Energy-Saving Approaches for 5G and Beyond: New Classification and Analysis

Hasna Fourati[1], Rihab Maaloul[2], Lamia Chaari[3], and Mohamed Jmaiel [4]

Abstract— **The evolution of 5G and Beyond (B5G) networks requires innovative solutions to address the growing complexity of network management and enhance Energy Efficiency (EE). Sleep Mode (SM) has emerged as an essential strategy for minimizing energy consumption in densely deployed networks, particularly in Base Stations (BS), significantly improving Energy Saving (ES) in 5G/B5G network. By dynamically deactivating underutilized BS components, SM can be effectively applied across various 5G infrastructures. In addition, the application of Artificial Intelligence (AI) and Self Organizing Networks (SON) provides advanced tools for automatic and intelligent system reconfiguration, further enhancing ES in B5G networks. This paper explores ES approaches centered on SM, providing an overview of their application in 5G architectures and the role of AI algorithms and the SON paradigm in improving ES. Finally, we discuss potential ES advancements for future networks, including the transition to 6G, highlighting the importance of intelligent and adaptive energy management in next-generation networks.**

I. INTRODUCTION

A. General context

Energy consumption has become a major concern due to economic, operational, and environmental factors. With increasing demand for high capacity, 5G and Beyond (B5G) networks must significantly expand to accommodate a growing number of users. Experts predict that monthly traffic volumes could reach tens of exabytes, with 5G offering up to 1000 times the capacity of current systems [1]. However, merely increasing transmission power in 5G is insufficient to meet these demands. At the same time, the European Commission has set ambitious targets to reduce CO2 emissions and improve Energy Efficiency (EE) by 20%. This is particularly crucial, as the high energy consumption of 5G network contributes significantly to both CO2 emissions and rising operational costs [2]. One key strategy for reducing energy consumption and CO2 emissions is optimizing Energy Saving (ES) in Base Stations (BSs), particularly through the selective deactivation of BS components—commonly referred to as sleep mode (SM). This approach can significantly enhance EE in 5G and Beyond (5G/B5G) networks. Extensive research effort has explored the application of SM through various approaches, including architectural redesign incorporating massive-MIMO, Mobile Edge Computing (MEC), Device-to-Device (D2D) communication, and millimeter-wave (mm-wave) technologies to further enhance EE. To support autonomous energy optimization, Self Organizing Networks (SON) are seamlessly integrated into 5G architectures. This integration plays a critical role in enhancing network performance while gradually replacing traditional ES techniques. Moreover, Artificial Intelligence (AI) serves as a powerful enabler for SON, allowing for intelligent and adaptive network optimization. AI-driven solutions enhance ES by enabling smarter decision-making and autonomous adjustment to dynamic network conditions.

B. Motivation and contribution

Several studies [3]–[6] surveyed energy consumption reduction in 5G/B5G networks, focusing on four main categories: Network Planning and Deployment (NPD), Energy Harvesting and Transfer (EHT), Hardware Design (HD) and Resource Allocation (RA). Our survey aligns with these areas but aims to address critical gaps left by previous works. For example, [3] emphasized EE, it overlooked the roles of AI and SON. Similarly, [5], [6] considered AI but did not integrate SON, thereby limiting the potential for autonomous optimization. Study [4] discussed both AI and SON but did not account for H-CRAN architecture or essential 5G technologies like power grids and energy storage batteries in its energy reduction analysis. Within the NPD category, [3]–[6] examined various SM levels by temporarily deactivating BS components during low network demand. While [3] explored various 5G technologies for ES, such as network densification and massive-MIMO, it considered mm-wave and D2D solely as complementary to energy harvesting, without evaluating their independent efficiency in optimizing overall energy performance. Additionally, the study [5] investigated the interplay between SM techniques and 5G technologies, including massive-MIMO, mm-wave, and dense network architectures. This combination enables dynamic power management, allowing antennas to enter SM during low-traffic periods. These technologies leverage beamforming techniques to create highly directional beams, reducing interference and improving signal strength, which in turn minimizes energy consumption in BS by supporting efficient SM operations. Another study [7] examined the ES capabilities of certain 5G technologies independently of SM. Additionally, [8] explored SON-AI integration to enhance 5G performance, without focusing on all 5G key technologies for ES improvement. In the EHT category, [9] proposed

