NOKIA

The path to 6G with unparalleled energy savings

A 3GPP standardization perspective

White paper

Daniela Laselva, Kamakshi L K, Ahlem Khlass, Mohamad Sayed Hassan, Mads Lauridsen, Maria Oikonomakou, Naizheng Zheng, Anna Pantelidou, Sina Khatibi, Tejas Subramanya, Borislava Gajic, Chaima Ghribi and Abdelrahman Abdelkader

Contents

Executive summary	3
Introduction	4
Foundations of sustainable 6G networks	6
End-to-end energy-saving design for 6G	8
6G RAN energy savings in 3GPP	9
On-demand SIB1	10
Paging adaptations in time domain	12
PRACH adaptation in time domain	13
On-demand SSB SCell for multi-carrier operation	14
AI/ML for 6G RAN energy savings	16
Current approaches	16
Advances towards 6G	17
Sustainable AI	18
Evaluating 6G RAN energy savings in 3GPP	20
Summary and outlook	22
Abbreviations	23
References	24

Executive summary

Mobile network operators face the challenge of meeting increasing traffic demands while adhering to sustainability goals and managing high energy costs. While 6G will be fundamental to accommodate the growing demand for network capacity, it is imperative that it is designed with sustainability at its core to benefit both the environment and society. From an environmental sustainability perspective, it is crucial to minimize the overall energy consumption of 6G networks through energy-saving designs right from the first release, with enhanced energy efficiency playing a key role to achieve this.

This white paper presents Nokia's vision for achieving unparalleled energy savings in 6G networks. It begins by sketching the foundational principles for designing, deploying and operating environmentally sustainable end-to-end 6G networks. Crucially, the 6G design should prioritize not only end-user performance but also optimizations based on energy costs, energy availability and carbon intensity. The paper then delves into energy-saving RAN design, emphasizing the importance of 3GPP standardization of an AI-native, energy-saving air interface and superior vendor innovations, such as advanced base station hardware and AI/ML optimizations. It also details the compelling RAN energy-saving features of 5G-Advanced and their potential adoption by 6G RAN design, along with their beneficial extensions tailored for 6G. The paper demonstrates how 5G-Advanced establishes a strong foundation for 6G, enabling dynamic and granular optimization of energy use in base stations according to load. This ensures efficient handling in 6G of all traffic scenarios from day one, including the often occurring low-to-medium load conditions.

Compared to 5G-Advanced, significant 6G RAN energy reduction can be expected due to the ability to apply the entire network energy-saving toolbox across all cells and all 6G devices from day one and, thanks to more pervasive AI/ML-driven optimizations, leveraging the native AI design of 6G. However, one of the key challenges in 6G will be balancing AI/ML performance with its environmental impact. Further energy reductions can be achieved in deployments where 6G leverages new power-efficient base station hardware.

Finally, the paper underscores the need for a standardized methodology to evaluate 6G RAN energy-saving potential, building upon the framework established in 5G-Advanced. This methodology will be crucial for identifying the most effective features to be standardized, ensuring a fair and consistent assessment across scenarios and technologies, and facilitating accurate comparisons of energy-saving improvements from 5G to 6G.

Introduction

Environmental sustainability and saving energy are key priorities for Nokia. We have set ambitious targets to reduce greenhouse gas (GHG) emissions and achieve net zero emissions [1]. By 2040, Nokia aims to achieve net zero in its total GHG emissions for Scope 1, 2 and 3. This encompasses emissions from direct operations (Scope 1), indirect emissions from purchased electricity (Scope 2), and indirect emissions from the value chain (Scope 3). Achieving net zero emissions is a significant milestone in Nokia's sustainability journey and reflects our dedication to mitigate climate change.

To reach the net zero targets, Nokia is taking various actions within the information and communication technologies (ICT) industry. One of the key focus areas is energy savings. Nokia recognizes the importance of optimizing energy consumption in its operations and products. By improving energy use in its products and offerings, Nokia can reduce its carbon footprint and contribute to a more sustainable future.

Mobile radio networks generate the vast majority (95%) of their lifecycle GHG emissions during their operational phase if renewable energy utilization is low, making energy reduction in operation crucial for lowering emissions and operational expenses. The radio access network (RAN) consumes the largest portion of energy in mobile networks, accounting for 76% of operator energy usage according to a GSMA report [2]. Thus, while energy reduction is crucial across the entire mobile network, optimizing RAN energy consumption is essential for climate goals and profitability. Consequently, this remains a top priority for 6G.

As 6G will play a crucial role in meeting the rising demand for network capacity, it is essential to minimize the overall energy use of 6G networks, considering the growing traffic demands and stringent sustainability targets [3]. Like previous generations, 6G is expected to further enhance energy efficiency through advancements in spectral efficiency, enabling higher data transmission with less energy consumption. However, these advancements often come at the cost of increased instantaneous power consumption, as they rely on power-hungry resources like extreme MIMO and functionalities like artificial intelligence and machine learning — AI/ML Deep Rx. Thus, although mobile network energy efficiency has improved significantly in recent years, as shown in Figure 1, particularly as the 5G radio generation with massive MIMO was adopted and its utilization increased, base stations remain energy intensive. This underscores the need for continued efforts to reduce network energy consumption.

The aim should be an overall reduction of 6G energy consumption compared to previous technologies as show in Figure 2. Special focus in 6G is needed on two fronts. Firstly, it is crucial to enhance energy savings during low-to-medium load scenarios, essentially moving towards near-zero power consumption when there are no active users. Although these scenarios consume lower power than high load scenarios, they have the largest energy-saving potential because they occur the most frequently in today's networks, which are characterized by highly uneven traffic distribution in time and space. For example, in [5], it was shown that today 70% of base stations carry only 20% of the total traffic resulting in their persistent under-utilization.

Secondly, to achieve a substantial reduction in energy per bit, it is also essential to maximize the efficiency of the network under mid-to-high load conditions. This can be accomplished by enhancing spectral efficiency and enabling energy-efficient data transfers, with dynamically adapting hardware resource utilization based on the load. Therefore, in this paper, we focus on network energy saving (NES) design for 6G, where energy efficiency improvements are a key strategy to achieve this goal.

Figure 1. Example of the positive evolution of energy efficiency (Gigabytes of data per kilowatt-hour) in mobile networks based on data from [4]

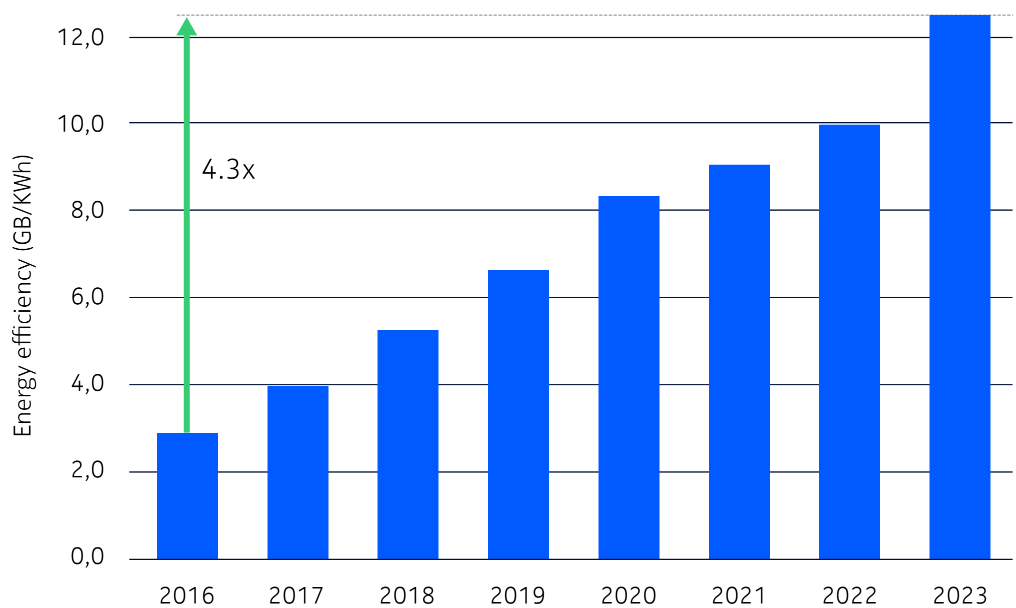
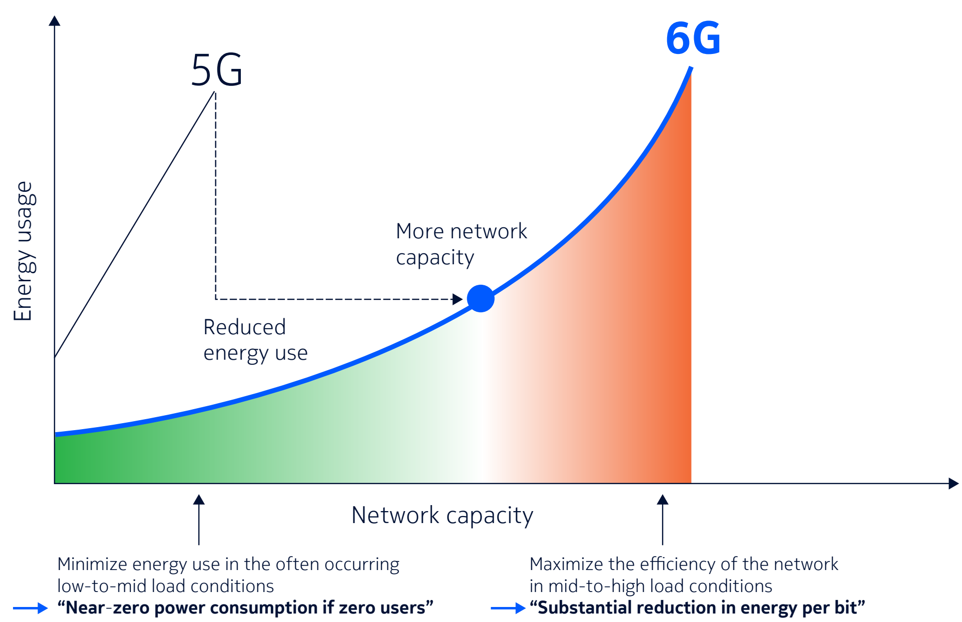


