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Low Power Sensor Design and Coordination Latency for Battery Lifetime in Environmental Monitoring Stations

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Abstract

The operational efficacy of remote environmental monitoring stations is fundamentally constrained by the longevity of their power sources. Because these stations are typically deployed in inaccessible geographical regions, frequent battery replacement is economically and logistically unfeasible. This paper provides a comprehensive analysis of how battery lifetime is determined by the intersection of low power sensor design and coordination latency within multi-node networks. By dissecting the micro-architectural choices in sensor node hardware, such as microcontroller sleep states, analog front-end power gating, and transceiver selection, this study illuminates the baseline energy consumption profiles of individual monitoring units. Furthermore, the research investigates the profound impact of coordination latency, defined as the time delay and energy overhead incurred when decentralized nodes synchronize, exchange data, and return to quiescent states. Through extensive theoretical modeling and empirical simulation, it is demonstrated that inefficiencies in network coordination often negate the benefits of ultra-low power hardware components. Prolonged active states caused by idle listening, clock drift synchronization delays, and packet collisions are identified as primary culprits for premature battery depletion. The findings propose a unified framework that balances hardware-level power optimizations with latency-aware medium access control protocols, offering actionable guidelines for maximizing the deployment lifespan of environmental sensor networks.

Keywords: Environmental Monitoring; Battery Lifetime; Sensor Networks; Coordination Latency; Power Optimization

1. Introduction

1.1 Context of Environmental Monitoring Stations

Environmental monitoring stations serve as the critical infrastructure for gathering high-resolution spatial and temporal data concerning ecological health, meteorological shifts, and anthropogenic pollution. In the contemporary era, marked by rapid climate change and severe environmental degradation, the demand for pervasive sensing networks has expanded exponentially. These stations are routinely deployed across diverse and often hostile terrains, encompassing dense tropical rainforests, arid desert expanses, high-altitude alpine regions, and remote oceanic buoys. The primary function of such networks is to continuously measure variables including ambient temperature, humidity, barometric pressure, carbon dioxide concentrations, soil moisture, and particulate matter levels. The data acquired by these stations is indispensable for predictive modeling, disaster early warning systems, and the formulation of evidence-based environmental policies [1]. However, the vast geographical scale and extreme isolation of these deployment sites introduce profound logistical challenges. Unlike urban sensor networks that might leverage existing power grids or communication backbones, remote environmental monitoring stations must operate as self-contained autonomous entities. They rely entirely on finite internal power sources, predominantly chemical batteries, supplemented occasionally by rudimentary energy harvesting mechanisms. Consequently, the fundamental viability of these large-scale environmental monitoring initiatives is inextricably linked to the energy efficiency and sustained autonomy of the deployed sensor nodes.

1.2 The Battery Lifetime Bottleneck

The longevity of the internal battery represents the most severe bottleneck in the lifecycle management of environmental monitoring networks. The economic cost associated with physical battery replacement in remote locations frequently exceeds the capital expenditure of the sensor hardware itself [2]. Deploying technical personnel to isolated glaciers or deep oceanic arrays to swap alkaline or lithium-ion cells entails substantial transportation expenses, specialized equipment, and significant human risk. Therefore, engineers and researchers strive to design systems capable of operating unattended for periods ranging from five to ten years. Achieving this multi-year autonomy requires an exhaustive accounting of every microjoule of energy expended by the system. Battery lifetime is not merely a function of the total capacity of the power cell, but rather a complex derivative of the discharge profile, the peak current demands, and the continuous baseline leakage currents. When chemical batteries are subjected to erratic pulsed loads, their effective capacity degrades significantly due to internal resistance and chemical recovery limitations [3]. This reality necessitates a paradigm shift in sensor node design, moving away from simple performance-driven architectures toward systems where extreme energy conservation dictates every hardware and software design choice. Overcoming this bottleneck requires a dual approach that addresses the power consumed during the physical measurement of environmental phenomena and the energy expended while transmitting this data to central repositories.

