, divided out on base stations and infrastructure. The outer circle shows the base station units: Radio processing, air conditioning, Baseband (BB) processing, power supply and main control.

- Proposing changes to the current network operator business model. Examining different opportunities on how network sharing can be realised.
- Inclusion of various deployment methods and opportunities for the different architectures and technologies proposed.
- An overview of research directions toward a more energy efficient 6G.

III. MODELLING THE RAN ENERGY CONSUMPTION

The mobile network traffic is continuously increasing, requiring continuous capacity extensions and expansions of the network. While, mobile network traffic is growing tremendously, nobody wants the energy consumption to grow with the same pace. Thus, methods to reduce the energy consumption of the mobile network is a widely researched area. However, different works propose different energy saving potentials and have different ways of calculating and presenting them. Hence, until now it has been difficult to gain an overview of the contributions of different works, and this is what this model provides: A simple comparison of the impact of different proposals in the bigger perspective of the overall mobile network energy consumption.

A. RAN ENERGY CONSUMPTION

In order to minimise the energy consumption of the mobile network, a starting point is, to understand where in the network, the energy is consumed. Looking into the energy consumption of the mobile network, then the RAN consumes 73% of the energy, the core network consumes 13%, the datacentres consume 9% and other operations account for 5% of the energy consumption [4], [61]. Figure 4 illustrates where energy is consumed in the mobile network.

The RAN energy consumption includes base stations as well as all associated infrastructure such as inverters, rectifiers, repeaters and MBH transport [61]. The energy consumption of the base station consists of 40% air conditioning, 40% radio processing, 7% power, 6.5% baseband processing and 3.5% main control [4]. The work in [4] is not more specific in defining what the different terms cover, therefore; some assumptions had to be made for this current work:

- Radio processing: is assumed to cover the energy consumed by the RUs and the antennas, which may vary by the amount of functions installed in the RU and the size of the antenna system as well as whether the antennas are active or passive. However, the baseline assumed is todays widely used RUs including only RF processing [62] and an active antenna system [63].

- Baseband processing: is expected to be the lower layers of BB processing, ie. Media Access Control (MAC) [15] and Radio Link Control (RLC) [15].
- Main control: is expected to be the upper control layers of the BB processing, handling inter site communication, ie. Packet Data Convergence Protocol (PDCP) [15] and Radio Resource Control (RRC) [15].
- Power supply: is expected to be cooling in the cabinet and the AC/DC conversion [64].
- Air condition: represents a large number in this context, but in reality the use of air condition is depending on the climate, and it can vary through different seasons. Hence, air condition is merely used in warmer climates and in summer times. For instance in [65] the authors set the air conditioning to 23 degrees Celsius, while the outer temperature will vary during day and night times as well as over seasons.
- The survey in [4], does not address the infrastructure energy consumption, but adding up the energy consumption of the remaining RAN installations, leaves 3% for the infrastructure.
- It is expected that the numbers come from distributed RAN installations [66].

The mobile network consumes a large amount of energy, and as illustrated in Fig 4, the base stations in the RAN are responsible for the majority of the energy consumption. Hence the first step for reduced energy consumption is to understand where in the network, most energy is consumed - where will changes have the highest impact? Another approach is to investigate, how can things be done differently than today? Today's mobile networks - or at least the majority of them (examples of other installation types will be provided throughout this survey), are run by one single operator, leading to multiple networks covering the same piece of land. Furthermore, the vast majority of network operators use only one RAN vendor or a minor group of vendors, potentially leading to less innovative solutions and longer time to market. At the base station, the most energy consuming element is the RU, and when one single RU is required for each band at each sector, many RUs must be installed at one single cell site. The users of a mobile network must always have coverage and capacity enough to fulfill their needs, which is particularly important since mobile networks provide critical infrastructure to today's society. Thus, mobile networks must be "always on", and constantly ready to respond to a user's request. This leads to under-utilisation of the network resources, which is energy consumed without any user traffic in the network. Hence, today's mobile networks with distributed RAN installation leaves room for many possible improvements which will be discussed throughout Sections IV–VI.

B. ENERGY CONSUMPTION COMPARISON

The model used by this paper provides an overview of the energy consumption of a particular unit in the network compared to the contribution in a bigger perspective. Hence, it is used for comparing the contribution of different works, but also for evaluating the energy consumption of specific elements to be used in the guidelines proposed in Section VII. The model concept is introduced in Eq. (1):

$$\varepsilon_Y^X = \varepsilon_Y^Z \cdot \varepsilon_Z^X \tag{1}$$

In Eq. (1), ε is the energy consumption in percent, then Y is the object under investigation and X is what the energy consumption is relative to. Z is the unit relating X and Y. Hence, calculating how much the energy consumption of the different base station elements takes up of the overall mobile network energy consumption is expressed in Eq. (2), where three levels are used, corresponding to X, Y and Z, these levels are illustrated in Fig. 5:

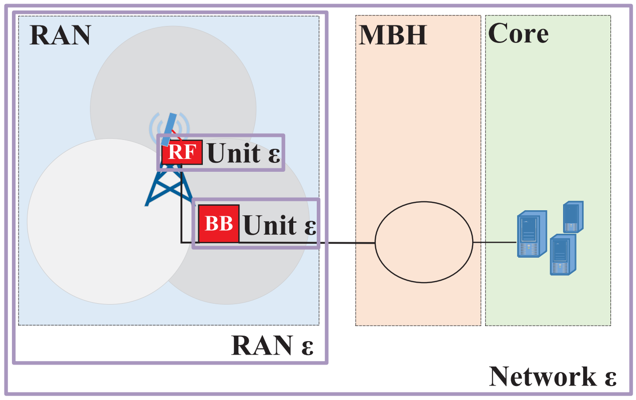

FIGURE 5. An illustration of the three measurable network levels: Network - the overall mobile network, RAN and unit - illustrated by the BBU and RU.

- Network: The overall mobile network
- RAN: consisting of base station and infrastructure
- Unit: Representing the different units in the RAN, ie. BB processing, power supply···

The percentile energy consumption achieved by different proposals of energy consumption reductions of different units, is calculated as:

$$\varepsilon_{Unit}^{Network} = \varepsilon_{Unit}^{RAN} \cdot \varepsilon_{RAN}^{Network} \tag{2}$$

Hence, for example if a proposal claims a 15% reduction in the radio processing energy consumption, it corresponds to a reduction of 4.4% of the overall mobile network energy consumption. Therefore, this model can be used to determine the impact, different energy reduction proposals will have on the overall mobile network energy consumption and thus; it is possible to compare different proposals. The energy consumption numbers provided in this section will be used in the remainder of this paper, to translate expected energy savings into the overall saving of the whole mobile network perspective. Finally the overall energy saving contributions are evaluated in Section VII.

IV. ENERGY EFFICIENT NETWORK ARCHITECTURES

Minimising the energy consumption is an agenda that has been researched widely within the field of mobile network architectures, revealing the benefits of shared processing and minimised amplifiers by the use of RUs. Hence, the potential energy savings when changing the RAN architecture is worth investigating. This section looks into the energy saving contributions enabled when changing the traditional distributed RAN architecture to virtual RAN (vRAN), C-RAN or open RAN. Three network architectures that can be combined or deployed independently of each other.

A. VIRTUAL RAN

A virtualisation of the RAN, defines the separation and decoupling of Hardware (HW) and Software (SW), and thus; enables the use of Commercial off the Shelf (COTS) HW in the RAN, as the network functions run in SW. This separation opens up for more specialised providers, which can potentially reduce the energy consumption of the RAN. Hence, using vRAN the baseband processing does not need to be a "one black box" solution, but network operators can choose the most energy efficient HW and the SW with the most energy optimising functions. vRAN is realised by a conversion of the network functions into Virtual Network Function (VNF)s which is an abstraction of network functions into SW. VNFs are SW applications that deliver network functions, deployed as virtual machines [67]. The infrastructure and provisioning of new VNFs are handled in the Management and Orchestration (MANO) framework [67]. The work in [68] reports on energy savings of 30% when VNFs are introduced in 5G. vRAN areas of potential reduced energy consumption counts:

- COTS hardware
- No location dependency
- Improved operational efficiency
- Power down un-used HW

The vRAN technique is an enabler for many energy saving opportunities. However, from an energy minimisation perspective, this work will focus only on the above mentioned benefits in the vRAN context. Hence, many opportunities described later in this paper will rely on virtualisation of the RAN functions.

COTS HW in an energy efficiency context, relates to the use of HW delivered by vendors who specialise in building the most energy efficient HW. Hence, dedicated HW is built to match its purpose and COTS HW is built to match many purposes. For example when multiple 5G workloads must be run simultaneously on the same HW multi-domain network functions, adds complexity [69]. Based on the use of COTS HW, Deutsche Telecom reports on up to 30% Central Processing Unit (CPU) power savings in their vRAN testlab environment based on realistic traffic profiles [70]. These savings are achieved using scalable processors and power consumption management. However, it is not clear what the baseline for these CPU power savings are. The NGMN report [4] proposes a 15% energy efficiency increase using the latest generation COTS systems, however; the source does not comment on how these power savings are achieved. Contradictory, the whitepaper [69] by Zain Group, stc, e&, Mobily, du, Batelco and Omantel, claims that dedicated HW consumes less energy compared to general purpose COTS servers. No timely and well documented research to back up the claims about COTS HW energy efficiency has been found, hence; it is not assumed to bring any energy consumption improvements. Furthermore, it is expected that the impact in CEX from choosing COTS HW, can vary with different vendors and products.

No location dependency will benefit the energy consumption in the way that processing can, in principle run on any server in the world - if it was not limited by latency. Hence, the processing can be run on the server where the highest degree of resource utilisation is met. On the other hand, energy consumption can also be saved due to shorter paths, and thus less energy consumption in the MBH [68]. In this regard, the processing is moved as close to the user as possible.

Improved operational efficiency is achieved when the virtualisation platform works in high-performance modes to optimally utilise the CPU powers [68]. This, however; requires for the CPU capacity to be fully utilised in order to have any effect on the energy consumption.

HW can be powered down when not in use, since vRAN will enable the BB SW to run on selected HW, leading to every RU not being attached to one single BBU, but rather one RU sending data to the HW with the highest resource utilisation. Hence, when HW is not in use, it can be periodically powered off or used for other purposes. Furthermore, HW sleep states can be used in low activity periods, to gradually shut down the HW [71]. The work in [72] achieves an average energy saving of 34% by optimising the location and utilisation of virtual machines running VNFs.

Energy saving potential: vRAN technology is the enabler of many power saving technologies, which will be mentioned later in this analysis, as well as the enabler of many features that will improve the CEX. On the other hand, the use of COTS HW can potentially lead to a decrease in CEX, this is yet to be investigated.

B. CLOUD RAN

Its is hard to say energy efficient network design without mentioning C-RAN. The initial approach of C-RAN was to minimise the RU and move it to the antenna tower for the amplifier to become as small as possible, leaving as much processing as possible to be shared in a centralised BBU datacenter. The C-RAN centralisation of processing functions introduces the very capacity demanding and latency strict fronthaul network, which is required to carry raw In-phase Quadrature (IQ) symbols in the Common Public Radio Interface (CPRI) protocol. To reduce these large fronthaul requirements, more functions were added to the RU. The exact division of functions left local in the RU and functions to be centralised is referred to as the functional split [15]. Hence, the trend is pointing towards more functions in the

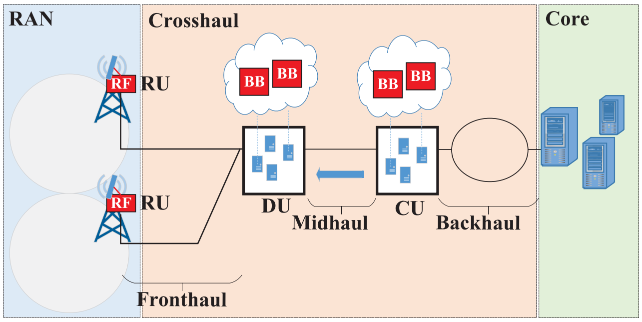

FIGURE 6. The evolved Cloud-RAN architecture where the radio functions are found in the Radio Unit (RU) and the baseband functions are divided into the Distributed Unit (DU) and Centralised Unit (CU), connected by the crosshaul network. The crosshaul network describes the fronthaul, midhaul and backhaul networks. The DU and CU can be placed at the same or different locations, illustrated by the blue arrow. The baseband processing functions are virtualised.