Figure 2. Targeted reduction in 6G power consumption compared to 5G

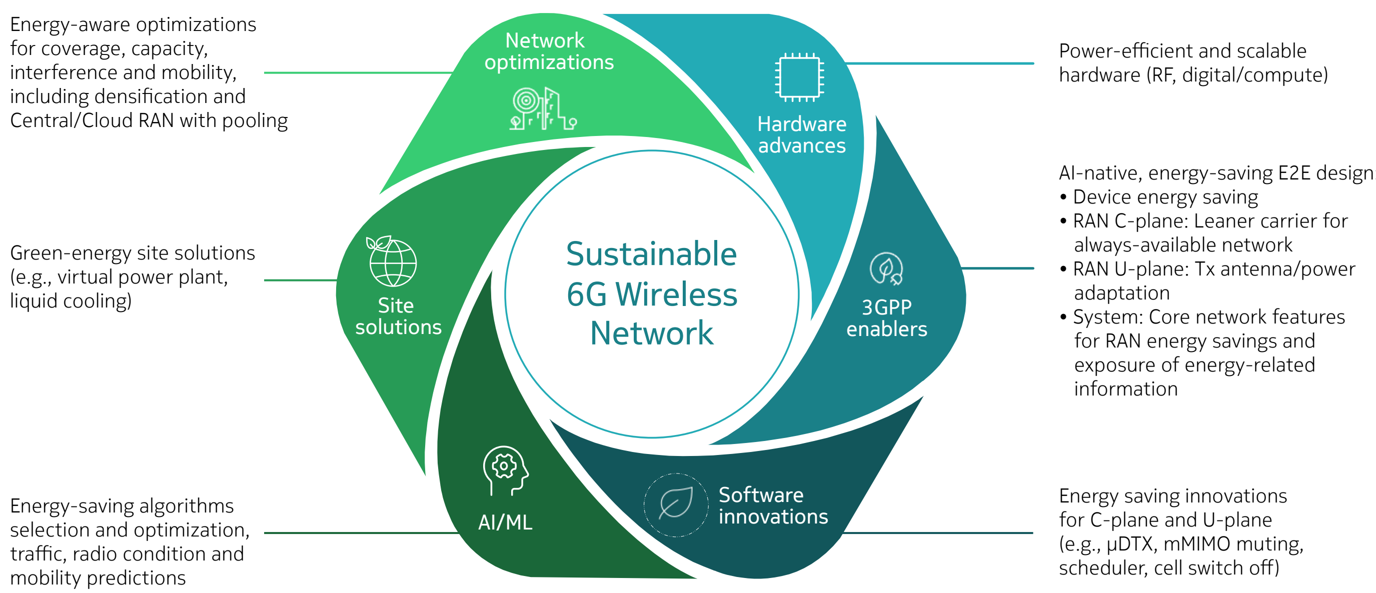


Foundations of sustainable 6G networks

The development and deployment of 6G networks are expected to align with and support broader societal goals, positively impacting both the environment and society. 6G networks should embody key sustainability values, acting as a transformative force for both society and industries, enhancing overall sustainability and increasing their positive handprint [6]. From an environmental perspective, achieving sustainability in mobile networks requires both reducing energy consumption and lowering the carbon intensity of the energy used. Therefore, 6G must prioritize energy savings, significantly improving energy use compared to 5G, particularly in low-to-medium loading scenarios. Additionally, the use of renewable energy sources should be prioritized to the greatest extent possible.

Nokia believes that to achieve this, six key sustainability strategies are required as shown in Figure 3.

Figure 3. Nokia's six key strategies for environmentally sustainable 6G networks



These strategies encompass:

1. **Advances in Nokia base station hardware**, such as fast deep sleep modes, efficient power amplifiers, modularized SoCs (system on a chip) and improved hybrid/analog beamforming architectures, aim to reduce power consumption [7]. Particularly, the ability of fast reactivating hardware radio frequency (RF) resources will significantly help limit unnecessary power usage.

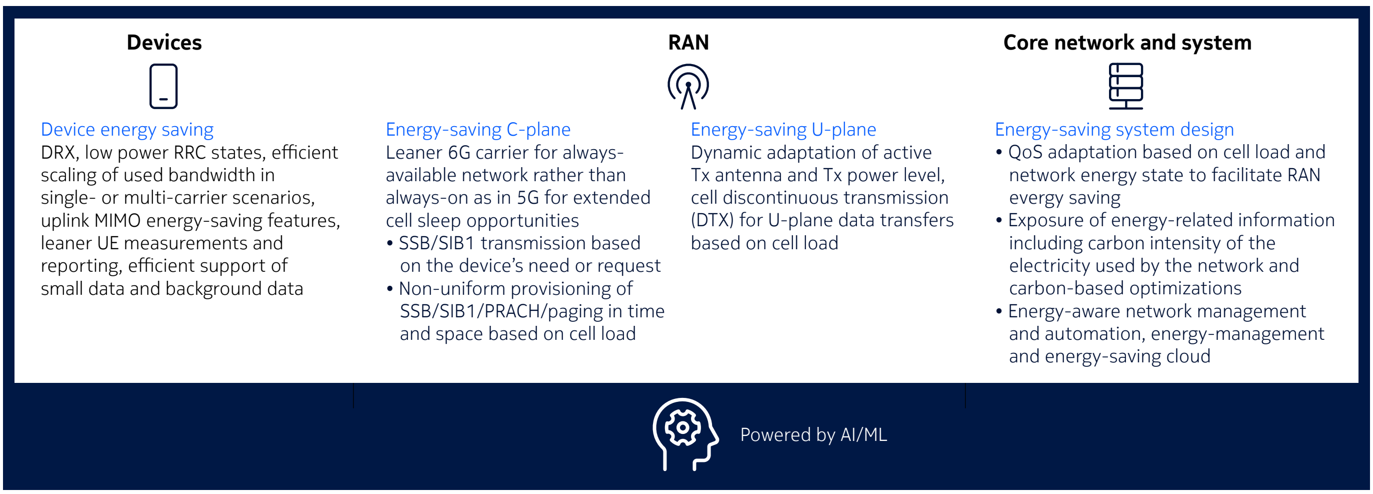
2. **3GPP enablers for energy savings and carbon emission reduction**, particularly in the RAN, but also encompassing devices, core network and system level, aim to ensure comprehensively end-to-end (E2E) energy use minimization. These enablers should be designed to reduce the air interface control-plane signalling and to dynamically adapt to dynamically adapt hardware resources utilization, aligning energy consumption with traffic fluctuations and quality of service/experience (QoS/QoE) targets. They should leverage the capabilities of efficient and modularized hardware to optimize energy use effectively. The 3GPP enablers are further elaborated in the section below, "End-to-end energy-saving design for 6G", focusing on the E2E perspective, and the following section, which details the RAN view.
3. **Nokia software innovations**, including improved scheduling and energy solutions, are key to enhance energy savings [8]. Furthermore, scalable signal processing, intelligent massive MIMO muting solutions, and advanced digital predistortion techniques, which improve the linearity and efficiency of power amplifiers in base stations, will be crucial for 6G. These advancements should leverage both new hardware capabilities and the 3GPP enablers discussed above.
4. **Energy-conscious AI/ML** can assist in selecting and optimizing energy-saving algorithms. By leveraging their predictive capabilities, AI/ML algorithms can optimize energy use by anticipating user equipment (UE) mobility and cell load variations, enabling optimal power state determination and dynamic adjustments for base stations. The application of AI/ML in the RAN, including aspects of data collection, model training and inference, and examples of Nokia offerings, are detailed in the section entitled "AI/ML for 6G RAN energy savings". However, the AI/ML solutions themselves must be designed with energy efficiency in mind and be energy conscious. It is crucial that the benefits of AI/ML systems outweigh their impact, and this impact should be assessed using standardized methods as described in [9].
5. **Nokia's sustainability site solutions** such as virtual power plant (VPP) for base stations and liquid cooling solutions [8] are essential to minimize the energy consumption and carbon intensity of the entire base station site. For example, Nokia's VPP aggregates power grids, renewable energy sources, and batteries to create a virtual power plant. Using AI/ML, it optimizes energy management, enabling dynamic response to grid fluctuations by utilizing available reserves. This improves grid stability and reduces energy costs.
6. **Energy-aware network and deployment optimizations** should balance energy consumption with network performance metrics like coverage and capacity [8]. For example, Nokia's Digital Design [8] optimizes radio configuration per cell and minimizes energy consumption by reducing overall transmit power while maintaining performance. Another example is network densification, which can enhance energy use by optimizing resource allocation closer to where it is needed. Furthermore, the implementation of network virtualization and cloudification in the RAN and core network minimizes redundant infrastructure and can scale up or down based on real-time traffic demands. During periods of low demand, virtual machines or network functions can be powered down or put into a low-power state, saving energy.

