# DYNAMIC DATA ENHANCING BATTERY EFFICIENCY THROUGH COLLECTION SCHEDULING IN IQRF WIRELESS SENSOR NETWORKS

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**ABSTRACT**

*In this study, we explore innovative strategies for enhancing energy efficiency in Wireless Sensor Networks (WSNs), with a focus on the IQRF network. Our approach integrates dynamic sleep scheduling and data collection methods to optimize battery usage and extend the network's operational lifespan. We introduce a battery life estimation model, taking into account various factors such as data collection frequency and network size. This model is instrumental in predicting battery longevity under different operational scenarios. Additionally, we develop a practical tool in the form of an API and an online calculator, aimed at assisting network designers in planning and maintaining energy-efficient WSNs. Our results, derived from a case study involving a CO2 sensor network, demonstrate the effectiveness of our methodologies in real-world applications. The study concludes that implementing dynamic data collection and sleep scheduling significantly enhances battery life, offering a valuable contribution to the sustainability and reliability of WSNs.*

***Keywords:*** *IQRF, FRC, flooding routing, wireless sensor network, dynamic deep sleep, dynamic data collecting schedule*

## 1. INTRODUCTION

Energy management in Wireless Sensor Networks (WSNs) is a critical factor determining the efficiency and longevity of these networks, particularly in remote applications where energy sources are limited. The core challenge lies in the inherent energy constraints of the sensor nodes, which are typically powered by batteries. The efficient use of energy is essential to prolong the operational lifespan of these sensor nodes, thereby enhancing the overall performance and reliability of the network. Considering the limited energy resources, several battery-driven energy conservation schemes have been proposed [1][2]. These schemes aim to ensure energy-efficient network operation without compromising the essential functionalities of the WSNs. One of the key observations in WSNs is that the maximum power consumption occurs during the reception and transmission of packets. Notably, the receive mode is identified as the most energy-intensive operation, which significantly influences the network's energy dynamics [3].

The significance of energy management in WSNs cannot be overstated, as higher energy consumption directly correlates with a shorter battery life. This relationship underscores the need for effective energy management strategies to extend the operational lifespan of the sensor nodes.

In our previous research focusing on the IQRF network, we conducted an extensive study on the energy consumption associated with different data collecting methods. This research led to the development of a comprehensive battery life estimation model specifically tailored for the IQRF network. This model utilized lithium thionyl chloride batteries and incorporated merged data collecting approaches to optimize energy usage [12].

Further, we presented a study on the implementation of a deep sleep schedule in the IQRF network [11]. This approach primarily focused on reducing power consumption through the synchronized sleep mode of the sensor nodes. By enabling the nodes to enter a low-power state during periods of inactivity, significant energy savings were achieved, contributing to the network's overall efficiency.

Building upon our earlier research and findings in the analysis of the IQRF network, the present study aims to explore and identify additional methodologies for reducing energy consumption in various IQRF network applications. By examining specific scenarios and their unique energy demands, this study seeks to further enhance the energy efficiency of WSNs, thereby extending their applicability and sustainability in diverse environments.

## 2. DYNAMIC SLEEP SCHEDULING FOR WSN

A dynamic sleep schedule in Wireless Sensor Networks (WSNs) is a strategy that varies sensor nodes' active and sleep states to optimize energy use and extend network life. It adapts in real-time to network demands and node energy levels. There are several approaches to implement this strategy, each tailored to specific network conditions and objectives. These methods collectively aim to reduce unnecessary energy consumption, thereby prolonging the operational lifespan of battery-powered, remotely deployed WSNs.

Numerous research efforts have been dedicated to exploring dynamic sleep scheduling in Wireless Sensor Networks (WSNs) as a strategy to curtail energy usage and thereby enhance network longevity. A notable contribution in this domain was made by Guruprakash *et al.* [4], who introduced the E2DR-MCS, a multi-objective clustering and sleep scheduling scheme. This approach effectively reduced energy consumption and overhead, simultaneously optimizing network lifetime and data delivery ratios.

In 2009, Ma *et al.* [5] delved into the realm of energy-efficient Time Division Multiple Access (TDMA) sleep scheduling. This study pioneered an innovative approach to

the interference-free TDMA sleep scheduling issue and presented both centralized and distributed algorithms to address this challenge.

Sasikala *et al.* [6] marked another significant advancement with the introduction of a cluster-based sleep/wake scheduling technique. The technique involves selecting cluster heads based on energy levels, putting some nodes in active mode and sending the remaining nodes into sleep mode, and comparing cluster energy with a standard threshold value.