[1]Hasna Fourati is with CRNS, Sfax, Tunisia, and also with Laboratory SMARTS, Sfax, Tunisia. email: hasna.fourati21@gmail.com,

[2] Rihab Maaloul is with ISIMa, University of Monastir, Mahdia, Tunisia, also with CRNS, Sfax, Tunisia, and also with Laboratory SMARTS, Sfax, Tunisia. email: rihabmaaloulabid@gmail.com,

[3] Lamia Chaari is with ISIMS, University of Sfax, Sfax, Tunisia, also with CRNS, Sfax, Tunisia, and also with Laboratory SMARTS, Sfax, Tunisia. email: lamiachaari1@gmail.com,

[4] Mohamed Jmaiel is with ENIS, University of Sfax, Sfax, Tunisia, also with Laboratory ReDCAD, Sfax, Tunisia. email: mohamed.jmaiel@redcad.org

integrating of power grids, energy storage batteries, and PhotoVoltaic (PV) technologies to optimize energy harvesting in Internet of Things (IoT) 5G cellular networks. These technologies support self-sustaining IoT devices, minimizing dependence on traditional power sources while facilitating low-power 5G communication. Within the HD category, EE design plays a crucial role in 5G architectures, including Heterogeneous Networks (HetNet), Cloud-Radio Access Networks (C-RAN), and Heterogeneous-C-RAN (H-CRAN). The study [10] explored integrating specific 5G technologies to enhance architectural performance and EE. The BBU pool in C-RAN reduces physical equipment and H-CRAN reduces inter-cell interference, improving spectral and EE for users at the cell edge. Regarding the RA category, other studies [5], [11] investigated the selection of suitable energy consumption models, distinguishing between static and dynamic approaches, while defining key objectives such as maximizing EE or minimizing energy consumption. These studies emphasized the integration of critical model components (e.g., system capacity, throughput, and outage capacity), which play a fundamental role in enhancing energy resource allocation within the BS system. Additionally, the use of advanced mathematical tools has further refined these models, ensuring optimal and efficient energy management. All these categories complement each other. The technologies under the EHT and NPD categories can be integrated into a 5G architecture and seamlessly combined using advanced mathematical tools to optimize ES. Table I summarizes key surveys in ES in 5G/B5G. To the best of our knowledge, no existing survey has comprehensively examined all the following aspects, which present diverse approaches and distinct technical solutions within the aforementioned categories for enhancing EE in 5G/B5G networks: (i) SM schemes (ii) the consistency between SM and 5G technologies (iii) the application of SON paradigm and AI solutions (iv) a synthesis of existing approaches and (v) lessons learned. This paper provides a comprehensive overview of ES approaches in 5G/B5G, focusing on approaches centered on SM and its schemes, and architecture-specific optimizations. In addition, it explores the role of the SON paradigm and AI algorithms in tackling the energy consumption challenges of 5G/B5G, offering insights into innovative solutions to improve EE in 6G. This paper is organized as follows. Section II presents the ES approaches for mitigating energy consumption in 5G/B5G, accompanied by a comprehensive synthesis. Section III discusses the lessons learned and anticipates future ES strategies in 6G.

TABLE I
KEY SURVEYS IN ES IN 5G/B5G

Category	Ref	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	Our survey
NPD	SM	✓	✓	✓	✓						✓
	Technologies	✓		✓		✓					✓
	SON						✓				✓
	AI			✓	✓		✓				✓
EHT								✓			✓
HD	Architectures								✓		✓
RA			✓							✓	✓

II. ENERGY SAVING APPROACHES IN 5G/B5G

In this section, we explore several studies proposing different solutions to enhance ES in 5G/B5G networks.