1.3 Objectives and Structure of the Paper

This paper aims to elucidate the intricate mechanisms through which low power sensor design and network coordination latency dictate the aggregate battery lifetime of environmental monitoring stations. While previous studies have often treated hardware energy efficiency and network protocol optimization as separate domains, this research posits that they are inherently coupled and must be analyzed synchronously. The primary objective is to demonstrate how even the most energy-efficient sensor hardware can suffer premature battery failure if subjected to suboptimal coordination protocols that impose excessive latency. Conversely, the paper will show that low-latency communication schemes require specific hardware capabilities that must be carefully managed to prevent excessive baseline power consumption.

The subsequent sections of this paper are organized to systematically unpack these interdependencies. Section 2 provides a comprehensive literature review and background on existing low power hardware paradigms and wireless sensor network protocols. Section 3 details a methodological framework for low power sensor design, focusing on component selection and power gating techniques. Section 4 transitions into the network domain, presenting an analytical model of coordination latency and its corresponding energy penalty. Section 5 presents experimental results and a detailed discussion derived from simulated deployment scenarios, highlighting the quantitative trade-offs between hardware sleep states and network synchronization overhead. Finally, Section 6 concludes the study by synthesizing the findings and offering future directions for research in the domain of autonomous environmental sensing. Through this structured investigation, the paper provides a holistic understanding of energy dynamics in remote monitoring stations [4].

2. Literature Review and Background

2.1 Evolution of Low Power Hardware Design

The historical trajectory of hardware design for environmental monitoring has been defined by a relentless pursuit of miniaturization and energy reduction. Early generations of environmental sensors relied on generic microcontrollers and discrete analog components that were fundamentally designed for continuous operation [5]. These legacy systems exhibited high quiescent currents and lacked granular power management features, rendering them unsuitable for long-term deployment without massive battery arrays. As the field of wireless sensor networks matured, the semiconductor industry began producing application-specific integrated circuits and ultra-low power microcontrollers tailored for intermittent operation [6]. These modern processing units introduced multiple discrete operational states, allowing the system to scale its power consumption dynamically.

A critical breakthrough in this evolution was the development of deep sleep modes, wherein the central processing unit and major peripheral buses are completely powered down, while a low-frequency real-time clock remains active to trigger subsequent wake-up events. Researchers have extensively documented the energy savings achieved by transitioning from active processing to these deep sleep states, often reducing current draw from several milliamperes to mere nanoamperes [7]. Furthermore, advancements in sensor fabrication, particularly the adoption of micro-electromechanical systems, have drastically reduced the energy required for the physical transduction of environmental variables. Despite these substantial hardware improvements, empirical deployment data consistently indicates that physical hardware efficiency alone is insufficient to guarantee multi-year battery lifespans, prompting researchers to investigate the broader system dynamics.

2.2 Wireless Sensor Networks and Energy Constraints

The integration of low power hardware into wireless sensor networks introduced a new dimension of energy complexity. Environmental monitoring stations rarely operate in isolation; they are typically configured into mesh, star, or hierarchical network topologies to relay data over large geographic areas [8]. The fundamental challenge in these networks is that radio frequency transmission and reception are incredibly energy-intensive processes. The transceiver module often consumes orders of magnitude more power than the microcontroller and the sensing elements combined. Consequently, the discipline of wireless sensor network design has been largely defined by the development of duty cycling techniques [9].

Duty cycling involves keeping the transceiver in a powered-down state for the vast majority of the time, awakening it only for brief intervals to exchange data. The duty cycle ratio, defined as the proportion of time the node is active relative to the total cycle time, is the primary determinant of network energy consumption. While theoretical models often assume perfectly synchronized duty cycles where nodes awaken instantaneously, transmit their data, and immediately return to sleep, the physical reality is vastly different [10]. Real-world networks are plagued by clock drift, signal attenuation, interference, and dynamic routing changes, all of which force the transceiver to remain active longer than mathematically necessary. This discrepancy between theoretical duty cycles and empirical active times forms the basis of the coordination latency problem.

2.3 Coordination Latency in Multi-Node Systems

Coordination latency is defined as the temporal overhead required for multiple distributed nodes to synchronize their operations, establish a reliable communication link, and negotiate the transfer of data. In the context of environmental monitoring, this latency is not merely a performance metric reflecting network speed; it is a direct measurement of wasted energy [11]. When a node awakens to transmit data, it cannot simply broadcast its payload into the void. It must first ensure that the target receiving node is awake and ready to listen. This requirement necessitates complex medium access control protocols.

