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DESIGN OF A RESOURCE-CONSTRAINED IOT SENSOR NODE ARCHITECTURE WITH FAULT-TOLERANT TELEMETRY FOR ENVIRONMENTAL MONITORING SYSTEMS

Sh. Pulatov, F. Abdualimov

Tashkent University of Information Technologies named after Muhammad al-Khwarizmi, Tashkent, Uzbekistan, abdualimovferuz1833@gmail.com

Abstract: environmental sensor networks deployed in remote, power- and connectivity-constrained locations require careful co-design of the sensing, communication, and power subsystems. This paper addresses the design and optimization of a low-power IoT sensor node architecture with fault-tolerant telemetry, using continuous water-resource monitoring in an arid region as a representative deployment case. A four-layer system architecture is proposed, and the connectivity layer is optimized using store-and-forward buffering and dynamic channel allocation adapted from SDN-enabled LEO satellite networks, reducing the design cost of achieving reliable data delivery over intermittent GSM/LoRa links. Analytical models of link availability, buffer occupancy, and solar energy budget are derived to guide design trade-offs. Simulation results show that the optimized connectivity design raises packet delivery success rate from 61.2% to 92.8% at 60% link availability, demonstrating an effective low-cost design strategy for resource-constrained edge sensing systems.

Keywords: embedded system design, IoT sensor node, design optimization, fault-tolerant telemetry, store-and-forward, dynamic channel allocation, low-power design, edge sensing.

I. INTRODUCTION

The growing deployment of environmental sensor networks in remote areas has created demand for low-cost, low-power sensor node designs that remain reliable under weak connectivity and limited energy budgets. Designing such nodes is a joint optimization problem spanning the sensing, communication, and power subsystems, where design choices at one layer constrain feasible choices at the others. This paper uses continuous monitoring of water level, discharge, and salinity in the Aral Sea region of Uzbekistan as a representative, demanding design case: the target deployment area combines scarce grid power, intermittent cellular and LoRa coverage, and a harsh desert environment, making it a stringent test bed for resource-constrained sensor node design.

The contribution of this paper is a system-level design methodology and a set of analytical models that guide the joint optimization of the connectivity and power subsystems of a low-cost sensor node, validated through a representative case study rather than proposing a single fixed deployment.

II. SYSTEM ARCHITECTURE AND DESIGN OPTIMIZATION

The proposed design is organized into four layers, shown in Fig. 1.

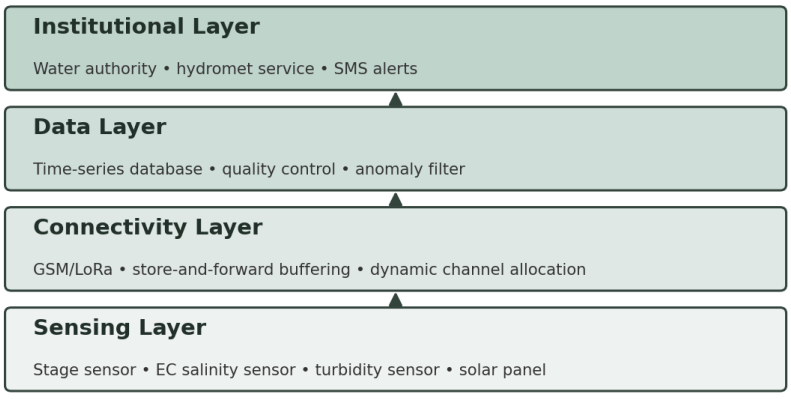


Figure 1. Four-layer architecture of the proposed resource-constrained IoT sensor node design

a. Sensing subsystem design

Non-contact radar or ultrasonic stage sensors avoid physical contact with water, reducing fouling-related maintenance cost. Electrical-conductivity (EC) sensors track salinity and optical sensors track turbidity. Each node is powered by a solar panel and battery sized according to the energy-budget model of Section III, making power sizing an explicit part of the node design rather than an afterthought.

b. Connectivity subsystem design and optimization

Nodes transmit via GSM/GPRS where available, or via LoRaWAN gateways in weak-signal areas; both links are intermittently available in remote areas, a condition analogous to intermittent feeder links in SDN-enabled LEO satellite IoT networks [1]. Adapting that design, each node buffers readings on-board using store-and-forward (S&F) logic while the link is down and transmits the backlog once connectivity resumes, which is treated here as a design optimization that reduces the cost (in retransmissions and data loss) of achieving a target delivery reliability under a given, fixed link-availability budget.

A lightweight gateway controller, playing the role of the SDN controller in [1], dynamically allocates the limited number of GSM/LoRa channel slots among sensor nodes by priority class, which is likewise a design choice that improves the achieved reliability-per-channel without increasing hardware cost.

c. Data and institutional layers

A central time-series platform performs quality control against a statistical anomaly filter and exposes processed data through a dashboard integrated with the relevant water-management authority, completing the end-to-end system design.