A. *Sleep mode for an efficient Energy Saving*

Since BSs are the primary contributors to high energy consumption in 5G networks, turning them off completely can significantly reduce energy consumption. However, this strategy often results in long delays when reactivating the BSs, affecting response times for users. To address this challenge, SM is regarded as an effective ES solution for the sustainable EE deployment of 5G/B5G networks. Energy can be saved by switching the cells between different power modes (i.e., ON, Standby, Sleep, OFF, etc.) according to network load and traffic demand. BSs can enter SM, where unnecessary components are powered down, offering a balance between ESs and responsiveness. Unlike simple switching between ON and OFF modes, several works [12], [13] indicated that switching between ON/Sleep or OFF/Sleep modes not only decreases energy consumption but also enhances responsiveness to traffic demands. The works [14], [15] integrated a multi-level sleep modes strategy: Advanced Sleep Modes (ASM). It consists in a gradual deactivation of the BS components depending on transition time. Although ASM technology can minimize the energy consumption by up to 90% at low loads, it causes a greater delay for users who arrive at the network and have to wait longer for components to reactivate. Therefore, a trade-off is sought between ES and latency.

B. *Sleep mode Schemes*

Greedy-ON/greedy-OFF, BS Sleep Control, Cell Zooming, Random and Repulsive Schemes are among the most widely recognized SM schemes.

– **Greedy-ON/greedy-OFF Schemes:** Rostami et al. [16] and Hao et al. [17] explored dynamic BS power mode transitions using greedy algorithms, aiming to improve overall network performance.

– **BS Sleep Control Scheme:** BS power modes adjust according to the number of User Equipements (UEs) that demand High Data (HD) rates and overlapping coverage [18]–[20].

– **Cell Zooming Scheme:** BS coverage areas adjust dynamically based on traffic load and channel conditions. High traffic loads cause BSs to zoom in, while others zoom out, allowing idle BSs to enter SM, improving EE and balancing load [21]. Dahal et al. [13] introduced a traffic-aware cell zooming approach that modulates BS power modes and reduces cell coverage under congestion, lowering power consumption by up to 20%.

– **Random and Repulsive Schemes:** In the random scheme, BSs turn off based on an assigned probability p. In the repulsive scheme, Small BSs (SBSs) within a certain radius R of a Macro BS (MBS) are deactivated [22].

C. Energy Saving through 5G architectures

To enhance ES in 5G/B5G, various ES schemes can be integrated into different 5G architectures, as depicted in Fig. 1.

1) HetNet Architecture: HetNets integrate different BS types (MBS, SBS, micro BS) incorporating technologies such as massive MIMO, MEC, D2D, mm-wave, Ultra-Dense Network (UDN) and control-data plane separation, boosting capacity, EE, and throughput by bringing users closer to BSs. SM further optimizes power consumption by deactivating massive-MIMO antennas during low usage [23]. Mm-wave technology boosts data rates using high-frequency spectrum bands [24] but its deployment requires integration with massive-MIMO to mitigate blocking effects and high attenuation. Salh et al. [25] aimed to enhance BS EE in mm-wave massive-MIMO systems without adding hardware complexity. Vallero et al. [26] proposed disabling the MBS's MEC server during off-peak hours and evenly distributing its cache across four micro BSs, improving EE while balancing latency and energy consumption. The macro cell, powered by power grid, energy batteries, and a PV panel system, dynamically controls micro BS power modes based on renewable energy availability. Pan et al. [27] introduced a resource allocation solution enabling D2D devices to change between licensed bands and license-free while dynamically adjusting transmit power, optimizing EE. Small cells powered by renewable energy can significantly reduce energy consumption and costs. Therefore, El Amine et al. [14] and Miozzo et al. [28] proposed a two-tier network system where solar-powered SBSs with rechargeable batteries are deployed in hotspots areas to offload traffic from MBSs, enhancing network performance. Additionally, traffic offloading enhances small cell performance while dynamically adapting to traffic variations. On the other side, BS sleep control schemes in HetNet architectures employ control and data planes separation, where MBSs maintain control signaling while SBSs handle data transmission. Fourati et al. [19] presented an enhanced design where MBSs also manage Low Data rate (LD) traffic, while SBSs focus on HD traffic, optimizing performance under high traffic density.