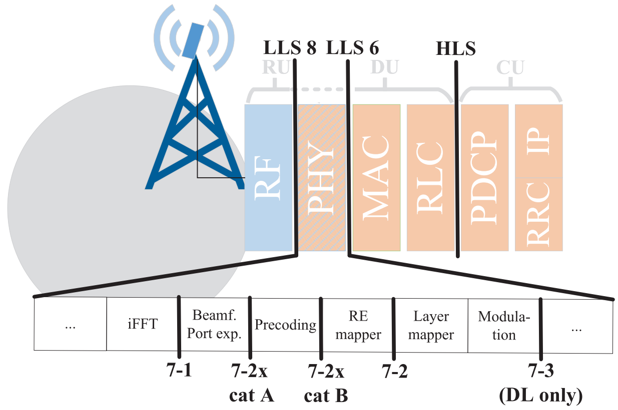

FIGURE 7. The functional division of High Layer Split (HLS) and proposals for Low Layer Split (LLS), where option 8 is the original C-RAN functional split. Option 7-2 is very interesting seen from an energy optimisation point of view since it improves the resource utilisation in the fronthaul network.

RU and less shared functions, which is not minimising the BB processing energy consumption.

The work in [73] and [74] show how the energy consumption of the fronthaul network is reduced when more functions are left in the RU. Hence, the energy consumption of C-RAN is a trade-off between shared processing and transport network. In [75], the correlation between energy consumption in RU, fronthaul and BBU is also explored showing how energy consumption is decreasing when the delay on task execution and data transmission is increasing. The energy consumption of the fronthaul network is dependent on a large amount of parameters depending on technology, for example required amount of Small Formfactor Pluggable (SFP)s as well as the number of hops and amplifiers along the path [74]. Hence, the trade-off between saving processing energy consumption and saving fronthaul energy consumption leaves room for further investigations. The work in [76] proposes a resource allocation scheme to explore the trade-off between fronthaul load and functional split.

Recent C-RAN architectures used by O-RAN Alliance [77], NGMN [78] and IEEE 1914 [79] divides the baseband processing into two units: Distributed Unit (DU) and Centralised Unit (CU). This opens up the opportunities for new mobile network architectures - whose energy efficiency is yet to be investigated. The network between the RU and DU is referred to as the fronthaul network, and the network between the DU and CU is referred to as the midhaul network. The fronthaul, midhaul and MBH networks form together the crosshaul network. The crosshaul network, as well as the RU, DU and CU constellation are illustrated in Fig. 6. The functional split separating the RU and DU functions are referred to as the Low Layer Split (LLS), and the functional split separating the DU and CU are referred to as the High Layer Split (HLS). HLS is selected as separating the RLC and PDCP functions [80], this is illustrated in Fig. 7. The LLS has not yet been determined and different approaches are proposed by different organs and alliances, examples can be seen in Fig. 7. From an energy optimisation point of view, functional split option 7-2 is very interesting, since it has the resource element mapper inside the RU, enabling a variable load on the fronthaul network [15], and thus; potentially higher utilisation of the fronthaul network resources. The fronthaul and midhaul networks are limited by different latency parameters. Therefore, the fronthaul transport must be $< 250\ \mu s$ [80] and the midhaul transport must be < 10 ms [80]. This can be converted into a maximum transmission distance using the fiber propagation delay, which is here assumed to be $10\ \mu s$/km [81]. Hence, seen from an energy reduction perspective, where as much shared processing as possible is wanted, we have two scenarios:

1) To place all DUs within a range of < 25 km transport in one datacenter and all CUs within a range of < 1000 km in another datacenter.
2) To place all DUs and CUs within a range of < 25 km transport in one datacenter.

The energy consumption impact of choosing between either of the two above scenarios is still an uninvestigated area. However, deployment scenarios where DUs or both DUs and CUs are located at the cell sites are seen as less energy optimised, since less or no functions are shared between sites.

To achieve most benefits from the baseband pooling in C-RAN, the baseband functions must be virtualised, which is enabled by vRAN. The energy minimising improvements benefitting from the virtualised and shared baseband processing enabled by C-RAN are listed below, and will be further elaborated on afterwards:

- Coordinated transmission
- Load consolidation
- Reduced Processing
- Fronthaul optimisation
- RU optimisation

Coordinated transmission implicates the RUs transmitting to the same user, improving network throughput and reducing interference. The work in [82] shows how energy efficiency, increasing the number of bits per joule; is improved by 51% using their proposed coordination scheme. However, this term does only define the improved utilisation of the network, and not how much energy consumption can be reduced. Another benefit of centralising the baseband processing is the support of Coordinated Multipoint (CoMP), which minimises interference and improves system performance [15]. As CoMP improves the Signal to Noise Ratio (SNR), it will also lower the required transmission power [8], and this will reduce the requirements of the power amplifier. The implications and benefits of CoMP and C-RAN are surveyed in [83]. The improvement from using coordinated transmission technologies is estimated to reduce the energy consumption of the radio processing by 5% and is expected to increase the CEX.

Load consolidation is by means the utilisation of having baseband processing from multiple cell sites gathered in one datacenter. Thus, this leads to the number of processing resources being minimised because resources can be assigned where they are needed, and de-activated when not needed. The work in [84] proposes two state transition strategies and shows energy saving efficiencies up to 74%. However, the energy saving efficiency is derived by dividing the maximum power of the BBU pool with the activation of all BBUs in the pool [84]. Hence, the energy saving efficiency cannot be compared to actual energy savings of using the two proposed strategies. The work in [85] illustrates the energy improvements of cloud processing compared to cell site processing in a distributed RAN architecture. This work measures the energy efficiency in bits/joule and with respect to both the channel correlation coefficient and the threshold [85]. In [86], a dynamic load consolidation algorithm is proposed which saves 21% power for the BB processing. This translates into a saving of 1% of the overall mobile network energy consumption. Authors in [87] investigate the optimisation problem of resource allocation and power control achieving an energy efficiency improvement of 57%. In [88], energy consumption savings up to 93% are proposed for a virtualised cloud-RAN. However, authors in [88] claim the energy consumption savings will decrease when adding more servers to the pool, that does not sound like good load consolidation, hence; it is expected that the energy consumption savings will increase when more servers are added to the pool. The improvement from using load consolidation techniques is estimated to reduce the BB processing and main control energy consumption by 20% and is not expected to have an impact on the CEX.

Reduced processing can be achieved in various ways. The work in [89] uses parallel processing, where each job runs on a single core and only one at the time, is used to minimise the runtime of the BB processing. In regard to energy efficiency, a reduced runtime will make room for more processing at the current server, and thus; higher resource utilisation. The work in [90] proposes an association scheme for reduced overhead between RU and BBU. Results show a 20% reduction in power consumption of the BB processing [90], this corresponds to almost 1% of the overall mobile network energy consumption. The improvement from using reduced processing techniques is estimated to reduce the BB processing energy consumption by 20% and is not expected to have an impact on the CEX.

Fronthaul optimisation provides energy consumption reductions when fronthaul resources are better utilised or the RU has more functions, reducing the fronthaul transmission rate. The work in [91] develops a successive convex approximation algorithm, which optimises the MIMO transmit powers, while lowering the fronthaul capacity. Results in [91] show energy efficiency improvements of 49% using the power based optimisation. It is not clearly stated in which part of the system the energy efficiency improvements are achieved, but it is implicated that it is in the fronthaul transmission part. However, the energy efficiency does not translate into energy consumption and thus the savings can not be related to overall energy reductions. The work in [23] states the huge impact, the functional split has on the energy consumption of the mobile network. Hence, using functional split 6, the fronthaul energy consumption does only account for around 2% of the overall mobile network energy consumption, while using functional split options 7 and 8 it accounts for 30% and 60%, respectively [23]. The huge energy consumption in the fronthaul network compared to different functional splits are investigated in [73], showing large differences in the fronthaul energy consumption for different functional splits. Hence, these results show how the introduction of C-RAN and fronthaul networks can radically increase the energy consumption of the mobile network, and thus; the great importance of choosing the right functional split. Thus, the trade-off between energy consumption in the fronthaul network and energy savings related to shared BB processing is a topic that leaves room for further investigations.

RU optimisation is important, since the RU is the most energy consuming part of the mobile network. Originally C-RAN greatly improved the energy consumption by dividing base station functions into the RU and BBU, minimising the amplifier. Newer releases of the RU actually merge the RU and antenna into one unit, minimising the amplifier as much as possible [92], referred to as an antenna unit. It is claimed that the introduction of the antenna unit can decrease the energy consumption by up to 43% [93]. A 43% reduction of antenna unit energy consumption translates into a saving of 28% of the overall mobile network energy consumption. However, the antenna unit is developed for large antenna arrays and thus; it does not directly translate into RU power reductions. The improvement from minimising the power amplifier in the RU is estimated to reduce the radio processing energy consumption by 20% and is not expected to have an impact on the CEX.

Energy saving potential: According to the original thoughts of C-RAN provided in 2010 by IBM [94] and in 2011 by China Mobile [95], then the pooling of BB processing will greatly reduce air conditioning since it is not required on-site anymore. Thus, saving energy by one central air conditioning system seems like a valid way to save at least half of the energy consumed by air conditioning. A 50% decrease in air conditioning energy consumption corresponds to more than 14% of the mobile network energy consumption. However, it is noted that not all areas use the same amount of air condition due to different climates and northern countries does not use air condition at all, they use ventilation installed in the cabinet, whose energy consumption will not be improved when introducing C-RAN. C-RAN is by this work estimated to reduce energy consumption of the power supply by 10% due to reduced on-site footprint and centralised processing. In summary of this subsection, then C-RAN will introduce a 40% reduction in BB processing, a 20% reduction in main control energy consumption and a 25% decrease in radio processing energy consumption. Furthermore, C-RAN is not only expected to decrease power consumption but also a slight increase in the CEX is expected due to the higher degree of transmission coordination. However, this is at the cost of additional user latency [96].

C. OPEN RAN

The emerging open RAN technology opens up the interfaces in the mobile network. More specifically the fronthaul interfaces between RU and DU as well as the Xn interface between CUs receive special attention. Opening these network interfaces will open up the opportunities for a multi-vendor network with highly specialised suppliers, where the network operators can mix and match equipment delivered by different vendors. From an energy efficiency perspective, then this will provide network operators the opportunity to select network equipment based on its energy consumption. NGMN highlights, in a recent whitepaper [4], the importance of not only improving the major parts of the equipment but to take minor subparts and improve their energy consumption. This is exemplified by the RU where they state that not only the power amplifier's energy consumption must be reduced, but also the consumption of small signal and digital intermediate frequency modules [4]. This follows the key reasoning of open RAN where subparts are improved by highly specialised vendors.

O-RAN Alliance is a major driver for open RAN specifications, and their specifications merges the concepts of C-RAN, vRAN and open RAN. This is illustrated in Fig. 8. The proposed O-RAN system is built upon the Network Function Virtualisation (NFV)-MANO reference architecture proposed by European Telecommunications Standards Institute (ETSI) [97]. Hence, the SW is separated from the HW and with different layers of control systems on top. This opens up for even more individually specialised components, and thus also opportunities for energy optimisation. The

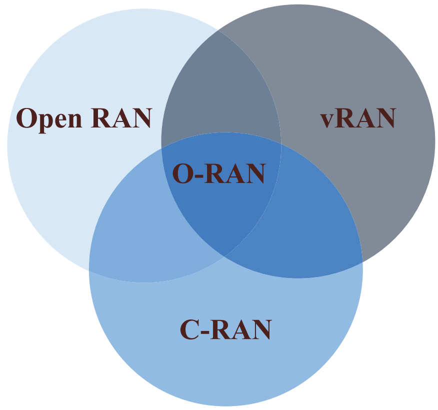

FIGURE 8. The O-RAN ecosystem embedding concepts of open RAN, Cloud-Radio Access Network (C-RAN) and virtual RAN (vRAN).