Lastly, in addition to the technological developments discussed above, promoting user awareness of their data consumption could also play a role in curbing data growth. Informing users about the impact of their data usage and encouraging more responsible consumption habits can complement technological advancements, leading to a more sustainable and efficient network ecosystem.

End-to-end energy-saving design for 6G

The 3GPP enablers for 6G, introduced above, are further elaborated in this section from an E2E perspective. Nokia envisions four key functionalities as necessary for an E2E 6G design that save energy and reduce carbon emissions , which should be powered by AI/ML, as shown in Figure 4.

Figure 4. Four key functionalities for E2E energy-saving and carbon emissions reduction in 6G design from a 3GPP standards perspective



These functionalities include device energy saving, where schemes like UE discontinuous reception (DRX) and efficient support for small data transmission will remain essential in 6G, just as they are in 5G [10]. Device energy saving not only promotes energy conservation but also enhances end-user satisfaction by providing extended battery life.

In the RAN, an energy-saving design for both the control plane (C-plane) and user plane (U-plane) of the 6G radio interface will be key. An energy-saving C-plane design is fundamental to achieving an 'always-available' 6G network rather than 'always-on', for example, by extending the schemes for on-demand request by a device of synchronization signal blocks (SSBs) and essential system information introduced in 5G-Advanced, and by decoupling SSB from system information transmissions (SIB1). The energy-saving U-plane design should enable dynamic radio resource adaptations based on cell load and QoS/QoE targets to ensure energy-efficient transmissions of user data when leveraging the new hardware capability of fast reactivation [11]. The RAN design is further elaborated in the following section.

Furthermore, 6G should adopt a holistic, energy-saving and carbon-aware system design. In contrast to today's mobile networks, which prioritize top end-user performance as the primary design criterion, 6G networks should be designed to consider additional factors such as energy costs, energy availability and carbon intensity. By incorporating these criteria, 6G networks can efficiently adjust data rates and latency to optimize performance and reduce environmental impact. This adaptability relies on exposing energy-related information within the network, enabling intelligent energy/carbon-aware decision-making. For example, QoS policy control can be implemented to adjust QoS parameters and U-plane path based on energy consumption and carbon emissions. Network function selection can be optimized to prioritize functions with lower energy footprints. Furthermore, energy-aware mobile subscriptions of end-users could incentivize lower energy usage through new charging mechanisms and rewards. These developments are currently being explored for 5G-Advanced, with Nokia being very active in driving these advancements. They are anticipated to be fully mature and ready for incorporation into 6G from day one.

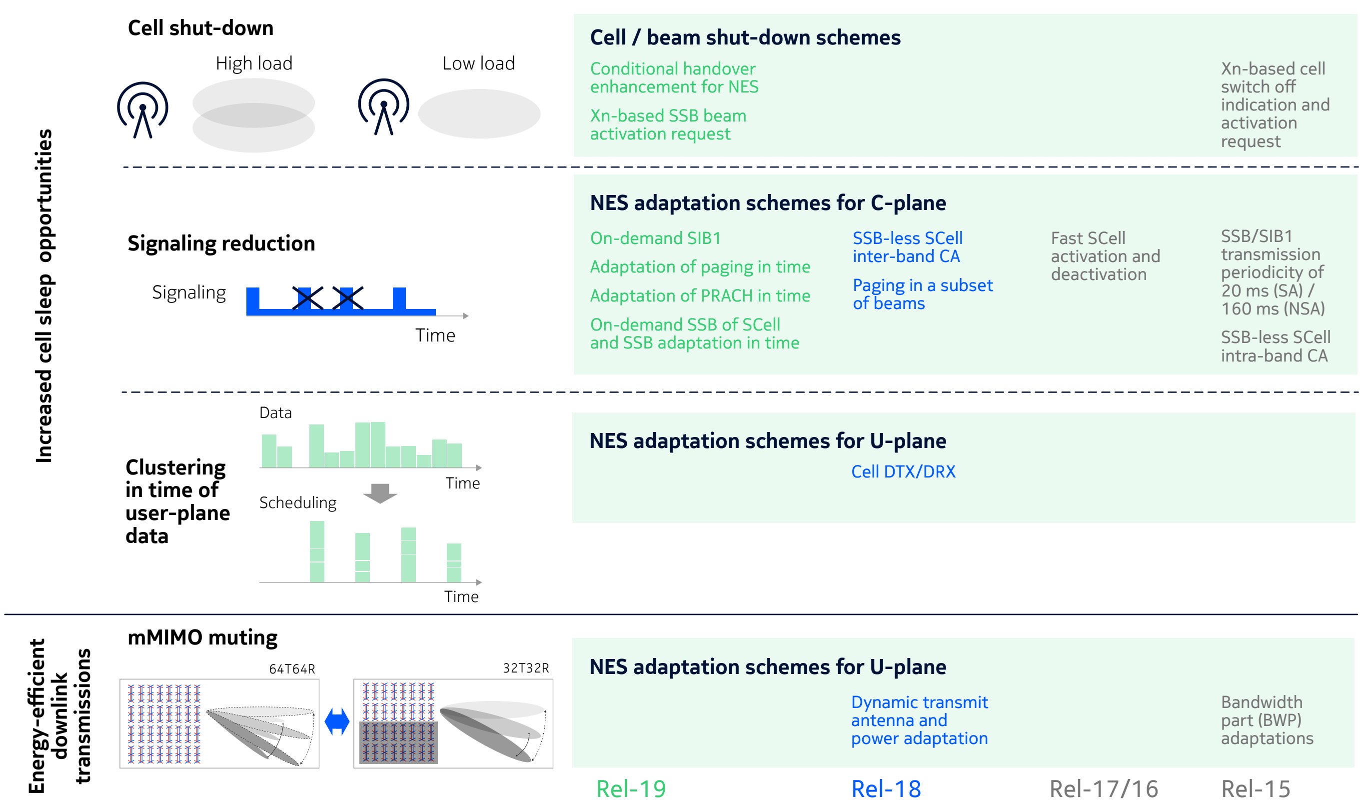
6G RAN energy savings in 3GPP

This section delves into the energy-saving design of the 6G RAN, specifically focusing on the C-plane and U-plane aspects. Building upon the strong foundation of 5G-Advanced, we aim for a smooth evolution that leverages proven energy-saving features of 5G-Advanced while incorporating extensions tailored to 6G. Our approach prioritizes the adoption of energy-saving solutions already validated in 5G-Advanced, which have demonstrated significant gains in network energy savings (NES) with manageable complexity. Unlike 5G-Advanced, where backward compatibility and UE support are a concern, in 6G we can assume that all devices will support these network energy-saving features from day one. This will allow 6G cells to serve all devices while benefiting from their full energy-saving potential. Furthermore, as our understanding of optimal energy-saving design evolves, exploration of more disruptive solutions for 6G will continue, but the trade-offs between energy savings and complexity should be carefully considered.

Figure 5 provides a comprehensive overview of proven energy-saving features in 5G-Advanced RANs, serving as a solid foundation for 6G development. These features are categorized based on their 3GPP release and the underlying NES gain mechanism:

- **Increasing cell sleep opportunities:** This category focuses on minimizing energy consumption during periods of network inactivity by maximizing cell sleep opportunities, effectively reducing power consumption when network traffic is low, leading to significant energy savings
- **Enabling more energy-efficient transmissions:** This category emphasizes optimizing energy consumption during active communication phases by implementing techniques that minimize energy expenditure during data transmission, ensuring efficient use of radio resources while maintaining high-quality communications.