Furthermore, Chauhan et al. [7] proposed a unique clustering algorithm based on information similarity. This algorithm was synergized with sleep scheduling strategies and a least spanning tree algorithm. The combination of these techniques was particularly effective in reducing redundant data transmission, which in turn led to a substantial reduction in overall energy usage, contributing to a marked improvement in the network's lifetime.

Wu *et al.* [8] focused on designing energy-efficient protocols for low-data-rate WSNs. Scheduling of sensor nodes' activities using TDMA at different radio states to reduce energy consumption. It involves allocating consecutive time slots for different radio states while minimizing the number of state transitions. Additionally, the paper proposes constructing a data gathering tree to optimize energy consumption and network throughput.

In technical terms, the dynamic sleep schedule approach means a network can automatically and flexibly change its sleep schedule based on varying conditions to boost energy efficiency. This self-adjustment suggests the network is controlled by a gateway with advanced software, serving as a coordinator in the WSN. While the schedule can be predefined, it's important that the network has the capability to dynamically adjust it as needed [4][5][8][11].

These studies collectively underscore the vital role of innovative sleep scheduling strategies in promoting energy efficiency and sustainability in WSNs. In this paper, we present a dynamic data collecting and deep sleep scheduling methodology specifically designed for IQRF networks utilizing the centralized FRC merged data collecting method.

## 3. BATTERY LIFE ESTIMATION FOR FRC

In this study, we introduce a dynamic data collecting and deep sleep scheduling method designed to improve energy efficiency and performance in IQRF networks. By optimizing when the network's sensors are active or asleep for data collection, our approach uses the Fast Response Command (FRC) to gather data more efficiently. This leads to reduced energy use and a longer life for the network. Our method makes data collection both smarter and more energy-conscious, offering a practical solution for enhancing the sustainability of IQRF networks.

The FRC in IQRF networks is an advanced data collection method that builds on the merged data collecting concept. It involves three key steps: sending a broadcast request, neighbouring data sharing, and collecting data in a response message. This approach allows for simultaneous data sampling and efficient data integration, where all sensor data is compiled in a single message, enhancing both the speed and reliability of data collection in IQRF networks. The FRC method is a centralized approach to data collection, operating on a request-response pattern. In this method, the initiation of data collection is always managed by the network coordinator [10][13][21].

Wireless sensor networks' battery longevity is closely tied to the balance between deep sleep schedules and data collection cycles. A key method for conserving battery power is the synchronized deep sleep mode, where sensor nodes enter a low-power state between data collection intervals. This method mainly involves turning off radio communications, a process that typically consumes a lot of energy.

During synchronized data collection, nodes are set to wake up shortly before they need to gather or transmit data. This timing reduces the duration they spend in energy-intensive modes. However, accurate timing is essential; a node waking up too late may miss its data collection window, leading to extended active periods and higher energy use. When executed correctly, deep sleep scheduling can significantly lower the network's energy usage. By spending most of their time in a low-power state, nodes help to substantially decrease battery drain, thereby extending the overall battery life of the system [11][12] [13][16].

The battery life estimation for FRC using a deep sleep schedule, as referenced in [13], builds upon the previously developed energy consumption model for FRC [12]. Below, we briefly summarize this foundational model:

The energy consumption model for FRC, outlined in [12], serves as the basis for estimating battery life in systems utilizing a deep sleep schedule. This model comprehensively addresses the energy dynamics within FRC frameworks, considering various operational states of the nodes. By integrating the principles from this model, we can accurately predict the battery lifespan in networks utilizes FRC employing deep sleep techniques, ensuring a more efficient and sustainable operation. The energy consumption model for FRC data collecting method using deep sleep periods simplifies energy calculations by categorizing sensor node communication into phases: deep sleep, idle, message routing, sensor processing, beacon packet sending, and response routing.

The model quantifies total energy consumption by summing the energy used during communication phases and deep sleep intervals:

$$E_{total} = n_r E_{FRC} + E_{dsleep} \quad (1)$$

Where $n_r$ represents the count of data requests within a single data collection period. The energy consumption of the FRC-based data collection, summing energy use across all phases detailed in [12]:

$$E_{FRC} = E_{idle} + E_{request} + E_{proc} + E_{beacon} + E_{response} \quad (2)$$

The network lifespan is based on the first node's battery failure, estimated by total energy consumption ($E_{total}$), the maximum number of data collecting cycles supported by the battery (based on its discharge characteristics), and battery discharge characteristics. Lithium thionyl chloride (Li/SOCl2) batteries are chosen for their high capacity, energy density, and low self-discharge rate, making them ideal for long-term applications. However, these batteries

have limitations like limited output current capability and complex self-discharge rates, which are factored into the life estimation model [13].