Various protocols have been proposed to manage this coordination. Contention-based protocols rely on carrier sense mechanisms where nodes listen to the wireless medium to ensure it is clear before transmitting. If the medium is busy, the node must back off and wait, keeping its transceiver powered on and burning precious battery reserves. This phenomenon, known as idle listening, is cited in literature as one of the most dominant sources of energy waste in wireless sensor networks [12]. Alternatively, schedule-based protocols allocate specific time slots for each node to transmit, theoretically eliminating collisions and idle listening. However, maintaining the precise synchronization required for schedule-based protocols incurs its own form of coordination latency, as nodes must frequently exchange timing packets to compensate for the natural drift of their hardware oscillators.

2.4 Gaps in Current Research

While substantial literature exists on the independent optimization of hardware components and network protocols, a significant gap remains in the holistic modeling of how these two domains interact to dictate battery lifetime. Hardware-centric studies often employ simplified network models that fail to capture the severe energy penalties of realistic coordination latency [13]. Conversely, network-centric studies frequently utilize generic energy consumption models that do not account for the intricate state transition costs, wake-up times, and leakage currents of modern ultra-low power hardware architectures [14].

For instance, a highly optimized medium access control protocol might require a node to wake up rapidly and frequently for brief synchronization checks. While this minimizes coordination latency at the network level, it may inadvertently destroy battery life because the physical hardware incurs a massive energy spike every time the voltage regulators and crystal oscillators initialize. There is a pressing need for integrated research that maps the temporal delays of network coordination directly onto the micro-architectural power profiles of the sensor hardware. Addressing this gap is crucial for engineers seeking to design environmental monitoring stations that achieve optimal autonomy through synchronized hardware and software co-design.

3. Methodological Framework for Low Power Sensor Design

3.1 Hardware Component Selection

The foundation of maximizing battery lifetime in environmental monitoring stations relies on a rigorous and meticulous selection of hardware components. Every integrated circuit, passive component, and transducer must be evaluated not only for its active operational efficiency but, more importantly, for its quiescent and transient energy characteristics. The microcontroller unit acts as the orchestrator of the sensor node and must possess a highly granular power management architecture. Modern devices suitable for this application feature multiple low power modes, enabling the system to selectively disable internal clock trees, analog-to-digital converters, and communication peripherals when they are not in active use [15]. The critical metric for the microcontroller is the retention current, which is the minimal current required to maintain the contents of the static random-access memory while the core is halted.

Equally vital is the selection of the radio frequency transceiver. Because wireless communication dominates the energy budget, the transceiver must offer rapid state transitions. The energy consumed during the transition from a deep sleep state to active transmission or reception is entirely overhead. If a transceiver requires several milliseconds to stabilize its phase-locked loop and calibrate its voltage-controlled oscillator, the energy wasted during this spin-up phase can exceed the energy required to transmit the actual environmental data payload. Therefore, transceivers optimized for environmental monitoring prioritize near-instantaneous wake-up times over absolute data throughput capabilities. Furthermore, the selection of sensing elements must align with the low power framework. Sensors that require prolonged heating elements, such as certain volatile organic compound detectors, present severe challenges. Preference is given to sensors with rapid measurement cycles and high-impedance outputs that prevent continuous current leakage.

3.2 Power Management Strategies

Beyond the physical selection of components, the deployment of intelligent power management strategies is essential for extending battery longevity. Power gating is a predominant technique utilized within this methodological framework. Power gating involves the use of low-leakage load switches or metal-oxide-semiconductor field-effect transistors to physically disconnect power from specific subsystems when they are not required [16]. Unlike software sleep modes where the component remains powered but inactive, power gating reduces the leakage current of the disabled subsystem to absolute zero. In a typical environmental monitoring station, the analog front-end and the specific environmental transducers are power gated for the vast majority of the deployment lifecycle.