Figure 5. Overview of the RAN NES techniques that can be leveraged in 6G, categorized based on the corresponding NES gain mechanism and 3GPP release



The Release 18 features, highlighted with blue marking in Figure 4, include enhanced conditional handover to enable robust traffic offloading upon cell switch-off, SSB-less secondary cell for inter-band scenarios, cell discontinuous transmission and reception (DTX/DRX), and dynamic power and antenna adaptations based on UE feedback. We analyzed these in [3], and the latter feature was proven to be the most effective and will be even more critical in 6G. Employing higher frequency bands above 6GHz, as anticipated in 6G, necessitates a greater number of RF chains, which consequently leads to increased instantaneous power consumption during full resource utilization. However, by strategically activating the full set of RF chains for limited durations and swiftly deactivating them when not needed, the overall energy consumption can be significantly mitigated.

In the following, we explore the new energy-saving features of Release 19, highlighted with green in Figure 4. We emphasize their potential for adoption and extension in 6G to enhance the efficiency of 6G networks by enabling non-uniform and dynamic provisioning of C-plane channels and signals such as essential system information, paging, PRACH, and SSBs in time/space based on load. While many aspects are still under discussion and the final specifications for Release 19 are expected by mid-2025, the logic and benefits of these techniques are already evident.

Release 20 of 5G-Advanced is also expected to introduce further enhancements. Once the details of these developments become available, their potential applicability to 6G should also be assessed. Notably, the features shown in Figure 4 can be optimized using ML-based algorithms for their configuration and (de)-activation. Section 6 elaborates on how AI/ML capabilities can be leveraged to achieve energy savings in 6G RAN and assist in optimizing energy-saving features.

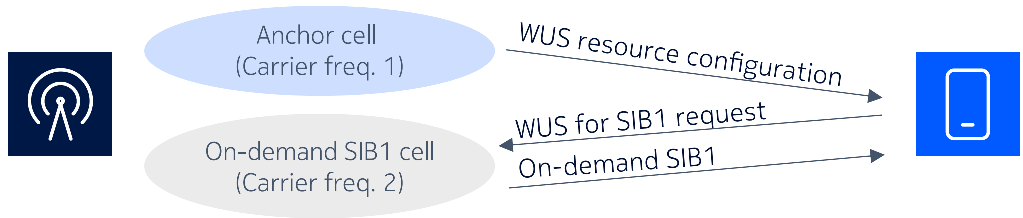
On-demand SIB1

The system information block 1 (SIB1) provides essential information that allows the UE in radio resource control (RRC) Idle/Inactive state to access the network and perform initial cell selection and reselection. In the current 5G new radio (NR) design, the SIB1 is transmitted periodically in all the SSB beam directions as an ‘always-on’ signal, regardless of whether any UE requires the SIB1 acquisition. This design results in relatively large and unnecessary network energy consumption. The on-demand SIB1 feature in Release 19, instead, enables the SIB1 transmission to be made on-demand, based on the UE requesting the transmission of SIB1 and only in the requested SSB beam direction. This enables the cell to enter sleep mode more frequently.

Upon need (e.g., at reselection of a cell using on-demand SIB1 operation), the UE can trigger the SIB1 transmission by sending a wakeup signal (WUS), i.e., a random-access preamble. This requires that the UE can detect and measure the cell (based on regular transmission of SSB) and is configured with WUS resources. While the on-demand SIB1 procedure may introduce a minor increase in SIB1 acquisition latency, this impact is expected to be negligible in practice. The procedure is carried out during cell reselection and does not affect user plane performance.

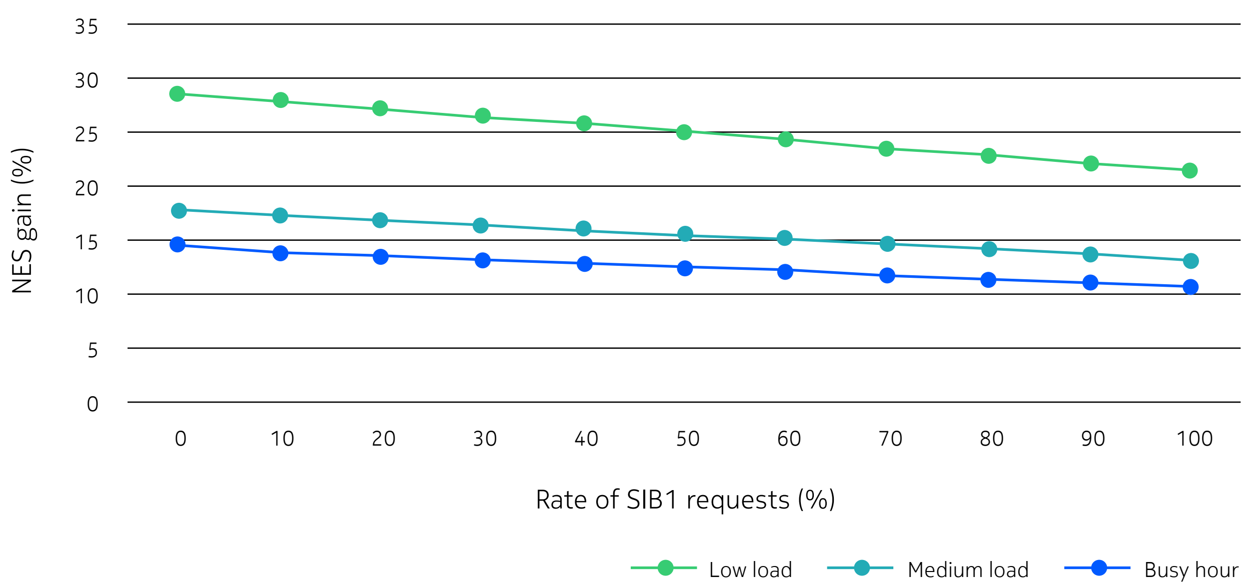
In Release 19, on-demand SIB1 can be applied only in multi-carrier scenarios, in which the cell using on-demand SIB1 mode (referred to as ‘NES cell’) is assisted by an anchor cell for the provisioning of the WUS resource configuration to the UEs, as shown in Figure 6. This is needed to minimize the impact on specifications and legacy UEs, which should bar the NES cell because they lack the capability to request SIB1. As a result, the activation of this feature in 5G-Advanced necessitates the creation of “Release 19 UE-only” cells, which are specifically designed for devices that support this new functionality.

Figure 6. On-demand-SIB1 operation with the support of an anchor cell



The NES gain achieved by on-demand SIB1 can be significant as per the results observed in Figure 6. Those are based on the 3GPP evaluation methodology, which assumes a specific radio configuration, FTP traffic model, and, importantly, 3GPP-defined base station power consumption modeling. The considered macro scenario has a colocated anchor cell and NES cell both using TDD, FR1, 64 Tx antennas and 5 Watt per Tx antenna, as reported in [14]. The gain varies between 11% and 29% depending on the SIB1 request rate and load. As expected, the gain increases when the NES cell load is lowest and the rate of SIB1 request is minimal. As observed, 11% gain is obtained at busy hour even for a SIB1 request rate of 100%, i.e., when there is at least one request for a beam every 20 ms. This is because the on-demand SIB1 transmission takes place on a single beam (from which the request comes) rather than all SSB beams, as in the baseline. Also, differently from user plane data that can be transmitted simultaneously over different beams, the SIB1 towards different beams must be transmitted in different time slots. Therefore, the number of SSB beams also influences the gain, as the baseline scenario entails regular SIB1 transmission over all the beam directions. In the presented results, eight SSB beams and 20 ms SIB1 repetition periodicity are assumed for the baseline scenario.

Figure 7. NES gain of on-demand-SIB1 operation as a function of the SIB1 request rate and for different NES cell load levels (low load, medium load, and busy hour as per ETSI definitions [13]) compared to today's SIB1 broadcasting every 20 ms



Potential for adoption and extensions for 6G

The regular beam-swept SIB1 transmission of NR incurs a high energy cost for the network and should therefore be minimized in 6G. On-demand SIB1 holds significant potential for adoption in 6G. As 6G overcomes the limitations of 5G-Advanced, several extensions of this feature can be considered for 6G, with standalone on-demand SIB1 operations (without the need for an anchor cell) being a key enhancement. Furthermore, the support of on-demand SIB1 by all UEs in 6G enables its wide adoption across all cells, including both coverage and capacity cells, provided that the service latency targets can be met. One alternative to reduce SIB1 transmissions is to eliminate these transmissions from capacity cells by relying on SIB1 provisioning via coverage cells, either through broadcast or on-demand methods, with the latter offering additional gains.

