MEMORY
COMPETENCE
CENTER

.MEMPHIS
WE KNOW MEMORY

SMART CITY
AIR QUALITY MONITORING

ARCHITECTING RESILIENT AI-EDGE SYSTEMS WITH NON-VOLATILE MEMORY

Executive Summary

Urbanization, climate change, and industrialization have significantly impacted air quality, elevating the urgency for intelligent, distributed monitoring systems. Particulate matter, especially PM2.5, poses a profound threat to public health. Traditional air monitoring infrastructures, while accurate, are limited in scale, responsiveness, and real-time adaptability.

This white paper presents an architecture for next-generation air quality sensor nodes, designed for deployment in smart cities. By integrating advanced optical sensing, embedded AI inference, and non-volatile memory (NVRAM) technologies – specifically Magnetoresistive RAM (MRAM) and Ferroelectric RAM (FeRAM) – the proposed system enhances responsiveness, autonomy, and data integrity. This document discusses the architecture, theoretical underpinnings, rationale for component selection, critical design metrics, and application opportunities across urban, industrial, and mobile platforms.

1. INTRODUCTION

Air pollution, particularly in the form of fine particulate matter (with a diameter below ≤2.5 μm, PM2.5), is associated with an increased risk of respiratory, cardiovascular, and neurological disorders. Smart cities require pervasive, real-time environmental intelligence to mitigate these risks. Sensor miniaturization has advanced to a point where accurate PM detection can be embedded into street fixtures, consumer devices, and wearable platforms. However, sensing alone is insufficient.

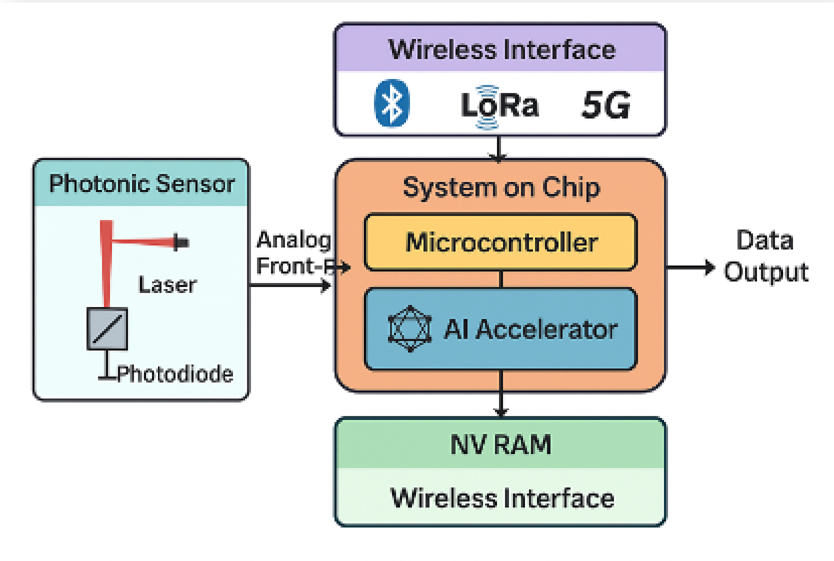
To transition from raw data acquisition to actionable insights, sensor systems must evolve into edge-intelligent nodes—capable of local inference, robust storage, and intermittent communication. Conventional memory technologies (e.g., Flash or DRAM) are ill-suited due to volatility, limited endurance, and high energy demands. This compels the use of non-volatile, high-endurance, and fast-access memories.

2. SYSTEM DESIGN PHILOSOPHY AND ARCHITECTURE

The proposed architecture is modular and comprises:

- Photonic PM Sensor: Employs laser light scattering and photodiode reception to estimate particulate density.
- Analog Signal Processing: Applies low-pass and frequency-domain filtering to condition the signal, represented mathematically as $y(t) = x(t) * h(t)$, where $h(t)$ is the impulse response of the system.
- Edge-AI Processing: A microcontroller or SoC executes embedded machine learning models to detect trends, anomalies, and thresholds in near real-time.
- Non-Volatile Memory (NVRAM): Acts as a high-speed, persistent data buffer for sensor logs, AI models, calibration data, and event history.
- Wireless Interface: Communicates via BLE, Wi-Fi, LoRa, or 5G, depending on deployment topology.