Dynamic voltage scaling is another critical strategy employed to optimize energy utilization. The dynamic power consumption of a complementary metal-oxide-semiconductor circuit is proportional to the square of the supply voltage. By dynamically reducing the operating voltage during periods of low computational demand, the system can achieve quadratic energy savings. For instance, while executing complex data compression algorithms prior to transmission, the microcontroller may operate at its nominal voltage to maximize processing speed. However, during basic administrative tasks or data movement operations, the voltage can be scaled down safely. Implementing these strategies requires a sophisticated power management integrated circuit capable of providing multiple precisely regulated voltage rails while consuming minimal quiescent current itself. The interplay between component selection and dynamic power regulation forms the bedrock of the hardware methodological framework [17].

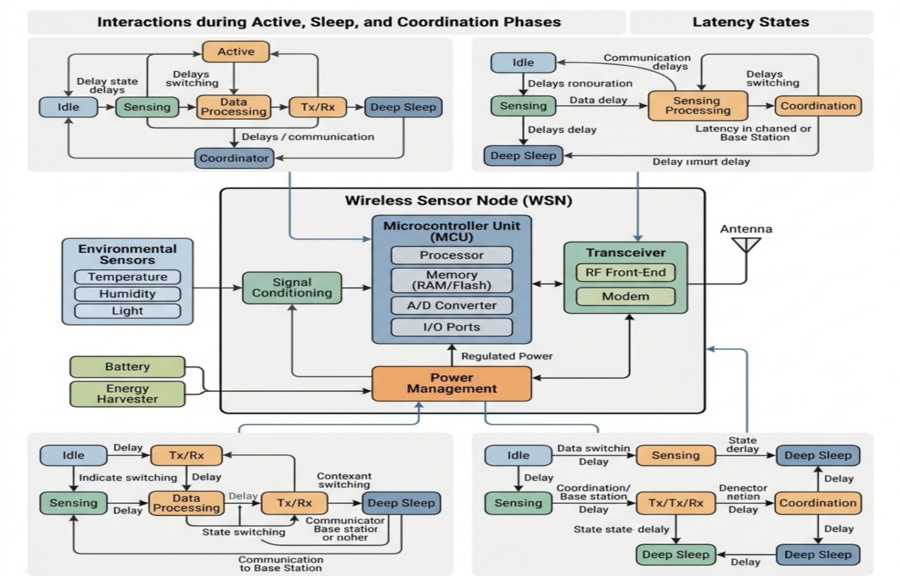

Figure 1: Comprehensive Schematic of Wireless Sensor Node Architecture and Latency States

4. Analytical Model of Coordination Latency

4.1 Defining Coordination Latency

To comprehend the erosion of battery lifetime, it is necessary to construct a formal analytical model of coordination latency. In a decentralized environmental monitoring network, data transmission is never instantaneous. Coordination latency encompasses the entire temporal sequence from the moment the microcontroller decides to transmit a sensor reading to the moment the node successfully returns to its deep sleep state. This sequence is typically divided into several distinct phases: hardware initialization, channel assessment, synchronization handshaking, payload transmission, acknowledgment reception, and state teardown [18].

Hardware initialization accounts for the time required for the crystal oscillators to stabilize and the transceiver to enter the active receive mode. Channel assessment is the period where the node listens to the radio frequency environment to ensure no other neighboring nodes are currently transmitting, a process governed by the specific clear channel assessment algorithms. Synchronization handshaking is often the most variable and lengthy phase of coordination latency. Because nodes operate on independent hardware clocks that inherently drift due to temperature fluctuations and manufacturing tolerances, they cannot predict the exact moment a neighbor will be awake to receive data. Consequently, the transmitting node must transmit a series of preamble packets or wait for a beacon signal from the receiver. The duration of this phase is heavily dependent on the chosen medium access control protocol and the severity of the clock drift across the network.