O-RAN contributors in the OpenRAN group, part of Telecom Infra Project (TIP), have in [58] released a set of technical priorities with focus on energy efficiency that includes Key Performance Indicator (KPI)s and features to improve energy efficiency. These features include radio features and power management at HW and cloud SW level [58]. In a laboratory setting, researchers from a number of companies achieved power consumption reductions of the O-RAN infrastructure by 9% in a peak traffic scenario and 12% during a low traffic scenario [98]. The source [98] does, however; not write anything about which components of the O-RAN infrastructure receives the power reduction or what the power reduction is compared to, to achieve given reductions. The O-RAN specifications provide the following power saving features:

- COTS HW
- Fronthaul
- Dynamic DU selection
- Intelligent control

COTS HW was already mentioned under vRAN.

Fronthaul energy reductions are achieved by lower fronthaul requirements, due to using functional split option 7-2x. The two categories A and B of functional split option 7-2x are illustrated in Fig. 7. O-RAN specifications promise significant lower fronthaul requirements compared to the original split 8 functional division carrying CPRI samples [99]. Further, the used transmission bandwidth grows proportional to the user bandwidth [99]. The DUs are not dedicated resources and can serve more than one RU [99]. However, O-RAN is not locked to one network architecture and thus the impact of fronthaul network energy consumption reductions will rely on the length of the fronthaul. Furthermore, functional split option 7-2x does not have the resource element mapper installed in the RU, which makes the fronthaul load constant.

Dynamic DU selection is a concept evolving in the O-RAN specifications, but based on the concept of no location dependency. The work in [100] is based on the fact that O-RAN

DU and CU processing pools can be located in different geographical places and have limited capacity, affecting the energy consumption and the performance of networks. Hence, authors in [100] propose a joint optimisation solution. When optimising the propagation delay between RUs and DUs, authors achieve at 40% improvement in energy consumption [100]. However, the authors do not state in which network element the energy reduction is received, and thus; it is difficult to compare the reduction to the bigger picture. In [101], the opportunity of executing DU and CU processing in different locations is explored, under the goal of choosing a proper location for running VNFs with respect to propagation delay and computational capacity. It is shown that by dynamically transferring the load to the most suitable DU, energy consumption is decreased by up to 50% [101]. The authors do not specifically state in which equipment the energy consumption is reduced, but it is assumed to be a reduction in the BB processing. A 50% reduction in the BB processing energy consumption corresponds to saving 2.4% of the energy consumption in the mobile network. The improvement from using dynamic DU selection techniques is estimated to reduce the BB processing energy consumption by 20%. However, it eliminates the benefits achieved by shared processing and load consolidation in C-RAN. Dynamic DU selection can potentially impact the CEX positively since the processing can be handled with the least amount of latency, if that is the criteria. On the other hand, it can also have a negative impact in case other criteria must be met.

Intelligent control is natively implemented in the O-RAN specifications inside the Radio Intelligent Controller (RIC)s which are deployed in near real time and non real time. RICs bring smart decision making into the RAN using Artificial Intelligence (AI) and Machine Learning (ML) frameworks. The work in [102] investigates resource allocation in the RIC using federated learning, in a network sliced environment where traffic must be forecast on a per slice level. Furthermore, the work in [103] surveys deep learning-based work for 5G and the integration to AI-enabled O-RAN architecture.

Energy saving potential: In general the open RAN concept itself does not add any other energy saving contributions than the potential improved energy consumption when choosing more specialised suppliers. However, in this work the energy savings enabled by the O-RAN specifications are also considered part of open RAN energy savings. The dynamic DU selection energy consumption reductions relate to 20% saving of the baseband processing energy consumption. However, the concept of dynamic DU selection is contradictory with the C-RAN shared DU processing. In [103], the three technologies of C-RAN, vRAN and O-RAN are compared and the authors claim that the centralisation of network functions in C-RAN causes the RAN energy consumption to decrease, and a virtualisation will reduce the energy consumption further. This is their claim to categorise C-RAN energy consumption as medium and that of O-RAN and vRAN is low. The CEX impact of introducing open RAN is yet an uninvestigated area. However, the native intelligence of the O-RAN systems will definitely bring improvements to the CEX and potentially also to the energy consumption.

V. TECHNOLOGY EVOLUTION

New technologies keep improving the energy efficiency compared to older generations, as new methods for building, running and maintaining the network are developed. Thus, this section highlights improvements occurring when the current 4G or 5G network is optimised, when implementing 5G and outline what is expected when going from 5G to 6G.

A. TECHNOLOGY IMPROVEMENTS

With the emerging 5G technology, the mobile network is not only specialised for specific use cases, it is also optimised in terms of utilising the existing resources. The introduction of 5G is an on-going process, some operators have not started and some operators are in the long lasting implementation phase. However, 5G will bring new opportunities in regards to energy saving potential, as well as the existing 4G network can be optimised in many areas. Existing technology improvements that will result in energy consumption reductions are listed below:

- Power amplifier improvements
- Spectral efficiency
- Reduced signalling
- Sleep modes
- Network virtualisation
- Artificial Intelligence

Power amplifier improvements play a significant role in reducing the energy consumption of mobile networks and can be carried out in numerous ways in 5G. One solution is to use high-efficient semiconductor material Gallium Nitride (GaN) for maximising the power density. In [104] GaN is used to manufacture an RF power amplifier which increases the efficiency by 40%. Another solution is to use the same amplifier to support multiple bands. Multi-band Radio will reduce the energy consumption of the RU since the power amplifier plays a key role in the energy consumption of a RU. Thus, reducing the energy consumption of the power amplifier will have a large impact on the overall energy consumption of the mobile network. In multi-band radio, wideband technology is used where multiple bands can be served by the same amplifier, reducing the number of total amplifiers [105]. Ericsson claims that their multi-band radios have increased energy efficiency by up to 20% compared to the earlier generation [93]. Furthermore, in [106] a computer model to study power amplifier performance was proposed, which can be used to optimise the utilisation of the amplifier. Another way to reduce power amplifier energy consumption is to use MIMO power control. MIMO power control ensures how the user is always served by the base station with the best coverage conditions. This is because, if the coverage is decreased, then the UEs must use a higher transmission power and when the UE is using resources at multiple base stations, the network will consume more energy. In this work, the improvements from using multi-band radios and GaN amplifiers are estimated to reduce the energy consumption of the radio processing by 20%. The use of GaN power amplifiers is envisioned to improve the CEX slightly where multi-band RUs can have a potential negative effect on the CEX in case of traffic congestion.

Increasing the *spectral efficiency* will make use of the spectrum more efficiently, and make the network more energy efficient as it requires less power to send the same amount of information. 5G includes many techniques for improving the spectral efficiency; filtered Orthogonal Frequency Division Multiplexing (OFDM), polar codes, Sparse Code Multiple Access (SCMA) technologies and mMIMO. mMIMO is a concept that significantly improves multiplexing and array gain of 5G transmission systems, since it is exploiting a large number of base station antennas for serving many users with the same time and frequency resources [107]. mMIMO systems with a large number of antennas installed, enable simpler precoding algorithms, signal detection and transmission at the base station, contributing to the reduction of the dissipated energy required for signal processing computations [107]. Furthermore, in mMIMO systems power amplifier losses during operations will be reduced which can bring significant power savings [107]. On the other hand, mMIMO increases the number of energy consuming Analogue-to-Digital Converter (ADC)s with corresponding digital circuitry and power amplifiers [107]. One of the 5G enablers, milimeter waves (mmwaves), consume much energy due to their complexity and because the technology requires analog precoders increasing the need for energy consuming signal mixers and ADCs [108]. Thus, hybrid analog–digital precoders are considered and mMIMO systems are used to reduce complexity and energy consumption [108]. The work in [109] investigates a mMIMO system with multiple arrays which must be located optimally to achieve most energy savings.

When *Reducing signalling*, less bits need to be transferred around in the network, leading to less operations and thus also less energy consumption. By introducing 5G, initiatives to simplify the signalling are already part of the network by use of the synchronisation signal block. Using the synchronisation signal block, continuous signals from 4G are in 5G broadcasted with a varying periodicity [4]. Furthermore, 5G allows for multiple granularities of time in-between signals, improving the resource utilisation by making room for sleep periods [4]. Hence, control signals are not consistently transmitted in every radio frame, but on demand and more sparsely, based on traffic requirements [23].

Sleep modes were developed as a way to get rid of underutilised resources, as mobile networks are deployed to meet peak hour demands. Hence, when resources are not in use, they are simply switched off. The lean carrier design of 5G, enables shut down of different base station components, or just longer periods between signals. Sleep modes come in five different levels: Symbol shutdown, traffic shaping, MIMO sleep mode, mMIMO muting and complete carrier shutdown.

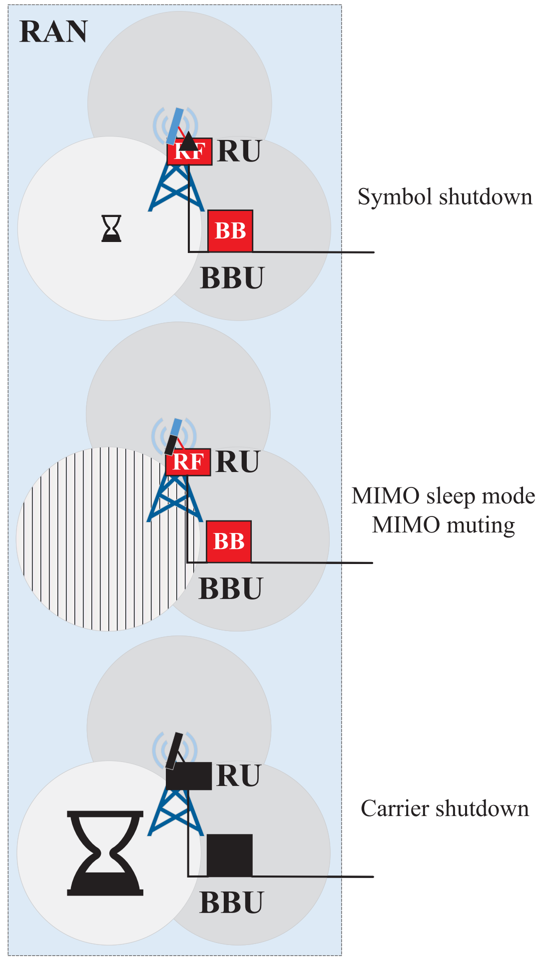

FIGURE 9. The sleep modes: Symbol shutdown, MIMO sleep mode/muting and complete carrier shutdown. The figure illustrates how using symbol shutdown, the amplifier is shutdown which implicates a minor latency. Using MIMO sleep mode and MIMO muting, some of the antenna array is shutdown which implicates lower capacity. And using complete carrier shutdown, the whole cell shuts down which implicates a larger delay before it is in normal operation again.

1) Symbol shutdown: Describes a periodical deactivation of RU power amplifier [4] the concept is also known as micro sleep [110]. Symbol shut down is foreseen to reduce power consumption by up to 30% [4]. The less required always-active signalling in 5G, described under “reduced signalling”, allow for longer micro-sleep periods of up to up to 160ms in the presence of bursty traffic [23]. However, for a coverage providing 5G carrier the default periodicity is 20 ms [111]. This translates into an approximately 100 times longer silent period compared to a LTE carrier [111]. However, the price to pay is reduced CEX since a slight latency is added to the transmission when the power amplifier is activated again. The symbol shutdown sleep mode and its minor latency implication is illustrated in Fig. 9.