The maximum number of data collecting cycles ($c_{max}$) supported by the lithium thionyl chloride battery of the sensor node with $E_{total}$ energy consumption:

$$c_{\max} = \left\lfloor \frac{Q_m U}{E_{total}} \right\rfloor \tag{3}$$

where $Q_m$ represents the battery's capacity as determined by its discharge characteristics towards the end of its lifecycle, U is the nominal battery voltage. The battery life can be calculated determined based on these:

$$t_{life} = c_{\max} t_{period} \tag{4}$$

where $t_{period}$ denotes the set duration between data collection requests, defining the fixed interval within the data collection schedule.

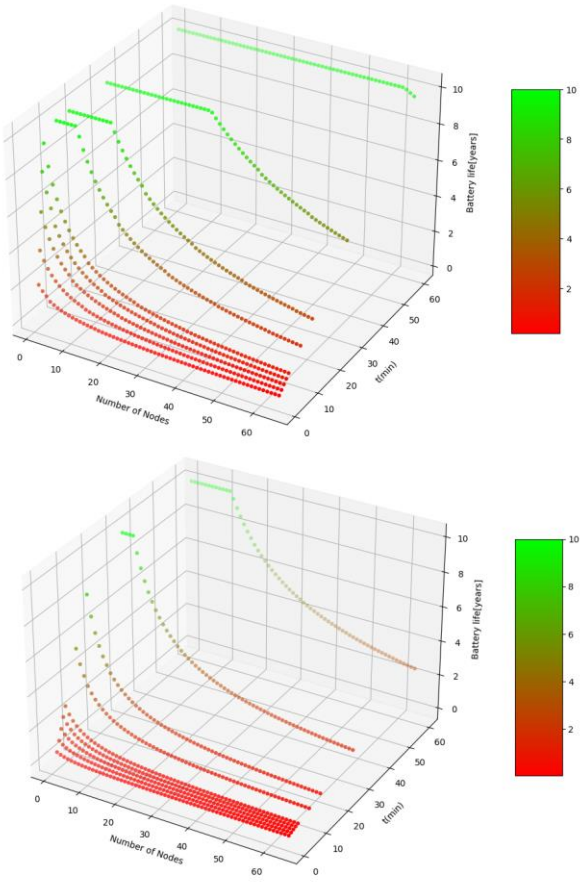



**Fig. 1** Estimated battery life for data collecting cycles between 1 and 60 minutes for networks up to 64 nodes with 1(up) and 4(down) requests per cycle

Fig 1. illustrates the estimated battery life for data collection cycles ranging from 1 to 60 minutes in networks with up to 64 nodes, with each cycle having either 1 or 4 data requests. The need for multiple data collection requests often occurs when more data is needed than what a single node can handle using the FRC method. For example, if the network needs to collect multiple types of measured values.

The diagrams reveal that increasing the number of nodes in the network or the frequency of data collection can significantly shorten battery life. However, this reduction in battery lifespan can be offset by decreasing the intervals between data collection cycles. This balancing act showcases the critical relationship between network size, data collection frequency, and battery sustainability, highlighting the need for strategic planning in network design to optimize battery life. To maximize battery life, it's important to find the right balance for deep sleep periods: long enough to save energy but short enough so nodes can collect data when needed. Getting this balance right helps reduce how often batteries need to be replaced and cuts down on network maintenance costs.

## 4. DYNAMIC DATA COLLECTING SCHEDULE FOR IQRF NETWORKS

In various applications where data collection exhibits seasonal or periodic trends, a dynamic scheduling approach can be highly beneficial. This strategy involves adapting the data collection frequency based on observed patterns in the time series data or using existing knowledge about the specific requirements of the application. For instance, let's consider Fig 2., which depicts the variations in carbon dioxide levels in an office environment over a week. In this example, the time series data clearly shows seasonal fluctuations, with distinct peaks and troughs corresponding to office occupancy patterns.

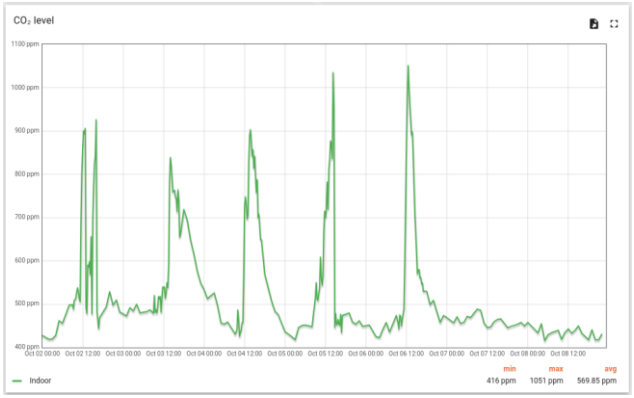



**Fig. 2** $CO_2$ level seasonality in an office during a week from a test sensor network

During periods with reduced activity, such as nights and weekends, it becomes evident that the necessity for high-frequency data collection diminishes. High-frequency data collection during these low-activity periods typically fails to yield additional valuable insights. This observation opens up opportunities for significant energy savings by adjusting the data collection intervals to be less frequent during these times.