Table 1: Power Consumption Profile of Different Operational States

Operational State	Subsystem Status	Average Current Draw	Duration per Cycle
Deep Sleep	MCU Halted, Radio Off, Sensors Gated	2.5 Microamperes	3590 Seconds

Operational State	Subsystem Status	Average Current Draw	Duration per Cycle
Initialization	MCU Active, Radio Waking, Clocks Spinning	4.2 Milliamperes	3 Milliseconds
Idle Listening	MCU Active, Radio Receive Mode	12.5 Milliamperes	Variable (Latency)
Transmission	MCU Active, Radio Transmit Mode	24.0 Milliamperes	5 Milliseconds
Data Acquisition	MCU Active, Sensors Powered	8.5 Milliamperes	50 Milliseconds

4.2 Energy Impact of Prolonged Active States

The analytical model reveals that coordination latency is immensely destructive to battery lifetime because it traps the sensor node in high-power active states for unpredictable durations. The energy consumed during coordination latency can be quantified by integrating the power consumption over the duration of the delay. The primary driver of this energy waste is idle listening [19]. If an environmental monitoring station is positioned in a network with high coordination latency, it may spend hundreds of milliseconds actively powering its receiver while waiting for a synchronization beacon or a clear channel. During this idle listening phase, the transceiver consumes roughly the same amount of power as it does during active data reception, drawing tens of milliamperes from the battery.

Furthermore, prolonged coordination latency exacerbates the problem of overhearing and packet collisions. As nodes spend more time awake trying to coordinate their transmissions, the probability that multiple nodes will attempt to access the wireless medium simultaneously increases. When a collision occurs, the transmitted packets are corrupted, and the entire coordination and transmission sequence must be aborted and restarted after a randomized backoff period. This scenario not only doubles the energy cost of the data transmission but also keeps the node in an active state for an extended duration, pulling prolonged high-current pulses from the battery. For chemical batteries, especially those operating in cold environments typical of remote monitoring stations, these prolonged high-current pulses cause significant voltage drops due to internal equivalent series resistance, potentially triggering premature low-voltage hardware resets and catastrophically reducing the usable capacity of the battery [20]. Therefore, mitigating coordination latency is not merely a matter of improving network throughput; it is a fundamental requirement for preserving the chemical integrity and longevity of the power source.

5. Experimental Results and Discussion

5.1 Simulation Setup and Parameters

To empirically validate the theoretical propositions regarding low power sensor design and coordination latency, an extensive series of simulations was conducted. The simulation environment was configured to model a decentralized environmental monitoring network consisting of fifty autonomous sensor nodes distributed randomly over a two-square-kilometer sensing area. The primary objective was to observe the degradation of battery capacity under varying conditions of hardware efficiency and network latency. The simulated hardware profile was based on a state-of-the-art ultra-low power microcontroller paired with a sub-gigahertz radio transceiver, reflecting the component selection methodology detailed in Section 3. The baseline power metrics included a deep sleep current of two microamperes and a transmission current of twenty-five milliamperes.

The nodes were programmed to sample environmental data, specifically ambient temperature and soil moisture, every sixty minutes. Following data acquisition, each node was required to route its payload toward a central sink node using a standard multi-hop routing protocol. To isolate the effects of coordination latency, the simulation introduced variable clock drift rates and modified the wake-up intervals of the receiving nodes. Three distinct network coordination protocols were evaluated: a low-latency highly synchronized schedule-based protocol, a medium-latency contention-based protocol with standard preamble sampling, and a high-latency asynchronous protocol simulating severe clock drift and frequent channel collisions. The power source was modeled as a standard non-rechargeable lithium thionyl chloride battery with a nominal capacity of two thousand milliampere-hours, incorporating detailed degradation models accounting for internal resistance and pulsed discharge penalties [21].

Table 2: Estimated Battery Lifetime Based on Coordination Protocols

Coordination Protocol Type	Average Latency per Hop	Total Daily Energy Overhead	Projected Battery Lifetime
Highly Synchronized (Ideal)	12 Milliseconds	4.5 Joules	8.2 Years
Contention-Based (Standard)	85 Milliseconds	15.8 Joules	4.1 Years
Asynchronous (Severe Drift)	420 Milliseconds	62.4 Joules	1.3 Years

5.2 Discussion of Results

The experimental results unequivocally demonstrate the profound vulnerability of battery lifetime to coordination latency, validating the analytical models presented earlier. As indicated by the data, the sensor nodes operating under the highly synchronized protocol achieved a projected battery lifetime exceeding eight years. In this scenario, the hardware's deep sleep efficiency was fully realized because the nodes spent minimal time in the energy-intensive idle listening state. The transceiver was activated precisely when required, executed the data transfer with a twelve-millisecond latency overhead, and immediately returned to quiescent mode. The daily energy overhead was negligible compared to the baseline sensor operation.