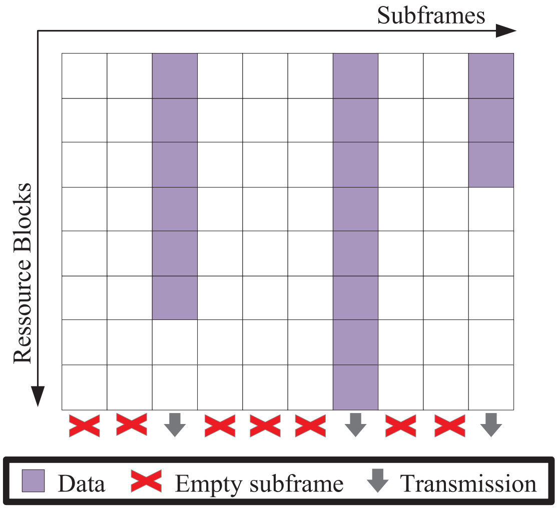

FIGURE 10. **The 5G frame structure where traffic has been shaped to only transmit in certain subframes, in order to improve the outcome of the symbol shutdown sleep mode. Hence, the RU power amplifier can be deactivated for the duration of the empty subframes.**

2) Traffic shaping: In 5G it is possible to create empty symbols, slots and subframes, by smart scheduling decisions [111]. Hence, traffic can be shaped for longer periods of symbol shutdown. Such techniques can be used to allow deeper sleep modes or improve the efficiency of the symbol shutdown [23]. However, these traffic shaping techniques comes at the cost of a minor latency. For example the Low Energy Scheduler Solution (LESS) [110] reschedules downlink transmissions for non-critical data [110]. This solution improves the symbol shut down efficiency because more timeslots are emptied and can trigger symbol shut down [110]. In [110] the combination of symbol shut down and LESS reduces the RU energy consumption by 15%. This corresponds to a 4% reduction of the overall mobile network energy consumption. Traffic shaping is illustrated in Fig. 10, where data is only transmitted in selected subframes, and the RU power amplifier can then be deactivated for the duration of the empty subframes.
3) MIMO sleep mode: Is the deactivation of a number of antenna branches in low traffic periods [110]. For example in the case of 8x8 MIMO or 4x4 MIMO the RU can be reconfigured to 2x2 MIMO mode in low traffic periods. Hence, the capacity of the cell is reduced in periods. The MIMO sleep mode and its reduced capacity implication is illustrated in Fig. 9.
4) mMIMO muting: Shutdown of channels in a low traffic period, results in reduced antenna gain leading to coverage loss [4], furthermore, the capacity of the cell is reduced in the muting period. Channel shutdown using mMIMO muting is foreseen to reduce power consumption by up to 20% [4], however; it is not stated in which network components the energy consumption is reduced. It is expected to be in the radio unit. MIMO muting and its reduced capacity implication is illustrated in Fig. 9.
5) Complete carrier shutdown: In this sleep mode, capacity layer cells are shut down. This can be done down to only the coverage layer cells retained. Compared to symbol shutdown, then this approach has less gain and might have a higher impact on the CEX [4]. Hence, carrier shutdown deactivates HW components for longer periods of time, scaling from minutes to hours and thus; adapts to long term variations of a cell [23]. Furthermore, it takes time to power on the whole system again which will implicate latency. Therefore, carrier shutdown is seen as a key proposal in low traffic periods, for example at night times. Deeper sleep modes are referred to as Advanced Sleep Mode (ASM), defined in [112] as a progressive shutdown of the base station depending on the activation and the deactivation times of the different components. The complete carrier shutdown sleep mode and its latency implication is illustrated in Fig. 9.

In this work, introduction of various sleep-modes are estimated to reduce the energy consumption by 8% of the radio processing using symbol shutdown and traffic shaping, by 2% of the radio processing using MIMO sleep mode and mMIMO muting respectively. Furthermore, the energy consumption of the whole base station is estimated to be reduced by 2% using complete carrier shutdown sleep mode. However, for coverage layer cells, only MIMO sleep is seen as an option, where capacity layer cells can use a combination of symbol shutdown, traffic shaping and carrier shutdown. Hence, the total potential of sleep modes are estimated to be 12% of the radio processing and 2% of the remaining base station units. Sleep modes come at the cost of decreased CEX, since the users will experience delays and/or decreased throughput.

Network virtualisation is continuously used in future generations of mobile networks. Cloud-Native Network Function (CNF)s is the successor of VNFs by using containers rather than virtual machines [67]. Containers pack the SW with all of the files necessary to run it; while sharing access to the operating system and other server resources, where CNFs are designed and implemented to run inside containers [67]. Hence, containers do not package anything bigger than an app and all the files necessary to run it. Thus, containers are often used to package single functions that perform specific tasks. CNFs are decomposed into microservices, which allows multiple versions during updates, and using available platform services [67]. Thus, unlike virtual machine migration, used in VNFs, where the CPU state, memory content, and content storage are considered during the migration process, then the migration of containers is primarily concerned with memory content [113]. Another benefit of using containers is that the use of virtualisation layers, like virtual machines in VNF to virtualise network functions, introduces fluctuations in processing time. These fluctuations makes it challenging to maintain connectivity because of the frequently missing real-time requirements and thus; this problem has been overcome in CNF [113]. The work in [113] studies live migration of network functions where containerised functions are migrated between two hosts, while keeping the users' connection active. Results in [113] show that the RAN could continue operations and remain synchronised with the rest of the network despite downtime periods of up to 8 ms, which is effectively the period of a single Hybrid Automatic Repeat Request (HARQ) Acknowledgement (ACK). The improvement from using network virtualisation technologies is estimated to reduce the energy consumption at the same level as for vRAN described in Section IV.

Artificial Intelligence is an area of computer science focusing on creating machines that can engage on behaviors that humans consider intelligent [111]. Hence, in terms of networking AI can be used to compute decisions that were before made by humans, based on predictions and real time measurements. Thus, AI is made up of three principal branches; big data, automation and artificial intelligence [111]. In this regard, big data uses analysis of large datasets, automation uses pre-programmed rules and artificial intelligence applies cognitive functions to machines [111]. AI is a key enabler of optimisations in all aspects paving its way into 5G, and also in terms of energy efficiency. However, the complexity of AI increases when entering wireless communication channels, such as mobile networks, since the conditions of the channel will vary by time. AI based energy saving use cases for 5G include:

- Traffic load forecast [111]
- Service awareness [111]
- Threshold optimisation [111]
- Beam pattern optimisation [111]
- Energy harvesting optimisation [114]
- Optimise the use of renewable resources [114]
- Estimation of the direction of arrival [115]
- Signal propagation prediction models [116]
- Energy optimisation [117]

AI comes at the expense of both a very long exploration phase as well as large requirements to computing powers and storage [23]. Furthermore, the continuous adapting of an optimal policy to variations of network settings is a challenge, especially when it is derived from and for a limited set of specific system configurations [23]. The introduction of AI is not envisioned to bring any energy savings itself, it is merely the combination of AI, network virtualisation and sleep modes or improved spectral efficiency that will improve energy consumption. Several solutions for systems using AI to reduce energy consumption in mobile networks are already on the market today, examples count: Nokia [118], Huawei [119], ZTE [120], Samsung [121] and Ericsson [122]. Where multiple solutions report on power savings up to 20% energy consumption [118], [120].

A subfield of AI is ML, where the machines learn based on the training they receive. A subfield of ML is Deep Learning (DL), where the machines learn to make decisions

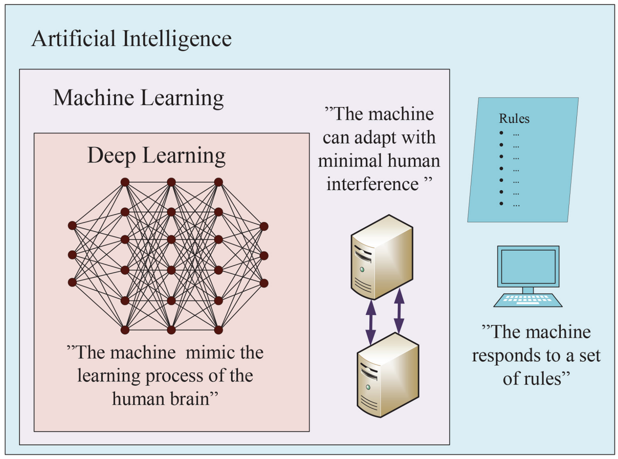

FIGURE 11. An illustration of the correlation between deep learning being a subfield of machine learning, being a subfield of artificial intelligence.

approaching a cognitive way of thinking. Further description of AI, ML and DL algorithms for communication can be found in [114], [123]. Figure 11 illustrates the correlation between AI, ML and DL. On a rough basis the three concepts can be defined as:

- AI: The machine responds to a set of rules
- ML: The machine can via learning adapt with minimal human interference [123]
- DL: The machine uses artificial neural networks to mimic the learning process of the human brain [123]

Below subsections focus on work done in the area of ML and DL.

Machine learning is a subfield of AI, which is widely used within mobile network predictions. ML enables machines to perform tasks by learning from data instead of running a static computer program [124]. Hence, ML uses statistical techniques to perform specific tasks, often requiring a smaller amount of data and with a lower time for application training [111]. ML tools can be divided into three types of learning: Supervised, unsupervised and reinforcement. The latter being learning through feedback. ML algorithms can provide both traffic predictions and energy predictions to enable utilisation of renewable energy sources [4]. ML can also be utilised to decode and encode transmissions, which will improve spectral efficiency by up to 20% [125]. 5G enhancements facilitates the usage of ML to derive optimal and network-wide energy efficient operation policies through centralised data gathering and processing [23]. Hence, the current 3GPP NR architecture introduces the Network Data Analytics Function (NWDAF) and the Management Data Analytics Function (MDAF) [23]. Within reinforcement learning, the Q-model is used in [112], [126], [127] and [128]. In [128], the authors utilise the Q-model to adapt a base station's resources according to the traffic demand, by optimising the use of sleep modes. Results in [128] reports on up to 16% energy consumption savings. Authors in [127] use a framework for effective strategy selection and optimisation policies and obtains up to 20%

energy savings in a high load scenario. The work in [126] utilises the Q-model to optimise the trade-off between QoS and energy efficiency. In [112] different cell loads are investigated using the Q-model, where for very low loads up to 55% energy savings can be achieved and 10% with a moderate load. Recent work in [129] proposes a ML mechanism that provides new sleep mode functionalities, where the greedy algorithm can save up to almost 80% of the energy. The work in [112], [128] and [129] do, however; not explain where in the network, the energy savings are achieved.

Deep learning is a subfield of ML, inspired of the human brain to solve problems that ML can not handle. Hence, the difference between DL and ML is bound in the learning complexity, and while both are AI, then AI is not DL nor ML [123]. DL uses artificial neural networks which require a more substantial amount of data to train models, allowing to process unlabeled data and solve end-to-end problems [111]. Hence, it utilises a set of tools for processing raw data. When large data sets are available, DL is known to outperform other ML techniques, since it is able to operate in a fully data-driven fashion [124] and is advantageous in high-dimensional data processing. The work in [130] uses a DL approach to optimise cell sleeping and beamforming, showing great improvements in performance. The authors in [131] utilises DL tools to subchannel assignment and power allocation strategies to optimise energy efficiency while maintaining bitrate conditions for the users. Also in [132], DL is used to evaluate the quality of candidate radio bands based on the spatial and spectral correlation between radio frequency signals. In [124], the authors show how Artificial Neural Networks (ANN) can be used to implement real-time resource allocation policies that are too complex for real-time by conventional theoretical optimisation approaches. Hence, the ANN tool is used to maximise the energy efficiency in real-time. The work in [133] uses deep reinforcement learning, which is a DL method to process high-dimensional input data and learn actions interactively from the environment, to achieve energy savings up to 27%. In [133] deep reinforcement learning is used to decide when to shut down radio bands that provide additional capacity to an area. Deep reinforcement learning is also used in [134], to optimise radio and energy resource management in renewable energy-powered wireless networks. A trade-off between energy consumption and Quality of Service (QoS) is investigated in [135], using DL to predict traffic. Hence, in [135] the energy consumption of two different strategies; resources on demand and resources on produced energy, are compared and show how the latter strategy is preferred. The work in [135] compares three techniques for traffic prediction to the baseline; Block Linear Regression (BLR), ANN and Long Short-Term Memory (LSTM).