2) C-RAN Architecture: Unlike traditional HetNet architectures, this design centralizes all Digital Signal Processing (DSP) operations within a cloud-hosted Baseband Units (BBUs) pool, while Remote Radio Heads (RRHs) focus on basic transmission tasks, compressing radio signals from UEs and forwarding them to BBUs. This centralized approach enhances network efficiency, scalability, and cost-effectiveness. The work [29] highlighted C-RAN's benefits, particularly the optimization of ESs through centralized BBU processing. They demonstrate greater advancement and stability compared to other works, ensuring superior performance in complex C-RAN environments.

3) H-CRAN Architecture: Several works proposed leveraging the advantages of both C-RAN and HetNet within the H-CRAN architecture to achieve efficient ES in 5G. The integration of 5G technologies into HetNet architecture, combined with cloud-hosted BBUs, enables efficient energy resource allocation and reduces energy consumption in B5G networks. Several studies [18], [20], [30] have explored EE in 5G H-CRAN. The work [30] proposed algorithms designed for dynamic resource allocation according to traffic arrival rates, which make it well-suited for environments with predictable traffic patterns in H-CRAN architecture. Furthermore, the proposed solution is implemented in ultra-dense deployments of RRHs within hotspot areas, where some RRHs can be turned off during low traffic periods to save energy. On other side, the solutions proposed in [18], [20] demonstrate their suitability for real-time and computationally constrained environments in H-CRAN architecture. Moreover, they implemented a HetNet with separated data and control planes, further enhancing ES in H-CRAN architecture.

D. Artificial Intelligence-Based Energy Saving Approaches

AI algorithms, including bio-inspired approaches such as Genetic Algorithms (GA) and Particle Swarm Optimization (PSO), alongside Machine Learning (ML) techniques, facilitate efficient and reliable intelligent ES mechanisms in 5G/B5G architectures by identifying the optimal set of BSs for deactivation.

1) Heuristic Algorithms applied to reinforce the sleep mode techniques in 5G/B5G: Fayad et al. [24] proposed a GA to solve the NP-hard energy consumption problem. Their evolutionary strategy ES scheme outperforms other methods in terms of EE. Further, Fourati et al. [18], [19] conducted a comparative analysis of two heuristic algorithms, GA and PSO, for ES solutions. Their study demonstrates that while GA achieves superior EE, it introduces higher aggregate delay compared to PSO, which may impact latency-sensitive applications.

2) Machine Learning applied to reinforce the sleep mode techniques in 5G/B5G: El Amine et al. [14] proposed proposes a Reinforcement Learning (RL)-based framework for intelligent SM control in 5G HetNet. Fourati et al. [20] proposed Q-Learning ML solution to enhance EE in B5G H-CRAN architecture. Expanding on this research, Iqbal et al. [29] developed an advanced energy-efficient resource allocation strategy for C-RANs based on Double Deep Q-Network (DDQN).