Based on the battery life estimation model described earlier, let's delve into a hypothetical wireless sensor network consisting of 40 nodes, each initially set to a

standard data collection interval of 15 minutes. Under this configuration, the estimated battery life for each node in the network would be approximately 3.87 years. However, by strategically modifying the data collection schedule to align with periods of reduced activity, we can extend the battery life considerably. For example, if the data collection interval is extended to 60 minutes during less active evening hours (from 17:00 to 08:00) and throughout weekends, the network can operate more efficiently with less frequent data transmissions.

According to our model, such adjustments in data collection frequency can have a substantial impact on battery life. By increasing the interval during identified inactive periods, the battery life of the nodes could be extended from the initial estimate of 3.87 years to about 5.57 years. Further, if the same 60-minute interval is applied throughout the weekends, the battery life could be extended even further, potentially reaching up to 8.33 years. This is a significant improvement and demonstrates the effectiveness of dynamic scheduling based on activity levels.

In synchronized data collection methods within IQRF networks, the coordinator dictates the timing of data collection cycles. To conserve energy, sensor nodes enter a deep sleep mode between collections, significantly reducing power consumption. This strategy, known as synchronized deep sleep mode, involves deactivating the nodes' radio modules until the onset of the next data collection period. As illustrated in Fig 3., after completing FRC data collection, all nodes in the network simultaneously enter deep sleep mode. It's vital that these nodes wake up before receiving the next collection request to avoid missed communications, which could lead to higher energy usage and possible network errors. The duration of the deep sleep must be carefully set to be shorter than the cycle of data collection. This ensures that the sensors emerge from deep sleep mode at the right time to successfully receive and process new data requests, thereby maintaining effective and reliable communication within the network [11][15][18].

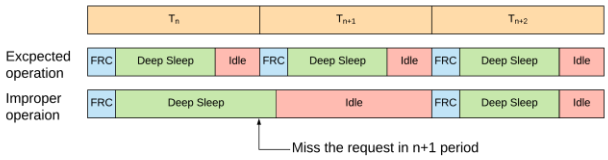



**Fig. 3** Expected and improper operation of deep sleep mode operation [11]

Implementing dynamic sleep cycles, tailored to the specific usage patterns of the network, can more than double the battery life in certain applications. This is achieved without compromising the quality or relevance of the data collected. We strongly recommend this adaptive approach in scenarios where the data collection needs vary distinctly between active and inactive periods. By doing so, networks can operate more sustainably, conserving energy, and reducing maintenance costs associated with battery replacements, all while ensuring that the data collected remains timely and relevant to the application's needs.

## 5. DYNAMIC DATA COLLECTING SCHEDULE CALCULATOR

For the practical application and implementation in real-world settings, we have developed an API and an online calculator specifically designed for installations using IQ Home wireless sensor devices, which operate on the IQRF technology platform. This development is particularly significant for professionals in the field of network design and maintenance, providing them with robust tools to optimize the performance and longevity of their wireless sensor networks.

In our study, we implemented an API in NodeJS [25] to estimate battery life in IQRF networks, building upon the battery life estimation model discussed earlier. This API intricately factors in various operational parameters such as network size, data collection cycles, and the specific active and inactive periods of the network, aligning with the established model to accurately predict battery longevity. Its design, centered around RESTful POST requests, ensures seamless integration and ease of use. Available for public use, this tool is a valuable asset for both researchers engaged in energy optimization studies and industry professionals focused on efficient network management, demonstrating a significant advancement in wireless network technology.

The online calculator shown in Fig 4 is a key tool for engineers and network designers, powered by our developed NodeJS API. It helps in planning networks precisely by letting users input their specific network needs. The calculator uses these inputs to give detailed estimations about when to change batteries and how the network will perform. This makes it easier to design efficient networks because it provides quick and clear information about how long the network will last and its upkeep needs under different setups.