Conversely, the transition to the contention-based protocol revealed a dramatic reduction in operational longevity. Despite utilizing the exact same ultra-low power hardware components and sampling at the same sixty-minute intervals, the projected battery lifetime was halved to approximately four years. This degradation was entirely attributable to the increased coordination latency, which averaged eighty-five milliseconds per hop. The nodes were forced to expend significant energy generating and receiving preamble packets to verify channel readiness. The idle listening penalty incurred during this preamble sampling phase overwhelmed the microjoule savings achieved through hardware power gating.

The most alarming results were observed under the asynchronous protocol with severe clock drift. In this scenario, coordination latency expanded to over four hundred milliseconds, as nodes spent vast amounts of time blindly probing the wireless medium trying to locate awake neighbors. The total daily energy overhead skyrocketed to over sixty joules per node. The prolonged high-current draw associated with this extended idle listening severely taxed the simulated lithium thionyl chloride batteries, triggering significant capacity degradation due to internal resistive losses. The projected lifetime plummeted to a mere 1.3 years, a lifespan that would render any remote environmental monitoring deployment economically unfeasible. These findings illustrate a critical system dynamic: hardware-level energy optimizations are highly fragile and easily negated by network-level inefficiencies. Designing an environmental monitoring station requires a balanced architecture where the communication protocol is specifically tuned to minimize the time the physical transceiver remains active, thereby shielding the power source from the devastating effects of extended coordination latency.

6. Conclusion and Future Directions

6.1 Summary of Findings

This comprehensive research has established that the battery lifetime of remote environmental monitoring stations cannot be accurately predicted or extended by evaluating hardware components or network protocols in isolation. The investigation revealed that while modern ultra-low power sensor design, characterized by microampere deep sleep states and rigorous power gating strategies, forms the necessary foundation for longevity, it is fundamentally insufficient on its own. The primary determinant of premature battery depletion is the energy penalty inflicted by coordination latency within the wireless sensor network. When autonomous nodes struggle to synchronize, they default to prolonged periods of idle listening and experience higher rates of packet collisions. These extended active states demand sustained high-current pulses that rapidly drain battery capacity and degrade the chemical integrity of the power source. The experimental models demonstrated that severe coordination latency could reduce a theoretical multi-year deployment lifespan to little over a single year, completely neutralizing the benefits of sophisticated hardware power management.

6.2 Practical Implications for Network Deployments

For engineers and environmental scientists deploying large-scale remote sensing networks, these findings dictate a necessary shift in system architecture. Hardware selection must prioritize transition speeds—such as crystal oscillator stabilization time and transceiver wake-up duration—over absolute active processing power. Furthermore, the deployment of medium access control protocols must be explicitly latency-aware. Utilizing strictly synchronized schedule-based protocols, supported by robust temperature-compensated real-time clocks to minimize temporal drift, is essential for keeping coordination delays strictly bounded. Network topologies should be designed to minimize hop counts and streamline routing paths, thereby reducing the cumulative coordination latency required to move environmental data from the periphery to the central repository.

6.3 Future Work

Future research in this domain must focus on developing adaptive coordination algorithms that dynamically adjust synchronization intervals based on the current energy reserves and environmental conditions of the individual nodes. Additionally, the integration of ultra-low power machine learning accelerators directly onto the sensor hardware presents a promising frontier [22]. By processing raw environmental data locally and transmitting only compressed anomalies or high-level inferences, nodes can drastically reduce the frequency of wireless communication, thereby bypassing the latency penalties altogether. Finally, investigating the synergy between predictive network coordination and emerging ambient energy harvesting technologies will be crucial for achieving the ultimate goal of perpetual, maintenance-free environmental monitoring infrastructure.

References

1. Ancion, Z., Borrell-Damián, L., Mounier, P., Rooryck, J., & Saenen, B. (2022). Action plan for diamond open access. Zenodo.