Paging adaptations in time domain

Paging enables the network to reach the UEs when they are in RRC Idle and Inactive state, as the UE will periodically monitor paging where the network can indicate it has pending data. The periodic monitoring, made according to the UE's paging cycle, benefits the UE battery life because the UE avoids continuous monitoring. This comes at the cost of increased packet latency since the UE can only be reached once per paging cycle (e.g., every second).

The paging cycle is composed of uniformly time-distributed paging frames occurring with 10–160 ms periodicity. Each paging frame is associated with one, two or four paging occasions, and a given UE is mapped to a single paging occasion based on the UE-specific identifier in the paging cycle. The paging occasion is a control channel monitoring occasion where the UE monitors for potential paging indication from the network. If received, such indication would trigger the UE to contact the network (e.g., in case of pending downlink data).

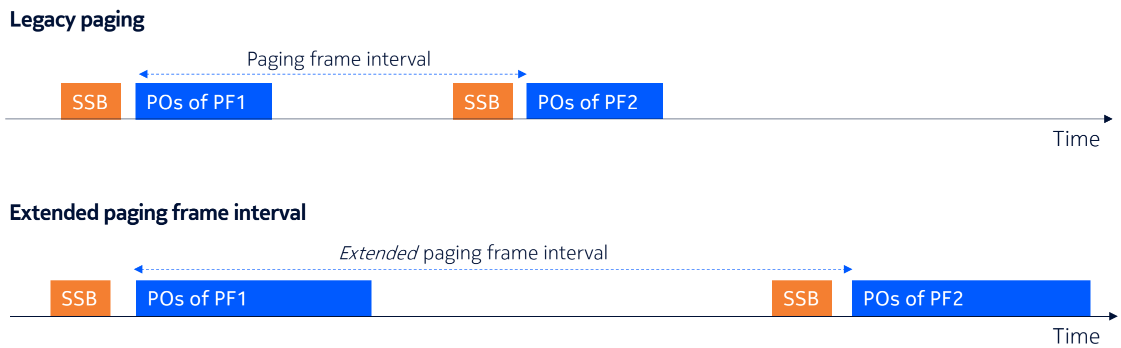
In summary, the current paging design causes the paging occasions of different UEs to be distributed in the time domain. The scheme was designed this way to distribute resource load over time and ensure sufficient resource capacity for paging signaling and the related random access (RA) procedure, which is started by a UE in response to the paging. Thus, the current paging design limits the RAN node sleeping opportunities, which is an important NES gain mechanism. Even at low paging load, the UEs may be paged in widely separated time occasions because the occasions are determined randomly based on the UE identifiers.

The Release 19 paging adaptation enhancement targets reduce the number of distributed paging transmissions by clustering the paging occasions of different UEs closely together in time. This enables longer cell sleeping opportunities and potentially allows the network to allocate less distributed RA occasions for the UE responses. Furthermore, it allows concentration of reference signal transmissions near the clustered paging for the UE to be ready to receive the paging.

The scheme may be implemented by extending the paging frame interval so that the paging frames are more interspaced as compared to the legacy interval, as illustrated in Figure 7. Each paging frame may, however, contain more paging occasions compared to the legacy paging to maintain the same paging capacity.

The clustering of paging occasions does not impact the paging latency because only the paging occasions within the paging cycle are changed for the Release 19 UEs and not the cycle itself. This is why legacy UEs can continue to operate according to the legacy paging scheme, which avoids backwards compatibility issues and "Release 19 UE-only" cells.

Figure 8. Enhanced paging with extended paging frame interval and legacy approach



Potential for adoption and extensions for 6G

In 6G, the non-uniform provisioning (in time) of paging opportunities based on paging load can enhance energy savings. Given that all UEs are expected to support clustered paging, this approach will significantly optimize energy use in 6G.

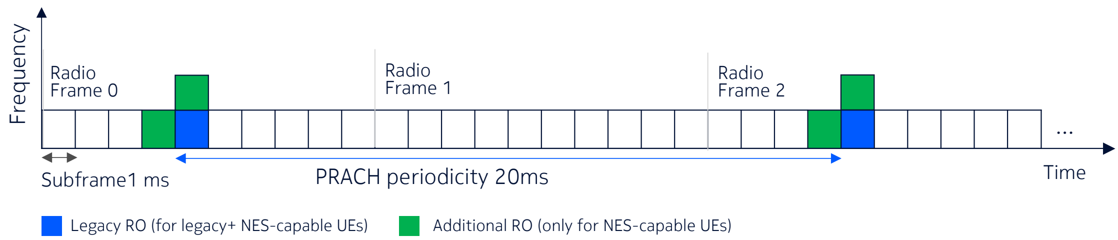
PRACH adaptation in time domain

The RA procedure allows the UE to establish or resume a connection with the network when it does not have any dedicated resources for signaling, for example, for initial access from an RRC Idle/Inactive state. The UE initiates the RA procedure by transmitting a physical RA channel (PRACH) preamble. The network is required to monitor for the regular PRACH transmission occasions, which may be potentially used by the UE, thus limiting cell sleep opportunities.

Release 19 time-domain adaptation of PRACH enables flexible resource allocation. This allows for provisioning sparser PRACH resources for legacy UEs in low-load scenarios, promoting energy savings, while providing additional resources to NES-capable UEs to increase RA channel (RACH) capacity when needed. The additional resources are designed for more dynamic activation and deactivation compared to current mechanisms, responding to changes in PRACH load, such as increased or decreased demand. In turn, this aims to scale the PRACH monitoring activity by the network based on the need, ensuring that energy consumption for initial access operations can decrease as the cell load decreases.

An example of PRACH adaptation is shown in Figure 8 for illustrative purposes only, as at the time of writing the realization of Release 19 is still open. In this example, the additional PRACH resources are provided in the time domain as additional RACH occasions (ROs), which are contiguous to the legacy ROs in time and/or frequency domain. We note that when an additional RO is provided earlier than a legacy RO, the NES-capable UEs will use the additional RO, which has the positive effect of decreasing the load of the legacy ROs and, in turn, the risk of collision with legacy UEs. The benefit from this approach is to keep all the PRACH monitoring occasions contiguous in time and frequency, which optimizes network energy consumption.

Figure 9. Example of additional PRACH resources contiguous in time and/or frequency domain to the legacy resources



Potential for adoption and extensions for 6G

In 6G, the support for PRACH resource adaptation (in time) across all UEs is beneficial. This enhances network flexibility by enabling more effective dynamic scaling of resources, both up and down, to meet fluctuating demand, thereby increasing energy-saving potential.

On-demand SSB SCell for multi-carrier operation

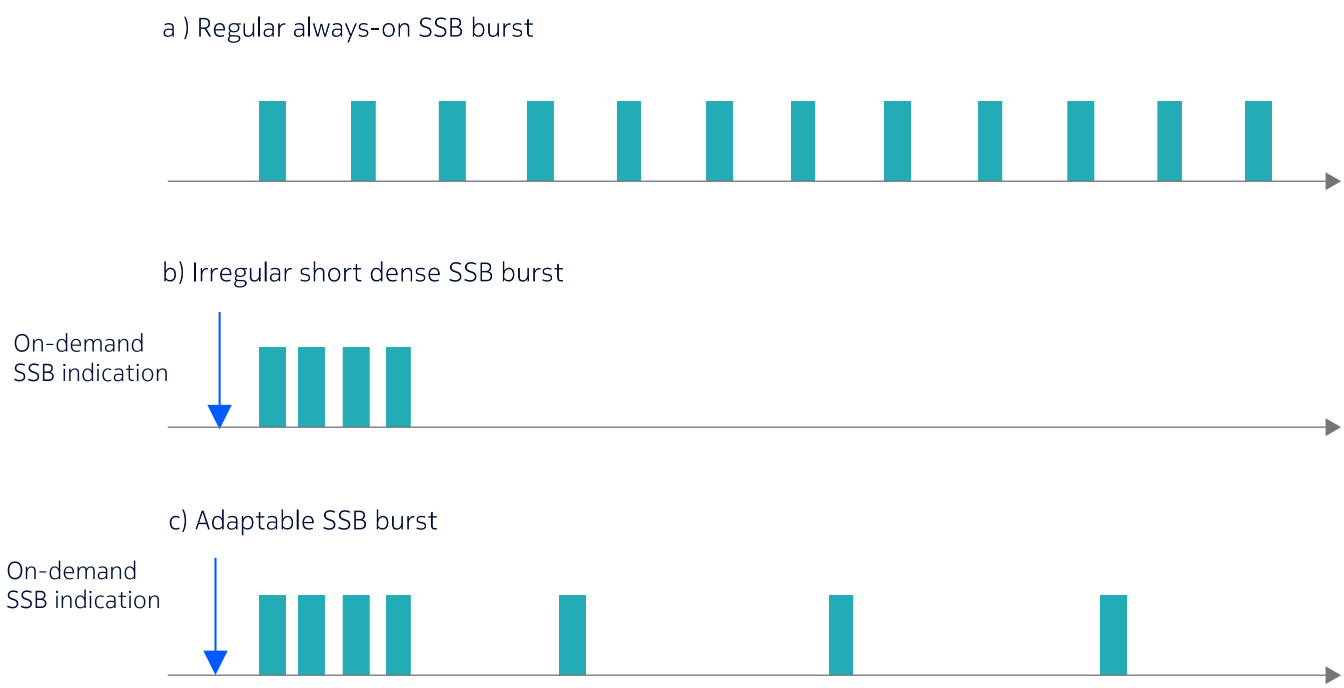
One of the techniques that can enhance network energy savings by increasing cell sleep opportunities is SSB adaptation. The SSB-less secondary cell (SCell) operation for the inter-band carrier aggregation (CA) was specified in Release 18. This feature enables the network to configure a UE with an inter-band carrier as an SSB-less SCell and a reference carrier. The reference carrier (e.g., the primary cell or PCell) should transmit SSBs regularly to be used as reference signals for basic time/frequency synchronization with the SCell, allowing the UE to only need to measure the tracking reference signal (TRS) on the SCell for fine synchronization. There are strict conditions to be met for the UE to be able to operate with the SSB-less SCell. The conditions require the receive time difference (RTD) and power imbalance between the reference carrier and SSB-less SCell to be within specified thresholds. Even if the UE has indicated the capability to support such functionality, neither the network nor UE knows upfront if the RTD conditions will be met under the actual conditions, which makes this solution not too attractive.