E. Self Organizing Networks Solutions for Energy Saving

SON enhances ES in 5G/B5G by automating network management, enabling BSs to autonomously enter SM, optimizing configurations based on traffic and conditions, reducing Capital Expenditures (CapEx) and Operating Expenses (OpEx), improving user experience, and minimizing interference while balancing network load. Besides, SON engines facilitate dynamic BS power mode adjustments to optimize EE in 5G/B5G. According to 3GPP Release 18 [31], enhancements in data collection and signaling support improve SON use cases, including ES, mobility optimization and load balancing. Beyond 3GPP, organizations are developing SON-based ES techniques through proposed projects. The Self-OrganizatioN towards reduced cost and eNergy per bit for future Emerging radio Technologies (SONNET)

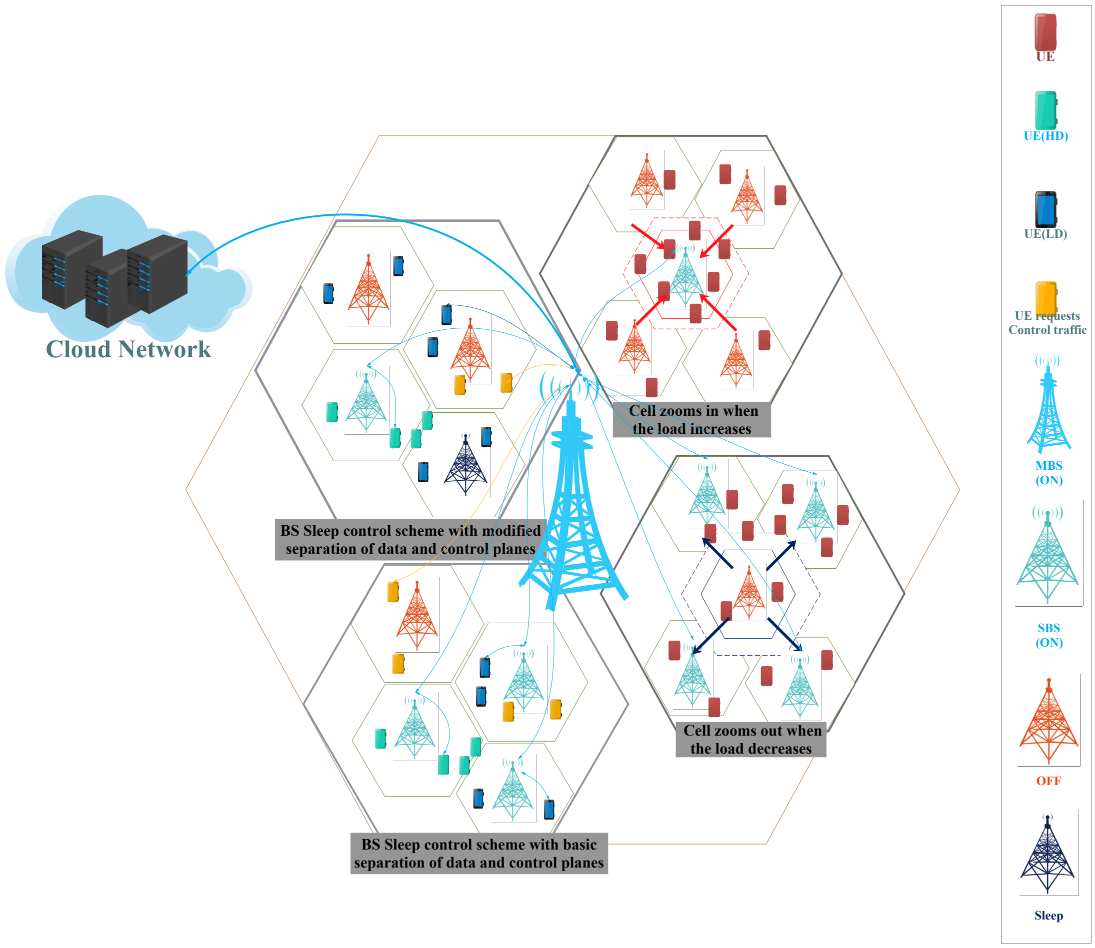

Fig. 1. ES schemes in 5G architectures.