Energy saving potential: By upgrading the existing 4G or 5G network, several improvements in terms of energy reductions can be seen. The savings estimated by this work translates into 2% of all parts of the RAN excluding the radio processing which can be reduced by 32%, which is very significant considering its large impact on the overall mobile network energy consumption.

B. ENERGY REDUCTION POTENTIAL BEYOND 5G

By the time of writing this survey, 6G is still in a very early stage, but indeed it will rely on high computational intelligence. The energy improvements enabled by 6G are related to the following topics:

- Zero touch networks
- Rate Splitting
- Intelligent reflecting surfaces
- Improved sampling techniques
- Energy Harvesting

Zero touch networks are envisioned to ease network operations in the future, by fully automated networks requiring no human interaction. This is achieved by the use of various kinds of AI techniques, since future intelligent network management will depend on the collaboration between the design, deployment and operational phase [114]. Network automation techniques include Self-Organising Network (SON), which uses AI to predict network behavior and control the network based on these findings. Hence, the ultimate goal of the zero touch networking concept is to enable an autonomous network system, which is capable of self-configuration, self-monitoring, self-healing, and self-optimisation based on service-level policies and rules without human intervention [136]. The work in [114] highlights three AI learning methods with great potential for 6G communication:

- Deep reinforcement learning: Using DL models to map from the state to the corresponding action [114].
- Transfer learning: Utilising the constructed knowledge system while solving a problem to the different but related problem [114].
- Federated learning: Decentralising the training process using AI models located on distributed devices [114] without sharing data to a centralised controller. Only model parameters for centralised model training are shared with the centralised controller.

Zero touch networking and AI techniques are used in [44] to optimise the energy consumption of a sliced network, and the same in [137]. The work in [138] proposes a fully automated optimisation and management framework which is claimed to improve energy efficiency by up to 84%, however; it is not stated where in the network the energy efficiency improvements are seen, and it is definitely a very high number. Furthermore, the work in [44] promises a ten-fold increase in energy efficiency gain. However, the work in [139] expresses how it is not possible to gain huge improvements in all metrics using zero touch networking, the example used, is that increasing the number of access points improves the admission rate while incurs more power consumption. The concept of zero touch networks are surveyed very recently in [136].

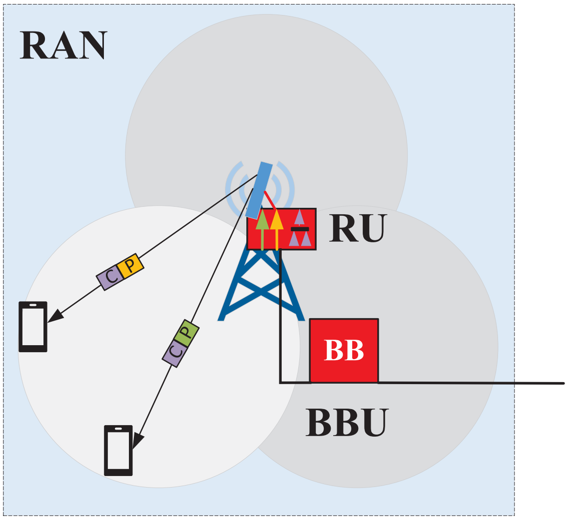

FIGURE 12. The concept of rate splitting where each users messages are split into a common and a private part. In the RU transmitter, the common parts of multiple messages are combined in one stream.

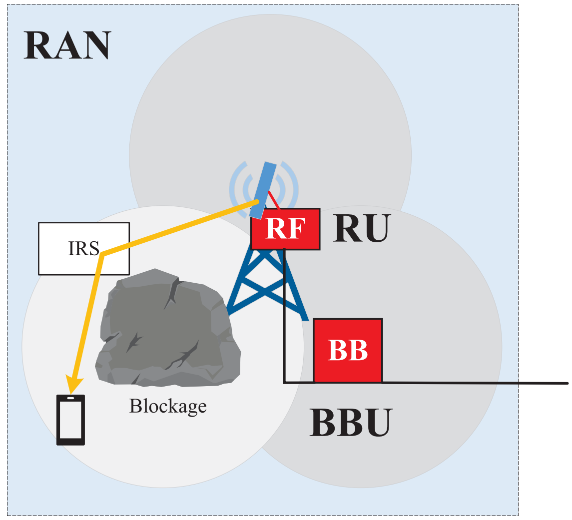

FIGURE 13. The concept of Intelligent Reflecting Surfaces (IRS) where IRS is used to redirect the radio signal sent from the base station around an obstacle.

Zero touch networks are envisioned to improve both energy consumption and CEX.

Rate Splitting is the multiple access technology currently envisioned for 6G communication systems. Rate splitting is an efficient interference mitigation strategy, where each user's message is split into a private part and a common part [140]. Rate splitting splits user messages, into a non-orthogonal transmission of common messages decoded by multiple users and a private message decoded by its corresponding user [141]. The concept of rate splitting is illustrated in Fig. 12. Rate splitting enables partially decoding the interference and partially treating the interference as noise, and thus; perform well at all levels of interference [141]. Hence, the users will decode parts of other users messages and treat the rest as noise. In the transmitter part of the RU, the common messages of multiple users are combined in one stream before the encoder. Then the one combined stream is sent to the user together with the current user's private stream. All users will decode the common part of the message first. Rate splitting results in huge interference improvements leading to continuous improved spectral efficiency resulting in improved energy efficiency [141]. The work in [142] demonstrates an energy efficiency gain of 97% when employing rate splitting instead of simply treating interference as noise combined with the proposed polynomial complexity algorithm. On the other hand, authors in [143] address the practical challenge of the transmitter only knowing the users statistical Channel State Information (CSI). One thing that must be carefully aligned in a rate splitting system is the rate allocation, and the work in [144] shows how careful alignment of the rate allocation can outperform Non-Orthogonal Multiple Access (NOMA) in terms of both energy efficiency and spectral efficiency. Rate splitting is envisioned to have a positive impact on the CEX and a large impact on the energy savings of the mobile network.

Intelligent Reflecting Surfaces (IRS) are meta surfaces, which consist of many low-cost reflection elements, able to induce real-time changes to the reflected signals [140]. The concept of IRS is illustrated in Fig. 13, where the signal from the antenna is reflected to another direction at the IRS. In practice, IRS consist of a large amount of reflecting diode units, able to reflect any incident electromagnetic signals with an adjustable phase shift [145], [146]. Hence, the signal can be not only reflected in the current angle of reflection, but also in other angles [147]. The reflective elements are considered two-dimensional structures because they have the length of multiple wavelengths, while they are only a fraction of a wavelength deep [147]. Each reflective element is individually adjustable, enabling passive beam-steering, which will result in an increased efficiency of the network [140], [146]. However, in a multi-user scenario, the utilisation of the passive beamsteering will introduce an increase in interference for the users [140]. The work in [140] investigates how rate splitting can mitigate the interference caused by IRS. IRS, will not use any power amplifier to amplify and forward the incoming signal. Thus, an IRS will consume much less energy than a regular relay transceiver [148], furthermore; the gradient descent and fractional programming of IRS will significantly optimise the phase shifts and thus; the transmit power [145]. The work in [149] confirms that IRS will improve the energy efficiency, however; it also shows that increasing the number of reflection elements, will not always ensure the improvement in energy efficiency. Authors in [145] defines IRS as a fundamental enabling technology for 6G with an immense potential toward energy efficiency. The work in [150] compares the energy efficiency of aerial IRS and aerial relaying and notes that the IRS system always outperforms the corresponding relays. Results in [150] show energy efficiency gains up to 74% using IRS. Meta surfaces are envisioned to have a larger positive impact on the CEX and a minor effect on the energy savings.

Sampling will be optimised in 6G mobile networks by introducing compressive sensing techniques. Compressive sensing describes how the signal is reconstructed by taking the samples at a higher rate [148]. More precisely the sampling rate in compressive sensing must be greater than equal to twice the highest frequency of that signal [148]. Compressive sensing is a sampling framework that can be sampled at a rate smaller than the Nyquist rate used today and the resulting, smaller set of samples are sufficient to reconstruct the original signal [148]. However this requires a signal characterised by sparsity and incoherence [148]. Compressive sensing is achieved in a computationally efficient manner, and in compressive sensing, both the sampling and compression is carried out at the same time, which it is not in todays networks [148]. Hence, compressive sensing is also a way to reduce the amount of data that need to be exchanged for required communication [148]. Compressive sensing is already known from sensor networks [151], [152]. Fundamental concepts and widely used algorithms for compressive sensing are comprised in [153]. Improved sampling is envisioned to have a significant positive impact on the CEX and a relative effect on the energy savings.

Energy harvesting is envisioned to extend the range and stand-by times of the mobile network by replacing the conventional ways of powering devices and sensors by tapping the energy from ambient environment [148]. The two broad class of sources for energy harvesting are [148]:

1) Natural sources
2) Man-made sources

Natural sources of energy harvesting count for example solar and wind power, which is energy supplies in macro scale. On the other hand, man-made sources, which is generating energy supplies in micro scale, such as μW and mW. Hence, energy harvesting from man-made sources is merely used for powering Internet of Things (IoT) devices in all communication networks. However, since a wireless signal can carry and transmit energy and information at the same time, energy harvesting can also prolong the service life of relay devices [154]. Examples of man-made energy harvesting sources count vibration, heat, mechanical movement and RF energy harvesting which is mainly used for wireless communication. RF energy harvesting is a promising technology for powering a huge number of devices, since it eliminates the need for powering those devices from an electric grid and also enables battery lifetime extension [107]. RF energy harvesting describes how to harvest energy from RF waves to extend the network lifetime [148], using the RF range between 300GHz to 3kHz [68]. Nodes that harvest more energy can share their energy with other nodes using energy cooperation [148]. For RF energy harvesting, the Synchronous Wireless Information and Power Transmission (SWIPT) technology is used, which is a combined technique of wireless information transfer and wireless power transfer [155]. Hence SWIPT has two conflicting goals: maximizing the amount of information transfer versus maximizing the amount of energy transfer [155]. SWIPT has two basic modes: Power Splitting (PS) and Time Switching (TS) [156]. In the receiver, the received signal is divided into an information part and an energy part, thereby the receiver is receiving both information and energy, respectively [156]. In TS, the receiver node separates time to process information and harvests energy, while in PS, the receiver node splits the received signal partly for information processing and partly for the energy harvesting [154]. The practical implementation of RF energy harvesting, requires an optimal balance among the harvested energy and the achievable transmission rates, which can be realised through different approaches [107]. Approaches to finding this optimal balance can be:

- To divide the received signal into two parts, one for energy supply obtained through energy harvesting and the other for information decoding [107]
- To split the information of transmission and energy harvesting in time, to first harvest energy from received signals and then perform wireless information transmission [107].

The realisation of RF energy harvesting requires system performance which is significantly limited by the severe RF signal path loss since this results in low energy conversion efficiency at the position of the energy harvester [107]. Another approach is to harvest energy from the interference. Interference energy harvesting can compensate for the loss of the SWIPT relay system rate caused by the interference [157]. This technique is also based on the existing two operation strategies, TS and PS, where the interference energy is divided among subsequent transmission blocks [157]. Energy harvesting is surveyed in [158], which is referred to for further details. Energy harvesting is not envisioned to have any effect on either the CEX nor the energy consumption, however; it will play an important part in the journey to CO2 neutrality.

Energy saving potential: The energy saving methods predicted for 6G are examined throughout this subsection. The solutions and proposals elaborated in this section are not yet available and thus; they will not be considered in the final analysis in Section VII. However, the techniques proposed for future mobile network generations are foreseen to provide significant improvements on the energy efficiency.