This configuration ensures autonomous functioning, secure data preservation, and rapid inferencing even when disconnected from the network or power supply.



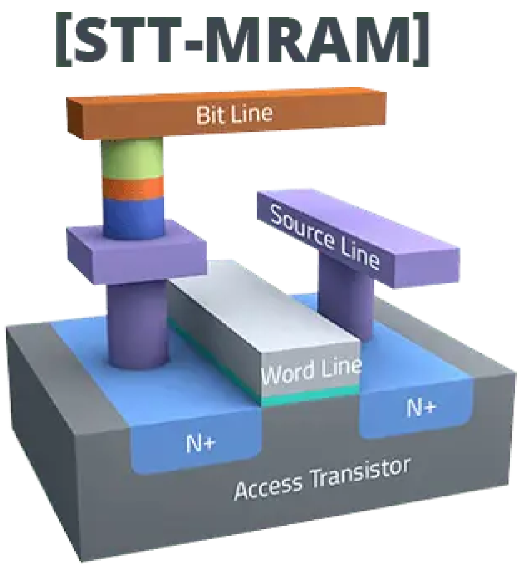
3. MEMORY ARCHITECTURE:

MRAM and FeRAM Rationale

Traditional Flash memory suffers from slow write cycles, limited write endurance, and high power requirements. DRAM, while fast, is volatile and requires constant refresh cycles, making it impractical for IoT edge deployments.

MRAM utilizes magnetic tunnel junctions offering virtually infinite write endurance (>10^{15} cycles), non-volatility, fast access (~35 ns), and radiation resistance. These make MRAM ideal for real-time logs, model updates, and event storage.

FeRAM operates by switching the polarization of a ferroelectric capacitor, offering low write energy, fast access, and moderate endurance (10^7–10^9 cycles), ideal for periodic logs such as calibration or maintenance records.



4. AI AT THE EDGE: PRINCIPLES AND PRACTICALITY

Embedded AI enables event-based sensing, data compression through local classification, and contextual behavior like adaptive sampling. TinyML models using TensorFlow Lite or Syntiant frameworks can be trained offline and deployed on neural accelerators or MCU-integrated AI engines with <1 mW power.

5. WORKING PRINCIPLE OF THE FULL NODE

1. Air is drawn or diffused into the sensing chamber.
2. A laser illuminates the particulates; scattered light is detected by photodiodes.
3. Analog signal is filtered, digitized, and sent to the processor.
4. Edge AI model evaluates air quality contextually.
5. Events and key states are stored in NVRAM—persisting through power loss.
6. Data is transmitted periodically or upon AI-triggered events.

This architecture supports synchronous and asynchronous operation, enabling efficiency and resilience.

6. CRITICAL-TO-QUALITY (CTQ) PARAMETERS

To ensure successful deployment and long-term operability, several Critical-to-Quality (CTQ) parameters must be established. These include:

- Sensor Resolution: ≤ 1 μg/m³ to meet WHO and EPA air quality standards.
- Edge Inference Latency: < 100 ms to allow real-time responsiveness.
- Power Consumption: < 50 mW average to support energy harvesting or battery operation.
- Memory Endurance: MRAM (>10^{15} cycles), FeRAM (>10^{9} cycles) to sustain constant writing.
- Operational Temperature Range: –40°C to +85°C for outdoor and industrial environments.
- Memory Retention: ≥ 10 years, to ensure compliance and historical data retention.
- Physical Footprint: ≤ 1 cm², compatible with miniaturized platforms.
- Secure Operation: Hardware encryption, secure boot, and protected memory.

7. COMPONENT-LEVEL DESIGN AND SELECTION

Component selection must balance performance, energy efficiency, and integration flexibility.