In Release 19, an alternative SSB adaptation technique is being specified for the SCell, namely the on-demand SSB SCell, where the SSB transmissions of the SCell can be confined in time for a specific purpose (e.g., SCell activation or layer three (L3) mobility) and thus their transmission patterns can be tailored based on the UE needs. In 5G-Advanced, this feature is specific to secondary cells and hence applicable when UEs in RRC connected mode configured with CA are present. The on-demand SSB transmission is triggered by the network.

Figure 10a depicts the regular ('always-on') SSBs by the SCell at 20 ms intervals. These can be replaced by denser on-demand SSB transmissions indicated by the network, e.g., to explicitly help speed up the SCell detection and/or activation by the UE (Figure 9b). It is also possible to supplement less frequent always-on SSBs with these dense SSBs (Figure 9c). This approach extends the applicability of the basic on-demand SSB SCell feature to scenarios where blind SCell configuration might not be feasible.

The NES gain achieved by on-demand SSB SCell operation can be significant. In macro scenarios with a PCell and one colocated SCell both operating in TDD, FR1, with 64 transmit antennas and 5 W per transmit antenna, simulations based on the 3GPP methodology outlined in [3], have shown promising results. The NES gain is estimated to be like the gain achieved by SSB-less SCell operation, i.e., 8–20%, which decreases with the SCell load. This assumes that the on-demand SSB is transmitted only shortly and utilizes the non-cell defining (NCD)-SSB type, which does not require associated SIB1 transmission.

Figure 10. Illustration of on-demand SSB burst in comparison to regular always-on SSB burst



Potential for adoption and extensions for 6G

The dynamic and reduced provisioning of reference signals, including SSBs, will remain a key feature in 6G, offering networks flexibility and energy savings. For example, in SSB-less SCells, the UE can reuse SSBs (or reference signals) from an anchor cell in scenarios where it is technically feasible, such as colocated deployments with intra-band and contiguous spectrum. In scenarios where such reuse of reference signals is not feasible, the on-demand SSB method could be considered. However, as 6G technology develops with its multi-carrier design, the way 5G-Advanced enables SSB adaptation will likely need to be extended in 6G.

In Release 19, other time domain adaptations of SSBs are also expected to be supported at least for the SCell, where, for example, the network may dynamically change the periodicity of the SSB transmission. The potential of these adaptations in 6G remains uncertain, as the specific solutions and use cases are still unclear at the time of writing. However, we see the need to enhance the SSB design in 6G also for RRC Idle and Inactive UEs. For example, firstly, it would be beneficial to relax the 5G standalone requirement to transmit SSBs with a minimum periodicity of 20 ms while avoiding excessive UE complexity.

Secondly, decoupling SSB from SIB1/MIB transmissions will be important to reduce SIB1 transmissions while allowing the less costly SSB to be transmitted more frequently. In this decoupling scenario, transmitting only the PSS/SSS rather than the entire SSB may be considered.

AI/ML for 6G RAN energy savings

Base stations can dynamically transition between different power states, including sleep states and active states, associated with varying capacity levels (e.g., utilizing different transmission power levels and active RF chains). This allows them to adapt their power consumption in response to fluctuating cell load throughout the day. In legacy solutions, typically the OAM (operations, administration and maintenance), having a wider overview of the RAN, is a major actor in determining energy saving decisions such as when a base station must switch on or off a cell. However, it operates in non-real time by monitoring RAN KPIs related, for instance, to traffic load or RAN energy consumption and by taking corrective actions in a reactive way. With AI/ML, the network aims instead to predict the issues and avoid them or mitigate them before they occur. By collecting and analyzing data on traffic patterns, cell load and user behavior, AI/ML algorithms can then dynamically optimize base station power states to enhance efficiency. Thus, AI/ML holds significant potential for optimizing energy consumption in the RAN.

Current approaches

Nokia's MantaRay Energy is well-equipped to leverage AI/ML technologies [8]. For example, the AI/ML algorithms in MantaRay Energy Saving Modules can today analyze the performance of each cell and automate the configuration and management of energy-saving techniques. This enhances the energy-saving effectiveness while ensuring high-quality service for end-users. These AI/ML-driven OAM-based solutions enhance the traditional OAM approach described above.

AI/ML in OAM for RAN energy savings can be categorized by four steps:

1. Identifying the energy related issue (e.g., high energy consumption, low energy efficiency), and identify the cell(s) or location area where the identified energy efficiency issue exists
2. Identifying the root cause(s) of the issue when necessary
3. Utilizing the network status analysis, leverage performance measurements from the RAN and predictions information of energy-related KPIs (including traffic load trends) to assist energy saving
4. Providing energy saving recommendations, including policies and configuration actions to guarantee the network performance and end user service experience. This may include recommending candidate cells:

   a) To enter the energy saving state

   b) To take over traffic from the energy saving cells

   c) Times to enter and terminate the energy saving state

   d) The load threshold(s) to enter and terminate the energy saving state for the energy saving cell.

For example, Nokia services for mobile networks leverage a unique combination of digital twins, AI and automation. AI-powered digital twins provide a real-time view of an entire network and its performance. They automatically recommend or trigger the right energy savings actions at the right time across network design and optimization.

In 5G-Advanced, enablers to operate AI/ML-based energy-saving algorithms in the RAN are introduced. AI/ML in the RAN, for instance, enables a node to optimally determine, in real time, its cell switch off decisions and corresponding offloading of UEs towards its neighbors based on feedback received from these neighbors (e.g., a cost metric). The node can compare how different actions would affect the overall cost in the neighborhood and, subsequently, prefer decisions that minimize it. In 5G-Advanced, the cost metric is defined as an energy cost index. To enable normalization of the energy cost values between different NG-RAN nodes, a mapping rule defined by the operator may be used in a neighborhood of NG-RAN nodes. This maps a minimum energy consumption in the neighborhood with a minimum energy cost value and, likewise, a maximum energy consumption in the neighborhood with a maximum energy cost value. The intermediate points can be determined either through a linear or non-linear function that could, for instance, consider different deployment characteristics (e.g., urban or suburban) and energy type used (e.g., renewable or non-renewable sources).

AI/ML energy-saving models applied by a base station can be trained in a base station or in the OAM. However, the OAM, having a broader visibility of the RAN, is better suited to train area-based models that seek to optimize energy savings over a broader area of RAN nodes.

Advances towards 6G

Moving towards 6G, AI/ML will gradually have a more pervasive presence in the network. This calls for a truly AI-native network that is designed, deployed and operated with AI/ML requirements in mind. It should natively support the entire life cycle of AI/ML algorithms including data collection, training management, inference, performance management and deployment. Moreover, an AI-native network enables enhanced coordination and collaboration between AI/ML algorithms through new interfaces, to solve more complex problems. This enables a larger and more effective utilization of the AI capabilities compared to 5G-Advanced, which lacks such AI-native design.

Future 6G energy saving potential can be improved by determining the most appropriate sleep modes and their duration given the current level of traffic and QoS requirements, including whether it is appropriate to use deep sleep modes with longer reactivation times, while maintaining QoS constraints. These optimizations can be assisted by AI/ML algorithms. AI/ML can allocate transmit power dynamically across cells based on current traffic demands and optimize antennas and beamforming to minimize energy usage. It can also anticipate future traffic demands, enabling proactive resource allocation and power management.

