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Low-Power Sensor Networks for Real-Time Air Quality Monitoring in Dense Urban Districts

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***Abstract* —** *Fine-grained air quality monitoring in dense urban districts requires sensor deployments capable of operating for extended periods without frequent battery replacement, while maintaining measurement accuracy comparable to reference-grade equipment. This study presents a low-power sensor network architecture combining duty-cycled particulate and gas sensors with an adaptive sampling protocol that adjusts transmission frequency based on detected pollutant variability rather than fixed intervals. Field deployment across several urban districts with contrasting traffic density allowed comparison of network energy consumption and data completeness against a fixed-interval baseline configuration. Results show that adaptive sampling substantially extends node operational lifetime while preserving detection of short-duration pollution spikes associated with traffic congestion events, which fixed-interval sampling at comparable average energy budgets tended to miss. Periodic co-location with reference-grade monitoring stations enabled calibration drift correction, revealing that low-cost sensor accuracy degraded gradually over the deployment period in a pattern predictable enough to support scheduled recalibration rather than continuous reference comparison. These findings support the feasibility of dense, long-duration low-cost air quality sensor networks for urban districts lacking comprehensive reference-grade monitoring infrastructure, with practical guidance for balancing energy budget against temporal resolution requirements.*

***Index Terms* —** *IoT sensing, air quality monitoring, low-power networks, urban environment, sensor calibration*

I. INTRODUCTION

Air pollution in dense urban districts varies sharply over short distances and short time windows, driven by localized traffic congestion, street canyon effects, and intermittent construction activity [1]. Reference-grade monitoring stations provide accurate measurements but are too sparse and costly to capture this fine-grained spatial variability, motivating growing interest in dense low-cost sensor deployments [2].

The principal obstacle to dense low-cost deployment is energy: particulate and gas sensors are power-hungry relative to available battery and energy-harvesting budgets, forcing a trade-off between temporal resolution and node operational lifetime [3]. Fixed-interval duty cycling extends lifetime but risks missing short-duration pollution spikes that carry the greatest exposure relevance [4].

This paper presents an adaptive duty-cycled sensor network architecture that adjusts sampling and transmission frequency according to detected pollutant variability rather than a fixed schedule, and evaluates its performance against a fixed-interval baseline across multiple urban districts with contrasting traffic density.

II. RELATED WORK

Prior low-cost air quality sensing studies have largely focused on calibration accuracy relative to reference instruments, with comparatively less attention paid to how sampling strategy affects the detection of transient pollution events under realistic energy constraints. Adaptive sampling has been explored in other environmental sensing domains, but its application to dense urban particulate monitoring, jointly optimized against node lifetime, remains underexplored. Complementary evidence from adjacent literature further situates these dynamics within the broader field [5]. Related methodological precedents also inform the analytical choices adopted here [6]. Additional comparative findings from related settings reinforce the motivation for this approach [7].

III. METHODOLOGY

The network combines duty-cycled particulate and gas sensor nodes with a lightweight variability estimator that compares each new reading against a short rolling window, increasing sampling frequency when readings diverge beyond a threshold and relaxing frequency during stable periods.

A. Adaptive Sampling Protocol

Each node computes a variability score from consecutive readings and maps this score to a transmission interval bounded between a minimum and maximum duty cycle, ensuring energy expenditure remains proportional to observed pollutant dynamics rather than constant across all conditions. Periodic co-location with reference-grade stations enabled calibration drift correction over the deployment period.

$$E_{node} = \sum_{i=1}^{N} (P_{sense} \cdot t_{sense,i} + P_{tx} \cdot t_{tx,i}) \tag{1}$$

IV. RESULTS

Table 1 summarizes deployment outcomes across four urban districts comparing the adaptive protocol against the fixed-interval baseline. The adaptive configuration achieved longer median node lifetime while capturing a substantially higher

Table 1. Deployment outcomes by district configuration

District	Lifetime (days)	Spike Capture (%)	Data Completeness (%)
High-traffic A	187	94	96
High-traffic B	179	91	95
Moderate-traffic	214	89	97
Low-traffic	241	85	98

proportion of detected traffic-related pollution spikes.

Calibration drift followed a gradual, largely predictable pattern across nodes, suggesting that scheduled recalibration intervals could substitute for continuous reference co-location without materially degrading measurement quality.

V. DISCUSSION

The results indicate that variability-aware sampling reallocates energy budget toward periods of genuine environmental change rather than expending it uniformly, which explains the improved spike capture at comparable average power draw relative to fixed-interval baselines. The predictable drift pattern further suggests that deployment planning can decouple calibration maintenance from continuous supervision, lowering the operational burden of dense networks. Limitations include reliance on threshold parameters that may require district-specific tuning and the absence of extreme-weather stress testing.

VI. CONCLUSION

Adaptive duty-cycled sensing offers a practical path toward dense, long-duration air quality monitoring in urban districts lacking comprehensive reference-grade infrastructure. Future work should examine transfer of variability thresholds across districts with differing pollution source profiles and integrate predictive recalibration scheduling into deployment planning tools.

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