project [32], concluded in 2021, focused on cost reduction by extending SON's network coverage. The project sought to enhance network sharing and Coordinated Multi-Point (CoMP) technologies through SON, aiming to lower both costs and energy consumption per bit in B5G networks. Other studies have explored SON implementations to enhance ES in 5G/B5G networks. Miozzo et al. [28] applied SON mechanisms to improve overall EE while minimizing human intervention. Maintaining optimal performance while reducing energy consumption is a key challenge for SON-based ES techniques, effectively addressed by AI-driven SON solutions [33]. AI enhances SON by predicting traffic patterns, learning from network behavior, and making proactive decisions to optimize energy consumption while minimizing service disruptions. Murudkar et al. [34] introduced user-centric SON approaches using ML to address 5G challenges, offering a seamlessly connected ecosystem and enhanced user experience.

F. Synthesis

In this section, we synthesize the previously discussed works and display the ES approaches proposed in the literature in 5G/B5G in Table II and Fig. 2. Various studies have explored the classification of power modes, ranging from basic modes (ON, OFF, Sleep) to advanced multi-level sleep modes. ASM improves EE and minimizes wake-up latency but complicates network management, requiring sophisticated algorithms for optimal mode selection. On the other side, a significant ES can be resulted without using SON, but often requires manual configuration and monitoring, which may not be as efficient in dynamic network environments. SON can reduce the need for manual intervention to make an efficient ES by handling the dynamic demand of traffic and UEs mobility. Their mechanisms can automate many ES processes, making the network more responsive to changing conditions. Moreover, AI can empower SON-based ES techniques by providing intelligence to the network in order to learn relevant parameters and provide a high performance. Compared to traditional solutions, AI/ML algorithms (e.g., heuristic algorithms, RL techniques, etc.) are proven their efficiency in ES enhancement in static and dynamic environments. In this context, Fourati et al. [20] demonstrated the effectiveness of ML, particularly RL, in improving ES performance in dynamic environments, outperforming traditional heuristic methods such as the GA using Transformation (TGA).

TABLE II
ENERGY SAVING APPROACHES IN LITERATURE.

Solutions		Ref
SM	Greedy-ON/Greedy-OFF	[16], [17]
	BS sleep control	[18]–[20]
	Cell zooming	[13], [21]
	Random and Repulsive	[22]
HetNet architecture	Massive-MIMO	[23], [25]
	Mm-wave	[24], [25], [35]
	MEC	[26]
	D2D	[27]
	Renewable energies	[14], [28]
	Sharing of control and data	[19]
C-RAN architecture		[29]
H-CRAN architecture		[18], [20], [30]
AI algorithms	Heuristic Algorithm	[18], [19], [24]
	ML Algorithm	[14], [20], [28], [29]
SON solutions	Release18, SONNET	[28], [31], [32]

In the literature, the primary objectives of ES studies utilizing AI/ML algorithms are broadly categorized into two key areas: (1) maximizing EE [13], [20], [23], [25], [27]–[29], [35] and (2) minimizing overall energy consumption [14], [16]–[19], [26], [36] within the system. These objectives highlight the dual focus of leveraging advanced algorithms to optimize both performance and sustainability in energy management. In the context of applying AI solutions, and based on the works discussed above, DDQN [29] proved its efficiency to achieve the high ES compared to traditional solutions applied in different 5G architectures. AI solutions [14], [19], [24], [28] can be performed in HetNet architecture which can significantly save the energy in 5G/B5G cellular networks. In C-RAN and H-CRAN architectures, AI algorithms [18], [20], [29] are performed in the centralized processing units which are implemented in cloud data centers. In addition, H-CRAN architecture maintains the same HetNet capabilities by deploying the multi-tier small cells that offload the traffic from macrocells, in order to reduce the need for high power transmissions [18], [20].

