A Survey of Energy-Efficient Synchronization Mechanisms in 6G Radio Access Networks

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Abstract

Energy consumption in cellular networks has become a major environmental and operational concern. The transition from 5G to 6G presents an opportunity to redesign radio access networks with energy efficiency as a core principle. This survey investigates the current state of the 3GPP RAN1 standardization work on two key air interface mechanisms: extending synchronization signal block (SSB) periodicity from 20 ms to around 160 ms to enable base station (BS) sleep and on-demand (OD) signaling through OD-SSB to avoid unnecessary always-on broadcasts.

Ⅰ. Introduction

Radio access network (RAN) power consumption now represents the dominant portion of the mobile network operators' operational expenditure. 5G base stations consume 2-5 kW of power continuously, which leads to significant annual energy costs and environmental carbon footprints. As data demands grow exponentially, the deployment of 6G will expand network density further, intensifying energy demands, which require architectural redesign [1].

In 5G standardization, energy efficiency was treated as an optimization target rather than a primary design constraint. 6G will adopt the principle 'Simpler, Smarter, More Efficient' from the outset, with energy efficiency as a basic design consideration [2]. This survey provides 6G RAN energy efficiency work in 3GPP RAN1, which focuses on:
(1) SSB periodicity extension: mechanisms to reduce SSB frequency, enabling deep sleep,
(2) On-demand signaling: network and UE-triggered provisioning of signals,
(3) Standardization status highlighting the agreements, open issues, and evaluation methods.

Ⅱ. 6G Energy Efficiency Techniques and Standardization

This section outlines how 6G standardization is shaping energy-efficient synchronization and signaling in RAN. The 3GPP RAN1 timeline framework situates the work within Release 20 and follows Release 21 phase. SSB periodicity extension and network deep sleep introduce longer SSB periods to enable BS sleep with quantified energy-latency trade-offs. On-demand signaling presents event-driven synchronization and system information delivery that reduces unnecessary broadcasts. The summary and open issues then condense the main insights and highlight remaining technical challenges for future study.

2.1 Background: 3GPP RAN1 Timeline Framework

6G radio access is being developed in 3GPP across Release 20 (study) and Release 21 (work), with RAN1 leading 6G study item (SI) work from 2025 and targeting completion around 2027. Energy efficiency is treated as a core day-one design objective rather than a late enhancement [2]. Major contributors, including vendors and chipset makers such as Samsung, Nokia, Ericsson, Vivo, Xiaomi, Apple, Qualcomm, and Huawei, are working within a common evaluation framework based on agreed BS/UE power models, standardized deployment scenarios (rural, urban, highway, and indoor), and metrics including BS power, UE battery consumption, spectral efficiency, latency, and coverage. Throughout these efforts, three principles guide 6G energy-efficient RAN design: AI-native control and optimization, reduced configuration and architectural complexity versus 5G, and modular, scalable support for diverse deployment scenarios without duplicating functionality [2], [3].

2.2 SSB Periodicity Extension and Network Deep Sleep

The synchronization signal block (SSB) in 5G NR is transmitted every 20 ms to support cell detection, beam management, and synchronization, which forces frequent beamforming and baseband activity and leads to substantial energy consumption even in light-load or coverage- overlapping scenarios. The current studies in 6G investigate extending the SSB periodicity to 40, 80, 160 ms, or beyond, using techniques such as clustered provisioning of SSB, system information block 1 (SIB1), and paging followed by deep sleep intervals; fat SSBs that convey richer in

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formation per burst; and sparser synchronization rasters that reduce the number of time-frequency candidate positions.

Industry evaluations report that increasing the SSB period can reduce BS power by roughly 50-77% through longer deep sleep durations, reduced cooling and site overhead, and lower beamforming duty cycles. However, it has disadvantages of higher initial access latency (e.g., the order of 50-150 ms), more fragile beam tracking in high mobility scenarios, and possible coverage loss near the cell edge [4]. The current work in 3GPP is therefore centered on comparing several candidates' periodicities via simulations, defining adaptive schemes that select the SSB period based on load and coverage constraints, and specifying robust collision handling rules that will meet the extended SSB period transmission coexistence with data channels.

2.3 On-Demand Signaling: OD-SSB and OD-SIB1

On-demand signaling replaces continuous broadcast transmissions with event-driven operation to improve RAN energy efficiency, whereby only needed signals are transmitted rather than at fixed periodic intervals. In 6G, OD-SSB generalizes the 5G concept by allowing UE or network-triggered SSB transmission via wake-up signaling in single-cell, multi-cell, and multi-transmitter-receiver point (TRP) deployments, with design constraints on the coordination between always-on and on-demand SSB periodicities, the use of OD-SSB as a subset of always-on (AO)-SSB beams to contain UE complexity, flexible UE measurement choices, and defined collision handling rules with data channels.

OD-SSB can lower BS energy consumption by roughly 30-50% by suppressing during idle-mode background SSB transmission in suitable traffic and deployment scenarios, while complementary OD-SIB1 removes redundant periodic SIB1 broadcast by using uplink wake-up signaling when UEs require updated information, which provides a further 11-35% saving at the cost of modest SIB1 acquisition delay (about 10-50 ms) and limited additional UE implementation complexity [1]. Therefore, the focus is currently on hybrid periodic and on-demand schemes that jointly tune SSB and SIB1 configurations to balance network efficiency against access latency and robustness for different load and mobility conditions.

2.4 Summary and Open Issues

Several technical challenges remain unresolved in the current 6G RAN1 studies. The concept of SSB-less secondary cell operation lacks a unified framework, specifically regarding UE measurement, reporting, and mobility procedures when combined with on-demand SSB and extended SSB transmission. Further, the optimal joint configuration of SSB periodicity, OD-SIB1, OD-SSB, and paging, including when and how to switch between periodic and on-demand modes, currently remains an open design space, especially under varying load and mobility conditions. Finally, the power models for UE and BS are still being refined, including the definition of new sleep states and transition overheads [4]. Table 1 summarizes our survey for energy-saving mechanisms in the current state of the 3GPP RAN1 standardization work.

Table 1. Summary of energy-saving mechanisms in the current state of the 3GPP RAN1 standardization work

Scenario	Main Energy-Saving Mechanism	Typical BS Energy Saving	Latency/ Performance Impact
Rural/sparse deployment	SSB periodicity extension to 80-160 ms with deep sleep	50-77% under light-medium load	+50-150 ms initial access delay; careful dimensioning needed for cell edge coverage
Urban/dense macro or small cells	Combination of clustered SSB/SIB1, OD-SSB and SIB1	30-50%, depending on traffic and overlap	+20-50 ms access delay in worst case: sensitivity to mobility and interference
Highway/ high-mobility	Moderately extended SSB periodicity with adaptive control	20-40% limited to mobility constraints	Need tighter SSB periodicity for beam tracking; smaller latency budget

Ⅲ. Conclusion

In this paper, we investigated the current state of energy-saving mechanisms in the 3GPP RAN1 standardization work. On-demand mechanisms and extended SSB periodicity can provide roughly 50-77% BS energy savings, but these benefits are scenario-dependent and entail trade-offs in terms of latency and mobility. Therefore, adaptive standard-aligned control of periodic and on-demand signaling needs to be studied further.

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