C. THE ROAD TO CO2 NEUTRALITY

So far, this work has examined many different proposals for minimising the energy consumption of the mobile network. However, the mobile network will always consume energy and thus; methods toward achieving CO2 neutrality are briefly considered in this subsection. These methods count:

- Alternative power sources
- Heat re-use
- Modern Batteries
- Liquid cooling

Alternative power sources are most widely known as solar panels, water- and wind power. Thus, if the mobile network is utilising alternative power sources when available, it will become CO2 neutral in that period of time. When the alternative energy sources are producing more energy than needed to run the network, energy can be saved on batteries for later use. The work in [159] utilises solar panels to power base stations and energy storage as well, to obtain carbon footprint reductions at the order of 50%. The work in [135] investigates power saving opportunities using ML predictions for a base station both equipped with a photovoltaic panel and connected to the power grid. Results show energy savings between 10% and 40% [135]. Most of the energy is produced locally by the photovoltaic panels, and only a small amount, between 8% and 23% of the energy, is purchased from the power grid, this is typically during night, when energy is cheaper [135]. The paper [135] does not state which components of the network achieve these large power savings, however; it is interesting that only up to 23% of the energy is provided by the power grid. However it must be noted that measurements were carried out in the sunny Milano, Italy [135].

Heat re-use can efficiently be used to improve the sustainability of the network. Datacenters generate heat, no matter if it is - in mobile network context, a larger datacenter carrying out baseband processing from a large number of C-RAN sites, or a small on-site datacenter only handling the baseband processing of the specific site. Hence, re-using the heat for warming up buildings will be an efficient way to save energy in other sectors. The work in [160] investigates how datacenters' waste heat can be re-used to warm up buildings, which is in [161] considered of much higher economic value than the thermodynamic value of the heat.

Modern Batteries can be of various types, for example flow batteries and lithium batteries. Lithium batteries are becoming an integral part of 5G sites to enhance energy management [23]. Flow batteries use cells in liquid form where the energy-storing materials flow in-between while undergoing redox reactions [162]. Hence, flow batteries are different from solid state batteries in terms of flow structure and decoupled power and energy [162]. Modern batteries are used to harvest energy at the right times, when alternative power sources are available, for example when the weather is sunny or windy, and store the energy until the day where its cloudy and no wind.

Liquid cooling is being implemented to reduce the need for air conditioning [23]. The concept uses cold liquids to cool down the heat generating equipment. The liquid is heated up by the equipment and will be led away to be cooled down by air, before the cyclic system leads it back again to cool the equipment once again.

VI. SHARING THE NETWORK

Mobile networks consume a large amount of energy. Hence, in principle it is a waste of resources when more than one network cover the same area. This is the reason why the concept of network sharing is relevant seen from an energy consumption minimisation perspective. However, multiple mobile networks covering the same area do also provide significant benefits in terms of reliability, avoiding monopoly and thus; obtain better prices for the customers. A shared network is a totally different business case than most operators use today, but it raises the question: Why have multiple networks covering the same piece of land, when in other sectors (sewer, power grid, traffic, i.e.,) only one network is necessary? This section will focus on different techniques for multiple operators to share the same network. For RAN sharing the two most commonly used solutions are Multi-Operator Core Networks (MOCN) and Multi-Operator RAN (MORAN). However, another approach is to use the concept of network slicing to create a multi tenant network. On the other hand, it is also possible for an operator rent capacity on another operators network, defined as roaming. The four approaches are defined below and illustrated in Fig. 14.

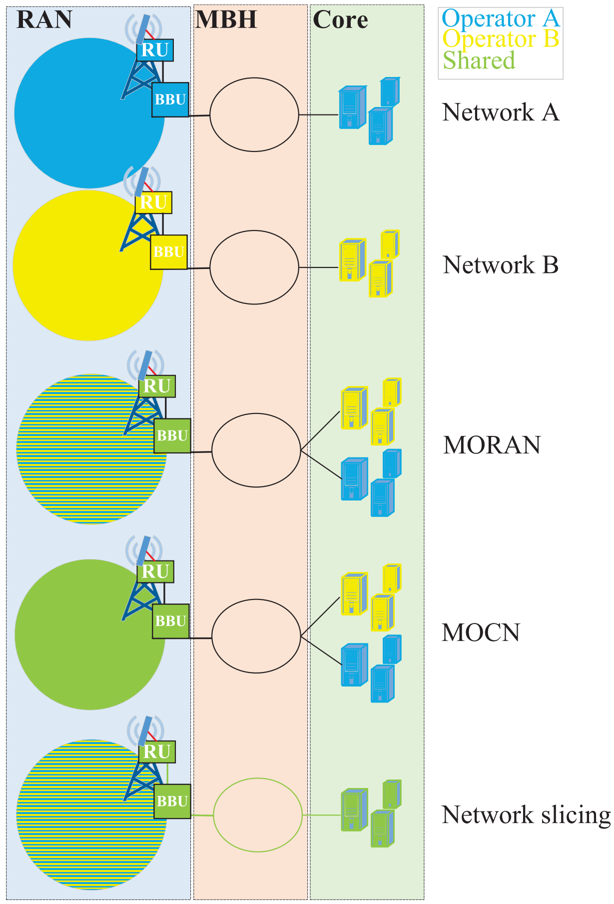

FIGURE 14. An illustration of two individual networks compared to using different types of network sharing: MORAN, MOCN and network slicing.

- Roaming: A network operator rents capacity on another network operator's network.
- MORAN: The whole RAN (antenna, cell site, power), except the radio frequencies, is shared between multiple operators.

- MOCN: Multiple core networks share the same RAN including the radio frequencies.
- Network slicing: Multiple tenants share or rent a slice of one network where resources are assigned based on an individual basis, which could be the amount of owned radio spectrum.

A. ROAMING

In a roaming scenario, traffic is moved from one network to another. Hence, from an energy saving perspective it might be cheaper, under specific circumstances, to buy resources in another network rather than paying for the energy consumption in ones own network. Furthermore, there might be potential energy savings in low traffic periods, if only one network is running in the time period and the remaining networks roam in case of any traffic. The concept is investigated in [163] where operators achieve up to 11% energy savings by deactivating their own base stations and roaming on other networks. The work in [164] evaluates different scenarios where a number of network operators can share one network in low utilisation periods. In general roaming is foreseen to bring a reduction in the energy consumption, since users are handled by another network which frees up time for enhanced sleep modes or deactivation of whole sites. Roaming can even bring improved resource utilisation, in case users in an area are gathered to be roaming on the same network. This could for example be in low traffic periods. The CEX impact of roaming will depend on acquired Service Level Agreement (SLA).

B. MULTI OPERATOR NETWORK

If the networks from multiple operators shall be merged, it must be taken into account that the different operators under some circumstances have different cell site positions. Hence, the total amount of site positions will increase in order to keep the same level of coverage and capacity to all operators' customers. Figure 14 illustrates how two operators can share the same network, either as MORAN or MOCN. The major difference between these two concepts is that in MOCN, everything is shared equally between the two operators despite from them having individual core networks. However, in MORAN the two operators operate on their own radio frequencies. Thus, if one own more spectrum than the other, then the operator with more spectrum will also have more capacity.

MOCN enables equal sharing of the RAN between multiple operators. MOCN is standardised by 3GPP in [165] and [166]. When two operators share the same RAN, scheduling fairness among the users served by the different operators is an important matter [167]. In [167] the scheduling fairness is evaluated based on different parameters like number of scheduling Physical Resource Block (PRB)s per slot, number of scheduling times per second and throughput. The RAN sharing of different operators' users can be realised by simultaneously broadcasting the Public Land Mobile Network (PLMN) IDs of all operators in two shared frequency bands, then users can access any of the shared frequency bands [167]. The work in [168] defines and verifies three key features of MOCN: Multiple PLMNs, inter-frequency handovers and prioritisation of different frequencies. Compared to MORAN, then the MOCN solution is more efficient also in terms of cost as well as it enables a better utilisation of the shared spectrum [169]. In Denmark, the TT Network uses MOCN configuration [170], but MOCN is also used in for example Sweden and Australia [171].

MORAN is the mainly adopted solution for network sharing due to its guaranty of capacity independence and service differentiation among the RAN sharing operators [169]. Hence, operators can independently control cell level operations like deciding their own optimisation parameters and transmission power to control the cell range as well as manage interference [172]. However, not much work relates to the use of MORAN alone, it is merely related to the use of network slicing which will be described under Multi Tenant Network. In Japan, the operators SoftBank Corp. and KDDI are deploying a shared network using MORAN technology [173], and it is already used in for example Spain or United Kingdom (U.K.) [171].

Multi-operator networking energy savings: Energy savings in a multi-operator network will depend on the amount of operators sharing the network. In this section, as an example, three networks are merged into one. Power consumption from RUs and air conditioning are expected to be reduced by 66% on a per site level, however; it is assumed that the operators will not share the exact same site positions. Thus, the number of sites will grow, but overall a large energy saving is expected in the range of 50%. The main control and baseband processing will save energy consumption based on the amount of improved resource utilisation, since the amount of traffic and number of users are the same. It is expected that 30% is a realistic saving due to improved utilisation of traffic fluctuations. A reduction in the power supply energy consumption is also expected since less components are supported, in the area of 10% since existing equipment will use more energy. From a CEX perspective, assuming the network is dimensioned after the new amount of users, MORAN is not expected to bring any CEX changes. However, MOCN users will be positively or negatively impacted depending on their operator's previous resource capacity and configurations.

C. MULTI TENANT NETWORK

Network slicing describes the ability of running multiple separate logical networks on top of one shared physical network infrastructure. Hence, one physical network composed of antenna masts, processing units and transport network connections will be able to handle individual logical networks with individual performance requirements. These logical networks are defined as "slices" and one or more slice can be rented by a tenant. Network slicing enables the opportunity of isolating different services optimised for a specific purpose, improving the performance compared to the traditional "one-size-fits-all" network. From an energy consumption perspective, the use of network slicing will enable only one network operator handling the network of multiple tenants and, using the country of Denmark as an example, reduce the number of networks from three main operators and a number of IoT and private network operators, to one physical network. Hence, network slicing requires from all nodes in the network to be able to separate individual data streams and provide differentiated QoS. The end-to-end network infrastructure for network slicing is issued in [174], [175], [176], [177]. The network slicing control framework layer is comprised of radio slice controllers, transport slice controllers and core slice controllers, controlling the RAN, crosshaul and core domains respectively [175]. In [178], the energy consumption of network slicing is investigated for two approaches; slice-based resource allocation and user-based resource allocation. The work in [178] illustrates how end-to-end network slicing provides larger decreases in energy consumption compared to slicing only the RAN. In this case up to 20% energy savings are achieved and up to 30% less bandwidth in a low load scenario for end-to-end slicing [178]. Hence, the implementation of network slicing requires all parts of the mobile network to be able to isolate traffic flows, including:

- Radio functions
- Baseband processing
- Crosshaul Transport
- Core network

The following part will analyse different options for network slicing implementation.