Sensing:

- Sensirion SPS30 / Plantower PMSA003: Highly integrated PM sensors with digital interfaces.
- AMS CCS811 / SGP40: VOC sensors for hybrid air quality measurements.Processing and AI:
- Nordic nRF52840: BLE SoC for low-power control.
- NXP RT1170 / Ambiq Apollo4 Blue: Advanced MCUs with embedded AI capabilities.
- Syntiant NDP120 / Google Coral TPU: Hardware accelerators for TinyML applications.

NVRAM:

- Ramxeed RFX-64K-SPI: FeRAM optimized for periodic low-energy logs.

Communication:

- ESP32-S3: Dual-core processor with Wi-Fi/BLE support.
- Semtech SX1262: LoRa module for long-range, low-power connectivity.
- Quectel RG500Q / Thales Cinterion MV32: 5G modules for high-bandwidth deployments.

Power and Security:

- TI TPS65218: Efficient multi-rail PMIC.
- e-peas AEM10941: Solar and RF energy harvesting PMIC.
- Microchip ATECC608A / NXP SE050: Security chips for cryptographic integrity.

8. USE CASES AND DEPLOYMENT SCENARIOS

Smart Cities:

- Distributed nodes on street poles, traffic lights, and buildings for grid-wide pollution analytics.
- Crowd-sourced exposure data feeding into municipal health dashboards.

Wearables:

- Personal air quality trackers with BLE-enabled exposure logs.
- Integration into smart helmets, badges, and fitness devices.

Industrial Monitoring:

- Continuous PM and gas detection in factories, warehouses, and clean rooms.
- Ensures air quality compliance and predictive maintenance.

Emergency Zones:

- Wildfire, construction, or chemical spill detection with autonomous alerts.
- Event-based storage and burst-mode 5G transmission upon re-connection.

9. INDUSTRY SUPPORT AND VENDOR TECHNOLOGIES

Netsol provides high-endurance STT-MRAM modules optimized for edge AI devices with industrial-grade retention, small form factor, and extended temperature support.

Ramxeed offers FeRAM-based ASICs and embedded memory platforms suitable for ultra-low-power applications such as wearables, medical devices, and specialized IoT tags. Their modules are often integrated into systems requiring microsecond-level write latency and minimal energy footprint.

Together, these vendors form the backbone of memory innovation within the AIoT ecosystem.

10. CONCLUSIONS

The convergence of optical sensing, embedded AI, and non-volatile memory forms a resilient, scalable platform for air quality monitoring. MRAM and FeRAM provide not only endurance and data safety but also empower intelligent inference under constrained energy budgets.

By designing architectures around these technologies, smart cities can deploy autonomous sensor grids that adapt, learn, and persist, ensuring long-term environmental intelligence