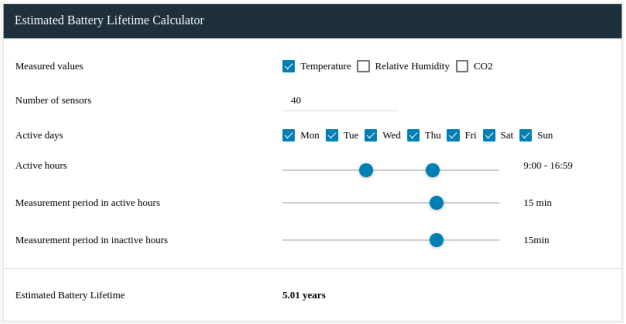



**Fig. 4** UI of the online calculator for estimating battery life with dynamic data collecting period schedule [23]

In addition to the calculator, the API we developed plays a critical role in enhancing the adaptability of the network. It allows for seamless integration with applications that require a dynamic approach to sleep scheduling. This is especially useful for applications where data collection needs are not fully known in advance or are expected to change over time. By leveraging the API, these applications can automatically adjust their data collection strategies, ensuring that the network remains efficient and responsive to changing data requirements. This adaptive refinement of dynamic sleep scheduling is a key feature for

maintaining optimal energy usage and extending the life of the network.

Furthermore, the API's capability extends to supporting applications in real-time data analysis and decision-making. It can enable applications to analyze trends in the collected data, identify patterns of activity or inactivity, and subsequently adjust the sleep scheduling parameters accordingly. This level of automation and intelligence in network management ensures that the network is not only energy-efficient but also highly responsive to the actual data needs, avoiding unnecessary data collection and transmission.

The combination of the online calculator and the API offers a comprehensive suite of tools for professionals working with IQRF technology-based wireless sensor networks. These tools support the design, implementation, and ongoing management of networks, ensuring that they are energy-efficient, adaptable, and aligned with the specific needs of the application. They represent a significant advancement in our ability to deploy and manage wireless sensor networks effectively in a variety of real-world scenarios.

The API and the online calculator tool, as previously mentioned, are not only conceptualized but also fully implemented and operational [23][24]. The primary function of the API is to augment the online calculator tool, simultaneously enabling gateways across networks, all equipped with sophisticated software, to make informed decisions based on the API's battery life estimations. This functionality is vital for the effective management of the network, particularly in strategizing sleep cycle adjustments to optimize battery longevity. Importantly, the API is not a universal solution for sleep schedule management; instead, it provides customized battery life predictions tailored to each network's specific configuration and data collection requirements. The exploration of various strategies for dynamic data collection scheduling remains a topic for further research, highlighting the potential for continued advancements in this field.

## 6. RESULTS

Our study focused on enhancing battery longevity in IQRF wireless sensor networks through a dynamic data collection schedule, integrating a deep sleep algorithm. This strategy is particularly suited for networks employing FRC merged data collection, where the network coordinator plays a pivotal role in determining and adjusting the sleep and active cycles of sensor nodes to conserve energy.

A significant aspect of our research was the application of this methodology to a case study involving a network of CO2 sensors in a building. This example demonstrated the practicality and effectiveness of our approach in a real-world scenario, revealing clear seasonal data trends. We found that the data collection frequency can be adapted based on these patterns, but with a limitation: it can only be increased after the nodes have completed their deep sleep cycle, as they need to finish this cycle before responding to new data collection requests.

Furthermore, a major outcome of our study was the development of an online calculator and accompanying API. This tool aids engineers in easily designing network battery life and maintenance schedules. It calculates the estimated battery life by considering various factors like network size, data collection specifics, and periods of high and low activity.

## 7. CONCLUSIONS

Our research offers a meaningful advancement in the realm of IQRF wireless sensor networks, particularly in the context of battery management. By implementing a dynamic data collection schedule, which intelligently incorporates deep sleep algorithms, we have demonstrated a tangible method for extending battery life in such networks. This approach proves especially effective in networks employing FRC merged data collection, where the flexibility of scheduling sleep cycles plays a critical role in energy conservation.

The case study, using a CO2 sensor network as an example, was instrumental in showcasing the practical application of our method. It highlighted the adaptability of our scheduling approach to varying data needs, reflecting realistic operational scenarios. Our findings underscore the importance of considering the deep sleep cycle duration when planning for increased data collection frequency, as this is a key factor affecting the overall battery life. A notable contribution of this research is the development of an online calculator and API. This tool serves a dual purpose: it not only aids in planning and predicting the battery life of networks under standard operating conditions but also provides valuable insights into how the integration of FRC and deep sleep schedules can impact battery longevity. By incorporating variables such as network size, data collection parameters, and activity cycles, the calculator offers a more accurate and practical estimation of battery life in real-world implementations.

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