Radio Functions provide capacity based on the amount of spectrum owned by the individual operator. Following 3GPP [80], each slice may be assigned to either shared or dedicated radio resources. Hence, different methods are proposed:

- Each slice has a fixed, predefined contiguous sub-band available [179]
- Each slice has a contiguous sub-band consisting of a fixed region and a variable region available [179]
- The resource grid is divided into regular sub-bands of fixed size, which can be assigned to different slices on demand [179]
- Assigning different Transmission Time Intervals (TTI)s to different slices, hence; a fixed time where each slice can transmit. This way, a certain number of PRBs will be assigned to each slice, enabling guaranteed performance [180]
- Dynamical reallocation of PRBs [169], [181]
- Scheduling a number of slots for each slice [175], [182], [183]

Baseband processing includes the very important MAC scheduler. The MAC scheduler can assign capacity dynamically to different slices and simultaneously keep track of the individual guaranties assigned to the different slices. The scheduler will also be responsible for traffic prioritisation in the core- and crosshaul networks. Three implementation options for a network slicing compatible MAC scheduler can be derived:

- One joint scheduler with specific rules for each network slice. This requires a MAC layer of high complexity to manage multiple different slices configurations demands. However, this one scheduler will have an overview of the entire system, enabling more efficient sharing of unused resources [179]
- Individual schedulers for individual slices. The individual schedulers require sufficient coordination in-between. However, the schedulers are simpler and provide a more flexible customisation of each individual network slice [179]
- One master MAC which allocates resources between slices and multiple customised slave MACs to schedule the resources within the different slices [175]

Crosshaul Transport is the infrastructure connecting the RAN to the core. The transport network infrastructure, used in a network slicing enabled network, has to carry the traffic from several logical networks, each having very different requirements to the one physical network. Hence, the crosshaul network must support separation of different flows and slice isolation in all crosshaul network nodes. Thus, options to be used for network slicing, for different types of crosshaul nodes implementation includes:

- Ethernet: Allows sharing of the network infrastructure through standardised virtualisation techniques [184], referred to as Virtual Local Area Network (VLAN) [185]. Thus, Ethernet can flexibly allocate and dynamically reserve resources for specific slices [81]. Using Ethernet, the physical resources can be highly utilised, as Ethernet flexibly allocates capacity within the fibers and the switches [81].
- Wave Division Multiplexing (WDM): Transports data from different sources on different wavelengths. Using WDM, it is possible for each slice to operate on its own wavelength. Wavelengths are isolated, and thus; they can carry individual QoS performance requirements. However, all traffic have to go to the same endpoint, and it is not possible to assign extra capacity on demand.
- Passive Optical Network (PON): Aggregate data to the same link in the Optical Line Terminal (OLT) and requires uplink and downlink traffic to be handled differently. In [186], the use of PON as a transport medium for network slicing is demonstrated using VLAN and a new control plane to improve the flexibility of resource management and enable creation of different slices on demand. The uplink transmission is demonstrated in [187] proposing isolation of traffic from different slices inside the OLT. This enables the network to handle different amounts of data from different sources and network slices will have access to the uplink resources at different times [187], [188]. The downlink transmission is demonstrated using a scheduler, to ensure required and isolated QoS for the different slices [189].

The Core network is where all user requests are processed. The 5G core network is a service-based architecture, in which network functions cooperate to perform signaling procedures, such as connection, registration, mobility management, and session management [190]. Slicing the core network involves specifying network services according to the functional and quality requirements [190]. Hence, each slice is composed of a set of core network resources and is assigned to one or more services [191]. When multiple network slices are supported by the core network, a network slice selection function helps in effective slice instance selection during the UE registration and session establishment to an access management function [192]. The core network has VNFs classified as common network functions and special network functions [175]. The common network functions are shared by different slices, and the special network functions are dedicated for the related slice [175].

Multi-tenant networking energy savings: Compared to the savings achieved in the multi-operator network, then the multi-tenant network will additionally save energy in the RAN infrastructure and the core network. Infrastructure savings are estimated to result in 30% since much more traffic has to be carried by one network, and thus; expansions are expected to be necessary. From a CEX perspective, multi-tenant networking is not expected to bring any negative impact, it might be a positive impact due to the specialised handling of different use cases.

VII. DISCUSSION AND GUIDELINES

This work provided multiple ways for a network operator to reduce their energy consumption, but the big question is; where to begin? This section will elaborate on the proposals provided in the previous sections and assess which savings will matter the most, based on which part of the network they contribute to. Hence, first a per-unit overview is provided and then a set of guidelines directing more implementation specific goals.

A. PER-UNIT ENERGY REDUCTIONS

This subsection provides an overview of all parts of the RAN presented in Section III and how to improve the energy efficiency in the specific part, based on the lessons learned from Sections IV to VI.

Radio Processing is represented by the RU, which depending on the functional split used, will contain more or less functions. However, what is always present in the RU, is the power amplifier, which is the most energy consuming part of the RU [4]. Thus, from a radio processing perspective, the changes with the highest impact on the energy consumption will concern the amplifier. The amplifier's energy consumption can be minimised by reducing the distance between RU and antenna, use multi-band RUs, GaN materials and sleep modes such as symbol shut down or mMIMO muting. Other ways to improve the energy consumption of the RU can be to choose the most energy efficient RU on the market - enabled by open RAN; to share one network between different operators, minimising the total amount of RUs; or to use coordinated transmissions and MIMO power control. The sum of estimated savings proposed for the radio processing in Sections IV and V is around 57% utilising sleep modes, multi-band radios, coordinated transmissions and RU optimisations. This reduction corresponds to a 12% reduction of the mobile network energy consumption.

Air conditioning may vary in its impact of energy consumption, by the capacity of the air conditioning units and the climate [4] but also by the seasonal temperatures. However, in [4] air conditioning is stated to contribute to a large amount of the base station energy consumption. The air conditioning energy consumption can be reduced by gathering all baseband processing servers in datacenters, following the C-RAN architecture. Another way to reduce air condition energy consumption is to re-use the heat generated by the servers for other purposes. Thus, the sum of estimated savings proposed in Sections IV and V is around 52%, but this number is highly depending on whether and how much air conditioning is used.

Baseband processing represents a minor share of the total base station energy consumption. Methods to improve the baseband processing energy consumption is to use the most energy efficient HW; workload scheduling and load consolidation enabled by vRAN and C-RAN; or to introduce HW sleep states. The sum of estimated savings proposed for the baseband processing in Sections IV and V is around 42%.

Main control energy consumption improvement techniques include to choose the most energy efficient HW; use HW sleep states; or reduced inter-BBU communication overhead. The estimated savings proposed for the main control in Sections IV and V is around 22% utilising coordinated transmission, improved resource utilisation and HW sleep states.

Power supply energy consumption, can be reduced if multiple operators share the same network or if a carrier is shut down. The sum of estimated savings proposed in Sections IV and V is around 12%.

Estimated energy reduction potential: The outcome of energy saving potentials listed in this section are illustrated in Fig. 15. The figure shows how the energy consumption of the mobile network can be reduced by up to 35% using methods suggested in this work. The baseline to achieve these large savings is a network using a proprietary installation of distributed RAN, with no sleep modes, processing resource utilisation and less efficient power amplifiers, ie. none of all what was described earlier in this section. The contributions from Sections IV–VI to this overall saving are listed in Table 2. Hence, Table 2 lists the energy consumption savings for the different components, which using the model in Section III provides a saving of more than 30% of the overall mobile network energy consumption. This number is only including architectural and technological contributions, which are listed in column "total". Furthermore, great potential for energy savings is seen from Section VI, where a large amount of the RAN energy consumption can be saved by

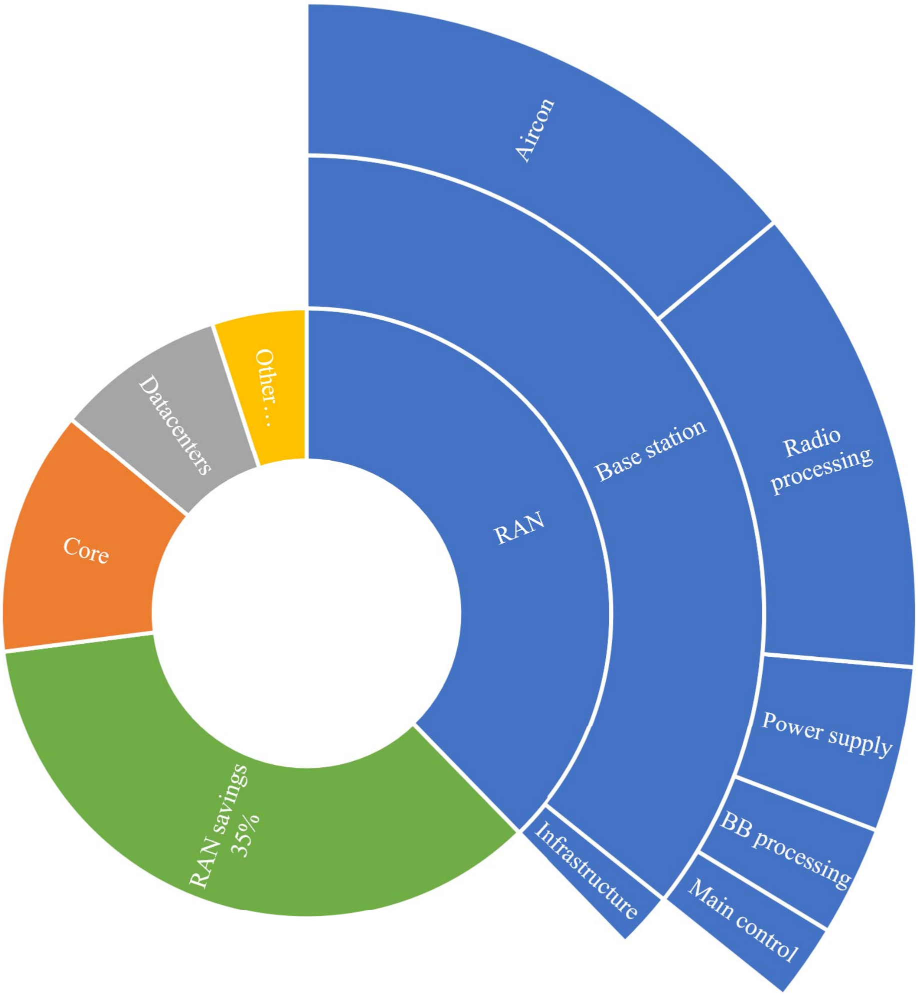

FIGURE 15. The energy consumption of the mobile network in the inner circle, showing 48% energy consumption savings in the RAN, corresponding to 35% of the total mobile network energy consumption. The middle circle shows the share of the RAN, divided out on base stations and infrastructure. The outer circle shows the base station components.

TABLE 2. Sum of estimated potential energy savings per base station component.

RAN component	Architecture	Technology	Total	Share of Mobile Network Energy Consumption Saving
Main control	20%	2%	22%	1%
Baseband processing	40%	2%	42%	2%
Power supply	10%	2%	12%	0.5%
Air condition	50%	2%	52%	15%
Radio processing	25%	32%	57%	16.5%

sharing the network with other operators. The exact number will, however; depend on a granularity of factors including the number of operators sharing the physical network.

B. GUIDELINES TOWARDS GREEN RAN

How will the future, energy optimised mobile network look like? This subsection provides guidelines for initial smaller changes with a large impact and then discusses the direction to move in for a brownfield operator and design implications for a greenfield operator.

1) INITIALLY

In a smaller and near-future timescale it is beneficial to look into changes that will show the largest possible impact with the least amount of work, the low-hanging fruits so to speak. Hence, a starting point is to consider optimisations of the RU, that can be incorporated as software updates. These optimisations count:

- Sleep modes
- AI predictions to optimise sleep modes
- Periodical roaming

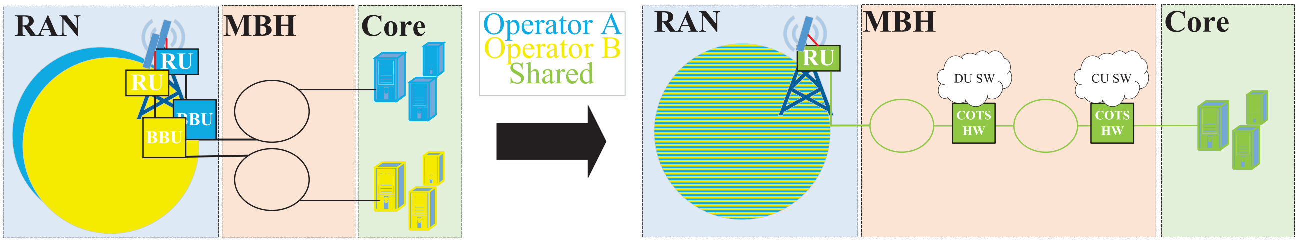

FIGURE 16. To the left is an illustration of the current network deployment for many operators. To the right is a proposal of the future energy optimised network architecture, exploiting the concepts of: C-RAN, vRAN and network sharing using network slicing. Hence, the baseband processing is carried out in software running on Commercial Off The Shelf (COTS) Hardware (HW) which is centralised in datacenters.