III. LESSONS LEARNED

5G networks are designed to meet various requirements, such as high system capacity achieved by increasing transmit power. However, the sharp increase in the user demands is leading to steadily increase in energy consumption and then unsustainable operating costs, which obstructs the desired increase in system capacity. The decisions to optimize the ES will be more difficult when using the traditional ES techniques [37]. Several constraints must be taken into account when determining the power mode for the BS, particularly in dynamic environments. Key factors to consider include data traffic requirements, wireless channel properties, user movement behaviors, and the operator's unique specifications [2]. In general, various 5G/B5G technologies are being enhanced to address the challenges posed by future 6G networks. In particular, New Radio (NR) technology is considered as the powerful key enabler to minimize the energy consumption in B5G. To effectively support network densification and the use of larger massive-MIMO antenna arrays for 6G networks,

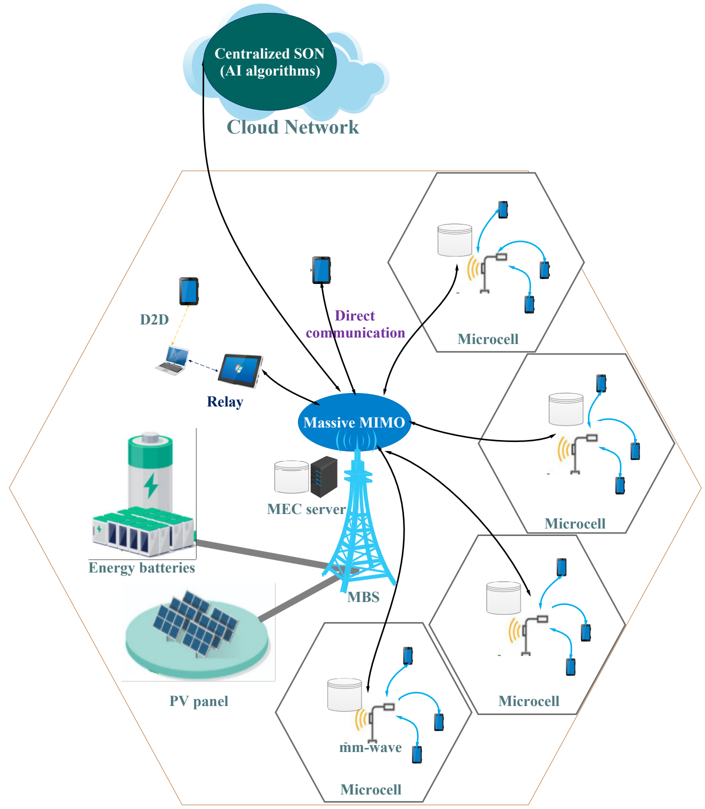

Fig. 2. Technologies that improve ES in 5G/B5G network

it is crucial to maintain and extend the core properties of NR technology. The amelioration involves minimizing spatial repetition as well as beam sweeping of OFF mode signals according to paging, system information and the synchronization. Despite these features, NR brings a high cost of energy consumption in specific situations (e.g., using ON instead OFF mode). A clear distinction is needed between situations where OFF or ON modes should be used to effectively use NR capabilities [38]. Despite the success achieved by using HetNet, C-RAN, and H-CRAN architectures to optimize ES in 5G/B5G cellular network, 6G will face many different challenges due to the dynamic changes that can occur in the environment, as well as other factors (e.g., inter-cell interference, load balancing and latency). As 6G demand ever stricter spectral efficiency, reliability, and latency, networks must become increasingly autonomous. This necessitates the development of new and more sustainable approach for network management (i.e., Self-Sustaining Network (SSN)). Indeed, SSNs allow to harness and manage their resources by efficiently collecting energy, using spectrum, and adapting their functions using ML solutions in order to achieve the durability of 6G Key Performance Indicator (KPI) [1], [8].

IV. CONCLUSION

This paper addresses the critical challenge of ES and explores solutions to mitigate the expected high energy consumption in 5G/B5G networks. We reviewed various ES strategies, including SM, HetNet architectures, and AI-driven and SON-enabled solutions, all aimed at optimizing EE. Finally, we highlight key insights, future opportunities, and ongoing challenges that will guide further research and development in energy-efficient mobile networks.

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