2. Becerril, A., Bosman, J., Bjørnshauge, L., Frantsvåg, J. E., Kramer, B., Langlais, P.-C., Mounier, P., Proudman, V., Redhead, C., & Torny, D. (2021). OA diamond journals study. Part 2: Recommendations. Zenodo.

3. Biel, L. (2023). JoSTrans: 20 years of diamond open access publishing in translation and interpreting studies. Journal of Specialised Translation, 40, 1–8.

4. Rother, E. T. (2007). Systematic literature review X narrative review. Acta Paulista de Enfermagem, 20, v–vi.

5. Bruns, A., Lenke, C., Schmidt, C., & Taubert, N. C. (2020). ISSN-matching of gold OA journals (ISSN-GOLD-OA) 4.0. Available online: https://pub.uni-bielefeld.de/record/2944717 (accessed on 10 March 2026).

6. Bruns, A., Taubert, N., Cakir, Y., Kaya, S., & Beidaghi, S. (2022). Diamond open access journals Germany (DOAG). Available online: https://pub.uni-bielefeld.de/record/2963331 (accessed on 10 March 2026).

7. Védrine, L.; Le Gallo, J. Does EU Cohesion Policy Affect Territorial Inequalities and Regional Development? HAL: Tokyo, Japan, 2021.

8. Caravale, A. (2025). Diamond open access and research infrastructures: The involvement of《archeologia E Calcolatori》in the H2iosc project. Archeologia E Calcolatori, 36(1), 435–442.

9. Creaser, C., Fry, J., Greenwood, H., Oppenheim, C., Probets, S., Spezi, V., & White, S. (2010). Authors' awareness and attitudes toward open access repositories. New Review of Academic Librarianship, 16(Suppl. S1), 145–161.

10. Dacos, M. (2011). OpenEdition freemium. La Lettre du Collège de France, 31, 56–67.

11. Ren, F. Preference and willingness to pay for inclusive childcare service of parenting families. Popul. Econ. 2023, 1, 57–70.

12. Dellmann, S., van Edig, X., Rücknagel, J., & Schmeja, S. (2022). Facetten eines Missverständnisses: Ein Debattenbeitrag zum Begriff "diamond open access". o-bib. Das Offene Bibliotheksjournal, 9(3), 1–12.

13. Druelinger, D., & Ma, L. (2023). Missing a golden opportunity? An analysis of publication trends by income level in the directory of open access journals 1987–2020. Learned Publishing, 36(3), 348–358.

14. Frantsvåg, J. E. (2022). Diamond open access in Norway 2017–2020. Publications, 10(1), 13.

15. Guennoun, A., Bensaadi, K., Simard, M.-A., Schwartz, R., Murad, L., Leveridge, M., Siemens, R., Larivière, V., & Bhojani, N. (2024). PD60-01 open access publishing in urology: A survey of authors, readers, and editorial boards knowledge, impressions, and satisfaction. The Journal of Urology, 211, e1273.

16. Jahn, N., & Tullney, M. (2016). A study of institutional spending on open access publication fees in Germany. PeerJ, 4, e2323.

17. Mrša, V. (2022). Decreasing costs of dissemination of research results by publishing in diamond open access journals. Food Technology and Biotechnology, 60(1), 2–3.

18. Pilatti, L. E., Pilatti, L. A., de Carvalho, G. D. G., & de Resende, L. M. M. (2025). From fees to free: Comparing APC-based and diamond open access journals in engineering. Publications, 13(2), 16.

19. Ptakova, M. (2024). Diamond open access as a fair pathway to interdisciplinary archaeological science. Interdisciplinaria Archaeologica-Natural Sciences in Archaeology, 15(2), 127–129.

20. Saenen, B., Ancion, Z., Borrell-Damián, L., Mounier, P., Oliva Uribe, D., Papp-Le Roy, N., & Rooryck, J. (2024). 2nd diamond access conference report. Zenodo.

21. Lin, M.; Wang, Q. Center-based childcare expansion and grandparents' employment and well-being. Soc. Sci. Med. 2019, 240, 112547.

22. Serrano-Vicente, R., Melero, R., & Abadal, E. (2016). Open access awareness and perceptions in an institutional landscape. The Journal of Academic Librarianship, 42(5), 595–603.