Following above recommendations will bring large energy savings to the network, but using minor changes. When equipment is changed any way, or new equipment is deployed, it will be beneficial to look into the following technologies:

- Multi-band RUs
- GaN amplifiers

This way, the network follows the energy optimised track and is prepared for future architectural changes. Another thing to introduce in the network, which will probably not bring the big energy savings right away, but rather prepare the network for future demands is:

- vRAN

2) LATER

In order to optimise the future mobile network in terms of energy usage, a completely new architectural design will result in the most significant impact. Hence, a proposal is illustrated in Fig. 16, utilising the concepts of:

- C-RAN
- Network sharing
- Open RAN

Paving the way towards the mobile network of the future, many operations can be executed by the operator self, and introducing C-RAN in a network already enabled by vRAN, the network operator must be mindful of; fronthaul network and cloud control. Furthermore, it is important to evolve a deployment strategy, determining if the CU and DU functions should be handled in the same datacenter or at different distances.

Moving to a shared network or to open RAN requires collaboration with more stakeholders. Moving to a shared network solution requires a number of network operators to agree on collaborating and corresponding terms and conditions. Moving to an open RAN solution requires for the network operator to find the right products and partnerships as well as finding a way to manage and orchestrate the multi-vendor network.

Figure 16 shows how the current network of today is designed in many countries; each network operator run their own network and BB processing is not shared. The proposal of the future energy optimised network architecture design, to the right in Fig. 16, utilises visions of shared RAN and shared BB processing. Furthermore, the SW is decoupled from the HW opening up the opportunity of choosing the most energy efficient equipment available and a much higher degree of network control. A centralised network control, which can be supported by AI techniques will optimise functions such as load control, load consolidation, dynamic processing selection and sleep modes. Furthermore, opportunities for achieving CO2 neutrality, as presented in Section V, can make a great change and lead the network operator towards a green, CO2 neutral future.

Changes toward an energy consumption minimised future RAN presented in this work are many-fold and in some cases they also point in opposite directions. Thus, choices to make as a network operator are not always straight forward, and changes can appear at many different levels. Figure 17 illustrates, the pains and gains of a network operator in terms of CEX and energy savings. Furthermore, the technologies presented are represented by how much effort their implementation require, this is illustrated by different colours. The graph shows in the upper right part technologies that will both improve CEX and energy consumption. In the lower right part of the graph are technologies that will not improve CEX, but will improve the energy consumption. Hence, introducing “sleep modes”, will lead to degraded CEX, as they add delay or reduce capacity, however; they improve the energy savings and they are fairly easy to implement. Thus, sleep modes are placed in a negative position on the CEX axis, in a positive position on the energy saving axis and coloured green for minimal effort. On the other hand introducing “zero touch networks”, requires a medium effort, because it is a complex process, maybe even tangible to large installation effort. However, zero touch networks will to a large extend optimise the networks and thus; is placed on a very positive position of both the CEX axis and the energy savings axis.

3) GREENFIELD GOING GREEN

Being a greenfield operator, starting from “the scratch”, means that there is no legacy to be mindful about. Hence, a greenfield operator can choose the most modern and energy efficient way to deploy the network. Thus, greenfield installations conducted within the latest years use both C-RAN, vRAN and open RAN architectures. As illustrated in the right side of Fig. 16. Examples of network operators deploying

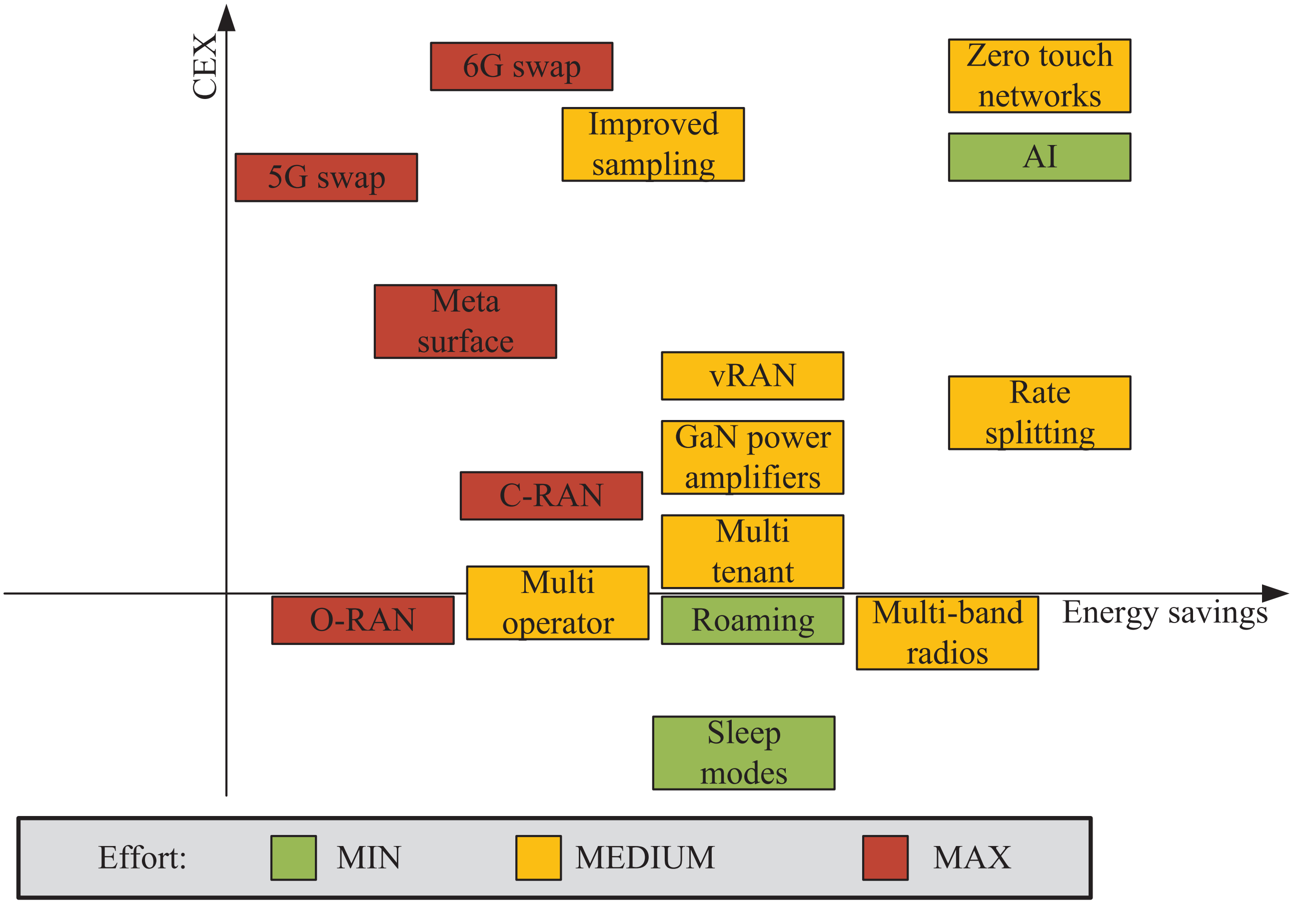

FIGURE 17. Pain and gain map over Customer Experience (CEX) and energy savings. Hence, the upper right part of the figure shows technologies that benefits both energy and CEX. Correspondingly, the lower right part of the figure shows the technologies that will benefit the energy consumption but at the cost of lower CEX. Technologies are marked by different colours depending on the implementation effort they require.

greenfield networks within the latest years count DISH in the U.S. [193], Rakuten in Japan [194], [195] and 1&1 in Germany [196]. However, these greenfield operators are rolling out their installations in countries where multiple other networks already exist, therefore; one may think, is yet another network actually necessary? On the other hand, these new and modern installations can potentially allow for future tenants, to minimise the footprint of mobile networks.

VIII. CONCLUSION

This work outlined different technological and architectural improvements that will minimise the energy consumption of future mobile networks. Furthermore, current research directions and visions for green 6G were examined. Different proposals for energy reductions were analysed and their contributions were compared and evaluated in the perspective of their energy consumption minimisation potential for future mobile networks. It was shown how future network architectures can be energy optimised by exploring the potential of new architectures, network sharing opportunities and features enabled by emerging technologies in different areas. Hence, by highlighting research trends in areas like power amplifier minimisation and resource utilisation. Opportunities identified by this work are proposed together with concrete deployment methods. Results demonstrate an overview of the different energy minimisation methods examined in relation to their overall energy reduction contributions. Results show that implementing selected features and architectures, the mobile network overall energy consumption can be reduced by approximately 30%. Following this, a set of guidelines for the brownfield network operator's road towards an energy optimised mobile network was provided. These guidelines proposed initial changes and changes for the longer run as well as a roadmap over pains and gains related to CEX and energy savings. Finally a vision for the future energy optimised mobile network architecture was presented utilising the concepts of C-RAN and multi-tenant networks.

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ACRONYMS

3GPP	3rd Generation Partnership Project.
ACK	Acknowledgement.
ADC	Analogue-to-Digital Converter.
AI	Artificial Intelligence.
ANN	Artificial Neural Networks.
ASM	Advanced Sleep Mode.
BB	Baseband.
BBU	Baseband Unit.
BLR	Block Linear Regression.
C-RAN	Cloud RAN.
CEX	Customer Experience.
CNF	Cloud-Native Network Function.
CoMP	Coordinated Multipoint.
COTS	Commercial off the Shelf.
CPRI	Common Public Radio Interface.
CPU	Central Processing Unit.
CSI	Channel State Information.
CU	Centralised Unit.
DL	Deep Learning.
DU	Distributed Unit.
ETSI	European Telecommunications Standards Institute.
GaN	Gallium Nitride.
GSMA	GSM Association.
HARQ	Hybrid Automatic Repeat Request.
HLS	High Layer Split.
HW	Hardware.
ICT	Information and Communications Technology.
IoT	Internet of Things.
IQ	In-phase Quadrature.
IRS	Intelligent Reflecting Surfaces.
KPI	Key Performance Indicator.
LESS	Low Energy Scheduler Solution.
LLS	Low Layer Split.
LSTM	Long Short-Term Memory.
MANO	Management and Orchestration.
MBH	Mobile Backhaul.
MDAF	Management Data Analytics Function.
MIMO	Multiple Input Multiple Output.
ML	Machine Learning.
mMIMO	massive MIMO.
mmwaves	milimeter waves.
MOCN	Multi-Operator Core Networks.
MORAN	Multi-Operator RAN.
NFV	Network Function Virtualisation.
NGMN	Next Generation Mobile Networks.
NOMA	Non-Orthogonal Multiple Access.
NWDAF	Network Data Analytics Function.
OFDM	Orthogonal Frequency Division Multiplexing.
OLT	Optical Line Terminal.
PLMN	Public Land Mobile Network.
PON	Passive Optical Network.
PRB	Physical Resource Block.
PS	Power Splitting.
QoS	Quality of Service.
RAN	Radio Access Network.
RATs	Radio Access Technologies.
RF	Radio Frequency.
RIC	Radio Intelligent Controller.
RU	Radio Unit.
SCMA	Sparse Code Multiple Access.
SFP	Small Formfactor Pluggable.
SLA	Service Level Agreement.
SNR	Signal to Noise Ratio.
SON	Self-Organising Network.
SW	Software.
SWIPT	Synchronous Wireless Information and Power Transmission.
TIP	Telecom Infra Project.
TS	Time Switching.
TTI	Transmission Time Intervals.
UE	User Entity.
UK	United Kingdom.
VLAN	Virtual Local Area Network.
VNF	Virtual Network Function.
vRAN	virtual RAN.
WDM	Wave Division Multiplexing.

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