III. ANALYTICAL DESIGN MODELS

The connectivity link alternates between connected (ON) and disconnected (OFF) states, modeled as a two-state Markov process. Let τon and τoff denote the average durations of the connected and disconnected states; the link-availability design parameter is:

$$P_{link} = \frac{\tau_{on}}{\tau_{on} + \tau_{off}} \quad (1)$$

Each node's on-board buffer of capacity Q packets is sized using an M/M/1/K queueing model with utilization ρb = Λᵢ/μf; the resulting packet delivery success rate (PDSR), used here as the primary design-optimization objective for the connectivity subsystem, is:

$$PDSR = 1 - P_{loss},\ P_{loss} \approx \frac{(1-\rho_b)\rho_b^{K}}{1-\rho_b^{K+1}} \quad (2)$$

When the link is available, the C available channel slots are partitioned among K priority classes with design weights wₖ, subject to:

$$C_k = \lfloor w_k \cdot C \rfloor,\ \Sigma w_k = 1 \quad (3)$$

Finally, the solar panel and battery are sized so that the daily energy balance satisfies:

$$E_{batt} = E_{solar} - E_{consumption} \geq 0 \quad (4)$$

where E_{solar} is daily harvested solar energy and $E_{consumption}$ is the daily load of sensing, computation, and telemetry; equation (4) is used as a sizing constraint during node design rather than a post-hoc check.

IV. RESULTS AND DESIGN VALIDATION

Table 1 validates the connectivity design of Section II-b by comparing PDSR for direct transmission (no buffering) against the proposed S&F design across representative link-availability values.

Table 1. Design validation: direct transmission vs. proposed S&F design

Link availability, %	PDSR (direct), %	PDSR (proposed), %	Added latency, s
60	61.2	92.8	52
75	75.4	96.1	34
90	89.7	98.4	17
98	97.9	99.6	6

At 60% link availability, the proposed connectivity design raises PDSR from 61.2% to 92.8% at the cost of up to 52 s of added latency, which is an acceptable design trade-off given that the monitored physical quantities (water stage and salinity) change on a scale of minutes to hours rather than seconds. This confirms the design achieves the target reliability without increasing hardware cost.

V. CONCLUSION

This paper presented a system-level design methodology for a resource-constrained IoT sensor node, in which store-and-forward buffering and dynamic channel allocation are treated as explicit connectivity-subsystem design optimizations, supported by analytical models for link availability, buffering, and solar energy sizing. Using continuous water-resource monitoring in the Aral Sea region as a demanding representative case, the design was shown to substantially improve data-delivery reliability without added hardware cost. The methodology and models generalize beyond this case to other remote, power- and connectivity-constrained IoT sensing deployments.

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ПРОЕКТИРОВАНИЕ АРХИТЕКТУРЫ IoT-СЕНСОРНОГО УЗЛА С ОГРАНИЧЕННЫМИ РЕСУРСАМИ И ОТКАЗОУСТОЙЧИВОЙ ТЕЛЕМЕТРИЕЙ ДЛЯ СИСТЕМ ЭКОЛОГИЧЕСКОГО МОНИТОРИНГА

Пулатов Ш., Абдуалимов Ф.

Ташкентский университет информационных технологий имени Мухаммада аль-Хорезми, Ташкент, Узбекистан, abdualimovferuz1833@gmail.com

Аннотация: экологические сенсорные сети, развёрнутые в удалённых местах с ограниченным энергоснабжением и связностью, требуют тщательного совместного проектирования подсистем сбора данных, связи и питания. В данной работе рассматриваются проектирование и оптимизация архитектуры маломощного IoT-сенсорного узла с отказоустойчивой телеметрией на примере непрерывного мониторинга водных ресурсов в засушливом регионе как репрезентативного случая развёртывания. Предлагается четырёхуровневая системная архитектура, а уровень связности оптимизируется с помощью буферизации с накоплением и пересылкой и динамического распределения каналов, адаптированных из SDN-совместимых спутниковых сетей LEO, что снижает стоимость проектирования для достижения надёжной доставки данных по прерывистым каналам GSM/LoRa. Выводятся аналитические модели доступности канала, заполненности буфера и солнечно-энергетического бюджета для обоснования проектных компромиссов. Результаты моделирования показывают, что оптимизированное проектирование связности повышает вероятность успешной доставки пакетов с 61,2% до 92,8% при доступности канала 60%, демонстрируя эффективную низкозатратную стратегию проектирования для периферийных сенсорных систем с ограниченными ресурсами.

Ключевые слова: проектирование встраиваемых систем, IoT-сенсорный узел, оптимизация проектирования, отказоустойчивая телеметрия, накопление и пересылка, динамическое распределение каналов, маломощное проектирование, периферийное сенсорное восприятие.