11. REFERENCES

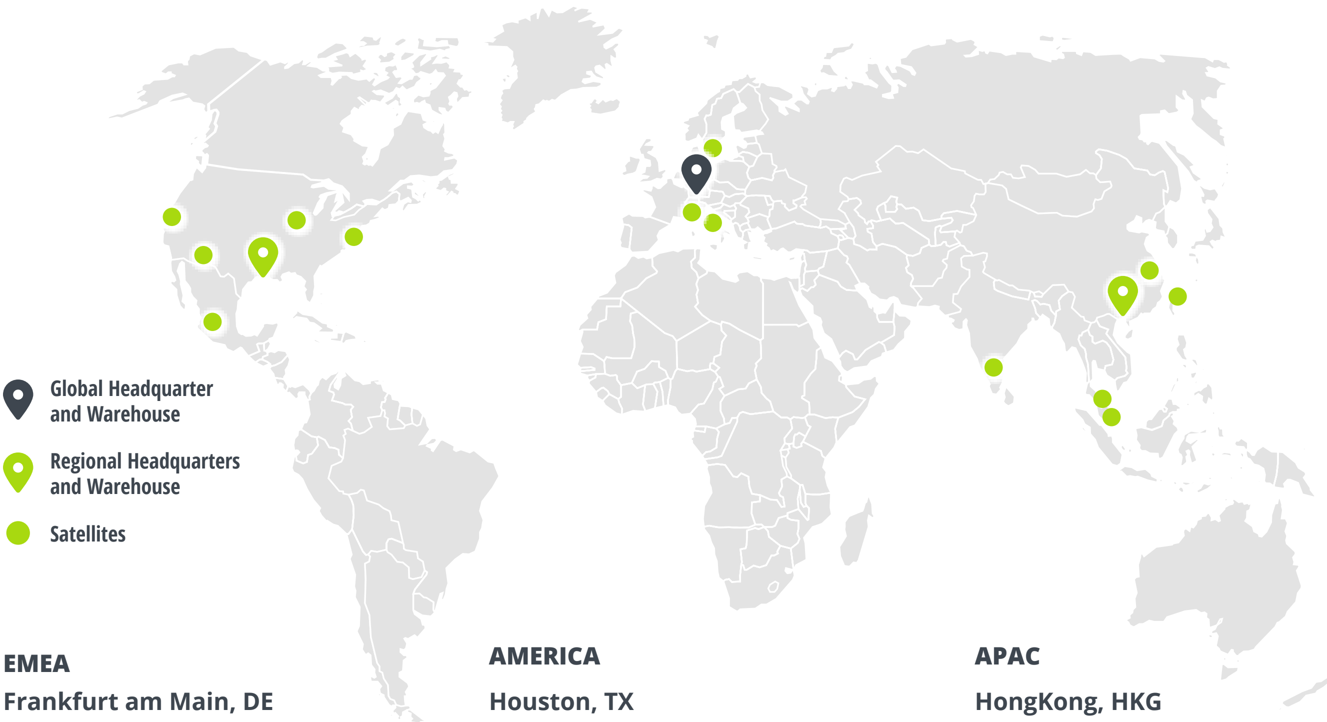
1. IEEE Sensors Journal. Smart Environmental Monitoring Using Edge AI, 2023.
2. ScienceDirect. Do Smart Cities Have Lower PM2.5?, 2022.
3. M. Sharifkhani et al. Non-Volatile Memories in AI-Edge Architectures, IEEE Trans. Emerging Topics in Computing, 2022.
4. Netsol Co. STT-MRAM for Edge IoT and Automotive, 2024.
5. Ramxeed Technologies. FeRAM-Embedded ASICs for Medical & Industrial IoT, 2025.

ABOUT US

MEMPHIS Electronic has been in the memory business for over 30 years. Due to our focus on memory only, we developed into a Memory Competence Center with an unmatched line card of over 18 different memory manufacturers (Samsung, Nanya, SK Hynix, Winbond, Huawei, SkyHigh, Ramxeed, Intelligent Memory, Apacer, Longsys, ESMT, Biwin and many more). We combine this with comprehensive supply chain solutions.

From legacy to latest components and modules, from standard to specialty memories – if it's a memory, we can help. Memory experts in 17 locations worldwide provide regional support and manufacturer recommendations, to ensure customers find the most suitable technology solution for every project.

MEMPHIS LOCATIONS



EMEA
- Frankfurt am Main, DE
- Copenhagen, DNK
- Geneva, CH
- Milan, IT

AMERICA
- Houston, TX
- Boston, MA
- Chicago, IL
- Phoenix, AZ
- San Jose, CA
- Guadalajara, MEX

APAC
- HongKong, HKG
- Shanghai, CN
- Taipei, TW
- Hsinchu, TW
- Singapore, SGP
- Kuala Lumpur, MY
- Bengaluru, IN

CONTACT US

For further information, data sheets or samples, please reach out.
We are only an email away: sales@memphis.de

MEMPHIS Electronic GmbH

www.memphis.de

info@memphis.de

MEMPHIS WE KNOW MEMORY