Specific examples of key use cases where AI/ML can save energy in the RAN include:

- **Probabilistic ML-based load threshold adjustment:** AI/ML can optimize the load thresholds for capacity cell switch-off, targeting cells for shutdown and optimizing shutdown duration [14]
- **ML-based 3D SSB beam grid optimization:** AI/ML can optimize the SSB beam grid configuration and deactivate beams at the SSB level based on beam-based load monitoring and prediction
- **AI/ML for massive MIMO antenna muting optimizations:** When using large mMIMO antenna arrays, AI/ML can learn the optimal number of RF chains and transmit antennas to be used for transmissions to the individual UE using techniques like Bayesian statistical analysis
- **AI/ML for monitoring and analysis:** AI/ML algorithms can leverage RAN data collection to monitor energy consumption, energy efficiency, and carbon emissions, providing valuable insights for optimization.

The above-mentioned energy-saving use cases rely on AI/ML solutions running in the RAN and operate on the scale of a single cell or a small group of cells. Additionally, for some of the use cases, the solutions may entail new interactions between network nodes and the served UEs (e.g., for SSB and mMIMO optimizations). However, to perform energy savings on a larger scale (e.g., geographical area or network level), the relevant energy saving optimizations and decisions can be performed in the OAM. This requires a high level of coordination and collaboration between AI/ML algorithms running in the RAN and OAM, which can only be achieved through AI-native 6G.

Also, when AI/ML solutions run in the RAN, the control and configuration from the OAM towards the RAN may need to be reconsidered. A RAN that is empowered through AI/ML intelligence can become more autonomous, requiring less configuration and coordination from the OAM and allowing the RAN more responsibility to make AI/ML-based energy-saving decisions. In which case, the OAM's input to the RAN with respect to cell activation and deactivation would be considered as assistance or recommendations that the RAN may accept or reject.

Cross-domain analytics for energy savings, particularly for the RAN, are another crucial aspect to optimize energy consumption in 6G networks. By integrating data from multiple sources such as the OAM, network performance monitoring tools, user behavior patterns, and digital twins of the mobile network, the AI/ML algorithms can gain a holistic view of network operations and identify hidden correlations that drive energy usage. These cross-domain approaches empower the RAN to make more intelligent and efficient energy-saving decisions across the entire network through centralized intelligence (similar to analytics provided by the 5G network data analytics function (NWDAF) or distributed intelligence in line with AI-native concepts. By analyzing network-wide data patterns, operators can proactively optimize cell performance, reducing energy consumption while maintaining high-quality service levels. Furthermore, this approach enables more efficient optimization of RAN energy usage by considering a broader range of factors, holding potential for significant reductions in energy consumption.

Sustainable AI

As discussed above, AI/ML solutions have been employed in 5G to learn the network status and provide recommendations to optimize certain objectives, thus improving performance for a variety of network use cases, e.g., energy savings, mobility management, traffic steering and resource optimization. In 6G, AI/ML is envisioned to become a native capability of the system to be employed ubiquitously across the network on a much wider scale than today. In order to achieve the objective of an environmentally sustainable end-to-end 6G network, the AI/ML solutions need to be designed, developed and operated in an energy-aware manner, ensuring that benefits surpass its impact on energy consumption.

Different phases of the AI/ML lifecycle may entail significant energy consumption. For example, AI/ML training may be performed using vast amounts of data requiring considerable computing power over even weeks or months. Occasionally, re-training may be necessary in order to keep the model up-to-date and mitigate deviations with respect to desired outcomes. In some cases, continuous use of AI/ML solutions may imply much longer time frames for inference computing compared to training, because inference may need to be performed almost continuously.

The foundation of energy-aware AI/ML management is the system's ability to measure the AI/ML energy consumption, so that operations such as (re-)training, model discovery and selection can be managed with energy in mind. There may be different indicators of AI/ML energy consumption, which can be expressed in relation to the underlying execution platform or independent of it. Examples of potential indicators are the number of floating-point operations (FLOPs) needed for AI/ML execution, energy consumption to run an AI/ML solution in Joules or Watts. Furthermore, the quantity of carbon emissions due to AI/ML operations may also be used as another AI/ML footprint metric, which depends on the consumed energy type (e.g., renewable or non-renewable energy). In addition, the AI/ML energy consumption indicators may be monitored in relation to different phases of the AI/ML lifecycle, i.e., training or inference. This approach enables developing and employing energy-saving means tailored to specific phases. Moreover, different phases, such as training and re-training, can be carried out based on certain energy consumption requirements. Overall, it will be crucial that the AI/ML impact is assessed using standardized methods as described in [9].

Apart from characteristics of the execution platform, there are many other factors influencing AI/ML energy consumption, mainly pertaining to AI/ML performance, such as model complexity, hyperparameter settings and amount of data used. More complex AI/ML solutions, trained on larger amount of data, may exhibit better performance but consume more energy compared to less performant AI/ML solutions. One of the key challenges in 6G will be balancing AI/ML performance with environmental sustainability, requiring the optimization of this tradeoff to enable energy-efficient, end-to-end 6G networks.

Evaluating 6G RAN energy savings in 3GPP

Assessing 6G energy-saving potential is crucial for 3GPP standardization to identify the most effective energy-saving features. Key considerations include:

- Individual and cumulative NES gains: Analyze both individual and combined energy savings, recognizing that some features might use the same energy saving opportunities, and individual benefits might not simply add up
- Scenario-specific considerations: Account for deployment scenarios, including macro and small cells, cell loading, UE locations, and traffic characteristics, as energy savings can vary significantly
- QoS/QoE impact: Evaluate the impact of energy-saving techniques on QoS/QoE, ensuring an acceptable trade-off between energy savings and potential performance impact.

To ensure fair and consistent evaluation, a standardized methodology is needed. The simulation evaluation methodology used in 5G-Advanced [14] can be adopted to compare energy-saving features in the 6G standard.

To align with the 5G-Advanced methodology in [14], the following should be defined for 6G:

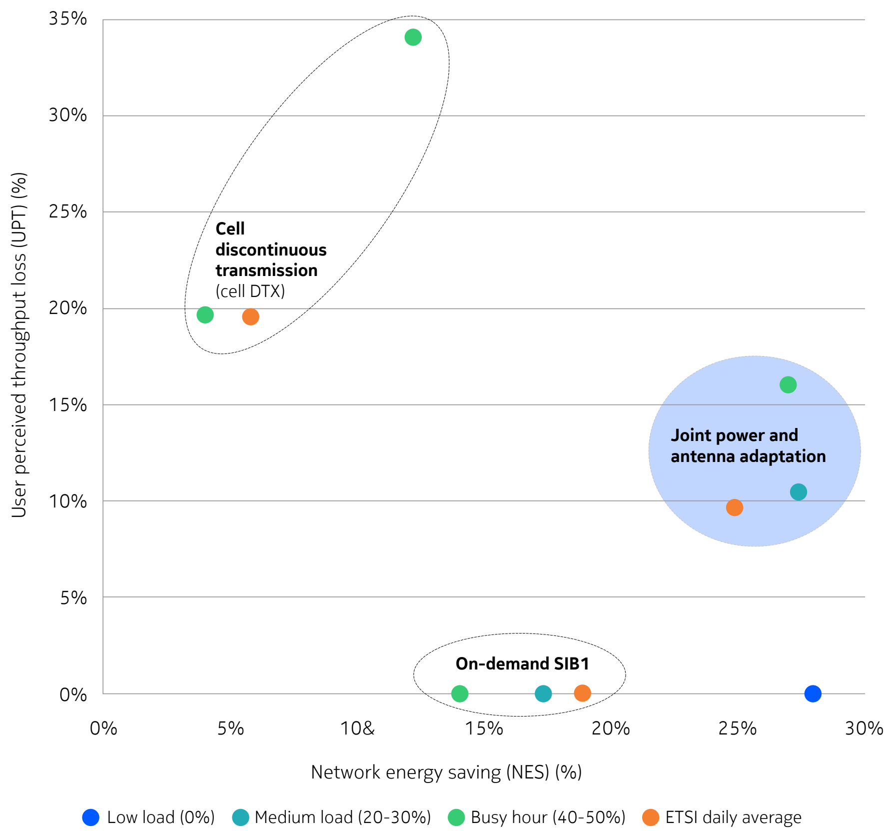
1. **Realistic 6G radio configuration(s):** Radio configurations—encompassing frequency range, duplex type, number of transmit antennas, and transmit power—significantly impact both spectral efficiency and power consumption of the base station's radio unit. Realistic configurations are essential for ensuring the accuracy and relevance of the assessment
2. **6G base station power consumption model:** This is crucial for consistent and accurate energy consumption evaluation across scenarios and technologies, enabling comparison of energy-saving improvements from 5G to 6G and guiding the development of more efficient and cost-effective networks.

The following could be directly reused from the 5G-Advanced methodology in [14]:

3. **Specific traffic model and load levels:** Following ETSI load definitions [13], three load levels are considered: low, medium, and busy hour. These are defined in terms of resource usage for user-plane data (physical downlink shared channel or PDSCH), corresponding to 0%, 20–30%, and 40–50% usage, respectively. Any load scenarios include overhead such as system information and reference signals. To assess long-term effectiveness, we also recommend evaluating performance under the ETSI daily average load [13], which weights load levels based on assumed daily traffic patterns.
4. **Performance metrics:** Network energy-saving potential is calculated as the NES gain achieved when applying an energy-saving feature compared to a baseline. Likewise, end-user performance impact is assessed by measuring user-perceived throughput, which includes both throughput and latency effects.

Figure 11 demonstrates an example of NES features' assessment for the different load levels, considering both NES gain and user-perceived throughput, based on the 3GPP 5G-Advanced methodology.

Figure 11. Example of NES features assessment at different load levels in terms of NES gain and user-perceived throughput loss according to the 3GPP 5G-Advanced methodology defined in [14]



Summary and outlook

Nokia's commitment to sustainability is reflected in its continuous efforts to optimize network energy consumption and support CSPs and enterprises in meeting their sustainability goals.

The upcoming 6G network design is also driven by a commitment to sustainability, with a strong focus on environmental sustainability and energy savings. However, reducing 6G network energy consumption and carbon emissions while maintaining network performance and user satisfaction is a complex challenge that necessitates multifaceted strategies. These strategies involve both standardization efforts and superior vendor innovations.

From an E2E 6G system design viewpoint, core network features for saving energy will include QoS adaptation based on cell load and network power state, e.g., to facilitate RAN energy savings. Additionally, the network will expose energy-related information, including the carbon intensity of the supplied electricity, to further optimize energy use.

From a 6G RAN design perspective, Nokia is active in defining several promising RAN energy-saving enhancements in 3GPP Release 18 and 19 of 5G-Advanced, which are designed to enhance cell sleep opportunities and transmission efficiency during periods of low load. Building on these 5G-Advanced developments, we envision that 6G incorporates proven energy-saving features, which can be exploited at their full potential in 6G by applying them across all cells and all 6G devices from day one. Techniques like on-demand SIB1, paging adaptations, PRACH adaptation, and on-demand SSB SCell for multi-carrier operation are highlighted for their potential to enhance energy savings in 6G. These developments lay a strong foundation for the 6G design of energy-saving features, enabling dynamic radio adaptations based on load from 6G day one. This is particularly effective for low-to-medium load scenarios, when leveraging advances in base station hardware, including fast hardware reactivation. Furthermore, 6G will harness advancements in AI/ML to optimize energy savings and leverage the AI-native 6G network design, enabling a larger and more effective utilization of the AI capabilities. For example, AI/ML-based dynamic optimizations of base station power states, prediction of traffic fluctuations, and efficient resource allocations such as mMIMO antenna will play a crucial role.

Lastly, evaluating 6G energy-saving potential is crucial for 3GPP standardization. To ensure a fair and consistent assessment, a standardized methodology, similar to the one used in 5G-Advanced, is needed. This methodology requires defining realistic 6G radio configurations, a 6G base station power consumption model, and utilizing specific traffic models, load levels and performance metrics as outlined in the 5G-Advanced methodology. By comparing energy-saving improvements from 5G to 6G, this methodology can guide the development of more efficient and cost-effective mobile networks.

Abbreviations

3GPP	Third-generation partnership project
4G	Fourth-generation mobile network
5G	Fifth-generation mobile network
6G	Sixth-generation mobile network
AI	Artificial intelligence
BWP	Bandwidth part
CA	Carrier aggregation
CN	Core network
C-Plane	Control plane
CSP	Communications service provider
DPD	Digital pre-distortion
DRX	Discontinuous reception
DTX	Discontinuous transmission
E2E	End to end
ETSI	European Telecommunications Standards Institute
FDD	Frequency division duplexing
FTP	File transfer protocol
GHG	Greenhouse gas
GSMA	Global system for mobile communications
gNB	Next-generation node B
L3	Layer three
LTE	Long-term evolution mobile network
ML	Machine learning
MIMO	Multiple-input multiple-output
mMIMO	Massive MIMO
NCD	Non-cell defining
NES	Network energy savings
NG-RAN	Next-generation RAN
NR	5G new radio
NWDAF	Network data analytics function
OAM	Operations, administration and maintenance
OFDM	Orthogonal frequency-division multiplexing
PA	Power amplifier
PCell	Primary cell
PDSCH	Physical downlink shared channel
PRACH	Physical random access channel
QoE	Quality of experience
QoS	Quality of service
RA	Random access
RACH	Random access channel
RAN	Radio access network
RF	Radio frequency
RFIC	Radio frequency integrated circuit
RO	RACH occasion
RRC	Radio resource control
RTD	Receive time difference
RU	Radio unit
SCell	Secondary cell
SIB1	System information block 1
SoC	System on a chip
SSB	Synchronization signal blocks
TDD	Time-division duplex
TRP	Transmission reception point
Tx	Transmission
UE	User equipment
U-Plane	User plane
WUS	Wakeup signal

References

[1] Nokia, “People and Planet 2023,” Nokia web site, 2023. Online: https://www.nokia.com/sites/default/files/2024-03/nokia_people_and_planet-2023.pdf

[2] Kolta, E. and Hatt, T., “Going green: measuring the energy efficiency of mobile networks,” GSMA Intelligence web site, Feb 2024. Online: https://data.gsmaintelligence.com/research/research/research-2024/going-green-measuring-the-energy-efficiency-of-mobile-networks

[3] Nokia, “Forging more sustainable mobile networks,” Nokia web site, Feb 2024. Online: https://www.nokia.com/about-us/newsroom/articles/forging-more-sustainable-mobile-networks/

[4] Elisa, “Energy efficiency in Elisa,” Elisa web site. Online: https://elisa.com/corporate/sustainability/energy-efficiency/

[5] Laselva, D. and Lauridsen, M., “Reducing energy with 5G-Advanced: the essential guide to RAN energy savings in 3GPP Release 18,” Nokia web site, 2023. Online: https://onestore.nokia.com/asset/213599

[6] Wikström, G. et al., “Key value indicators: A framework for values-driven next-generation ICT solutions,” Telecommunications Policy, Vol 48:6, Jul 2024. Online: https://www.sciencedirect.com/science/article/pii/S0308596124000752

[7] Du, J. et al., “Energy efficiency in next-generation mobile networks,” Nokia Bell Labs web site, Nov 2022. Online: https://www.bell-labs.com/institute/white-papers/energy-efficiency-in-next-generation-mobile-networks/

[8] Nokia, “Radio access network energy efficiency,” Nokia web site, 2024. Online: https://onestore.nokia.com/asset/213911

[9] Kallio, S. and Farzan, M., “A transparent and standards-way to assess the environmental impact of AI systems,” Nokia web site, 2024. Online: https://onestore.nokia.com/asset/214115

[10] Laselva, D. and Lauridsen, M., “How network adaptations for 5G devices will lead to superior battery life: the essential guide to device energy saving in 5G NR,” Nokia web site, 2023. Online: https://onestore.nokia.com/asset/210981

[11] Laselva, S. et al., “On the Potential of Radio Adaptations for 6G Network Energy Saving,” 2024 Joint European Conference on Networks and Communications & 6G Summit (EuCNC/6G Summit), Antwerp, Belgium, 2024, pp. 1157-1162. Online: https://ieeexplore.ieee.org/document/10597015

[12] Nokia, “Transforming the 6G vision to action,” Nokia white paper, 2024. Online: https://onestore.nokia.com/asset/214027

[13] ETSI 202 706-1, “Environmental Engineering (EE) - Metrics and measurement method for energy efficiency of wireless access network equipment - Part 1: Power consumption - static measurement method,” V1.7.1, Sep 2022. Online: https://www.etsi.org/deliver/etsi_es/202700_202799/20270601/01.07.01_60/es_20270601v010701p.pdf

[14] 3GPP Technical Report 38.864, “Study on network energy savings for NR,” Mar 2023. Online: https://www.3gpp.org/ftp/Specs/archive/38_series/38.864/38864-i10.zip

About Nokia

At Nokia, we create technology that helps the world act together.

As a B2B technology innovation leader, we are pioneering networks that sense, think and act by leveraging our work across mobile, fixed and cloud networks. In addition, we create value with intellectual property and long-term research, led by the award-winning Nokia Bell Labs.

With truly open architectures that seamlessly integrate into any ecosystem, our high-performance networks create new opportunities for monetization and scale. Service providers, enterprises and partners worldwide trust Nokia to deliver secure, reliable and sustainable networks today – and work with us to create the digital services and applications of the future.

Nokia OYJ
Karakaari 7
02610 Espoo
Finland
Tel. +358 (0) 10 44 88 000

Document code: CID214113 (December)