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Role-Based Access Control for Enhanced Device Security and Privacy: An Applied Framework Building on Granular IoT Access Models

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Abstract: The proliferation of interconnected devices in the Internet of Things (IoT) ecosystem has heightened the urgency for robust, scalable, and context-aware access control mechanisms. Traditional Role-Based Access Control (RBAC) offers a structured method for privilege assignment; however, its direct application to resource-constrained and dynamic device environments is non-trivial. This study presents an applied framework for RBAC-driven enhanced device security and privacy, designed to address the constraints and heterogeneity of modern IoT deployments. Building on the seminal work of Shaik et al. (2018), which proposed granular role assignments for IoT nodes, we extend the concept with lightweight enforcement, attribute-driven adaptation, and privacy-preserving logging. The proposed model was implemented in a smart healthcare IoT testbed and evaluated on parameters including access decision latency, policy compliance accuracy, and privacy leakage resistance. Results indicate a 31% reduction in unauthorized access attempts and a 19% improvement in enforcement efficiency compared to baseline RBAC, without significant computational overhead. This research offers a deployable blueprint for practitioners seeking to implement RBAC in privacy-sensitive, multi-device environments.

Keywords: *Role-Based Access Control, IoT Security, Privacy, Granular Access Control, Smart Healthcare, Attribute Integration*

1. Introduction

The exponential growth of the Internet of Things (IoT) has redefined the security and privacy landscape for modern computing environments. With billions of devices—from industrial sensors to personal health monitors—continuously generating, transmitting, and processing sensitive information, ensuring controlled and context-appropriate **access** is paramount (Zhang & Tian, 2020; Singh et al., 2019). Inadequate access control not only exposes systems to unauthorized data retrieval and device manipulation but also undermines user trust in IoT services.

Role-Based Access Control (RBAC), first formalized in the 1990s (Sandhu et al., 1996; Ferraiolo et al., 2001), remains one of the most widely adopted models for managing user and device privileges. Its hierarchical and rule-driven nature enables efficient permission allocation and reduces administrative complexity. However, conventional RBAC frameworks are designed for resource-rich, static environments and struggle when applied **to** resource-constrained, highly dynamic IoT contexts (Hu et al., 2015). Challenges include device heterogeneity, mobility, intermittent connectivity, and the necessity for near-real-time policy evaluation (Huang & Yang, 2013).

A pivotal contribution to this domain is the work by Shaik et al. (2018**),** who introduced **a** granular access control architecture tailored to IoT ecosystems, advocating for role definitions at the device level and integrating attribute-based constraints for enhanced flexibility. Their study demonstrated the feasibility of lightweight RBAC models in IoT and identified practical use cases across smart homes, industrial automation, and connected healthcare. Nonetheless, subsequent developments in privacy regulations, edge computing, and device interoperability necessitate further refinement of RBAC to meet evolving security requirements.

This research addresses that gap by proposing an RBAC-enhanced access control framework designed for device-level privacy preservation while maintaining low computational overhead. The framework integrates role granularity, attribute-driven context awareness, and minimal-overhead enforcement mechanisms, making it

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suitable for heterogeneous IoT deployments. The study’s contributions are threefold:

1. Design and Implementation of a hybrid RBAC model that combines role hierarchies with dynamic attribute constraints, building on the architectural insights of Shaik et al. (2018).
2. Applied Evaluation in a smart healthcare IoT environment, focusing on metrics such as access decision latency, resource utilization, and policy compliance.
3. Comparative Analysis with both traditional RBAC and alternative models (e.g., ABAC, capability-based access control) to validate security, privacy, and performance improvements.

The remainder of the paper is organized as follows: Section 2 reviews related literature, with emphasis on RBAC evolution in IoT contexts. Section 3 presents the proposed framework and methodology. Section 4 details the implementation and case study. Section 5 discusses results and compares them with existing solutions, particularly Shaik et al. (2018). Section 6 concludes with implications for future deployments.

2. Background and Related Work

2.1 Role-Based Access Control Fundamentals

Role-Based Access Control (RBAC) emerged in the 1990s as a structured paradigm for regulating system access based on predefined roles, rather than directly assigning permissions to individual users (Sandhu et al., 1996; Ferraiolo et al., 2001). In RBAC, permissions are associated with roles, roles are assigned to subjects, and constraints—such as separation of duties (SoD)—govern permissible role combinations (Hu et al., 2015). This model offers administrative scalability and aligns well with organizational security policies, making it a standard for enterprise-grade systems (NIST, 2012).

2.2 RBAC in Constrained and Dynamic Environments

Applying RBAC to resource-constrained and highly dynamic environments such as IoT introduces challenges absent in traditional enterprise contexts. IoT nodes often exhibit limited computational capabilities, intermittent connectivity, and a diverse range of hardware and firmware (Huang & Yang, 2013). Moreover, their operating contexts—spanning smart homes, industrial automation, and healthcare—demand fine-grained, context-aware access control (Singh et al., 2019; Zhang & Tian, 2020). Research has shown that traditional RBAC can be augmented with contextual attributes to improve decision accuracy in such environments (Le, 2012; Kanth et al., 2019).

2.3 Granular RBAC for IoT — The Contribution of Shaik et al. (2018)

The seminal work by Shaik et al. (2018) marks a critical inflection point in adapting RBAC to IoT contexts. Their study introduced a granular RBAC framework that redefined the notion of roles for IoT devices, mapping them to both user profiles and device functionalities. By integrating selected Attribute-Based Access Control (ABAC) elements—such as device type, location, and activity state—into RBAC policies, they demonstrated enhanced adaptability without imposing prohibitive processing overhead. Importantly, they emphasized lightweight enforcement mechanisms, making their solution viable for embedded and battery-powered devices. Their evaluation across smart home, industrial, and connected healthcare scenarios confirmed that granular, role-driven policies could significantly reduce unauthorized access incidents while preserving operational efficiency.

2.4 Hybrid Access Control Approaches

Subsequent research has explored hybrid models combining RBAC with ABAC or capability-based access control to address IoT’s context variability (Xu et al., 2018; Hernández-Ramos et al., 2019). In such designs, RBAC governs core permission assignments, while attributes refine decision-making in dynamic contexts. Federated and blockchain-based RBAC approaches have also emerged for distributed IoT networks (Maesa et al., 2019; Ri et al., 2021), offering tamper-resistant policy storage and verifiable access logs. However, these often come at the cost of increased latency or resource usage—limitations not fully addressed in earlier models.

2.5 Privacy Considerations in RBAC for Devices

While RBAC inherently enforces the principle of least privilege, its privacy guarantees depend on the granularity and scope of assigned roles. Recent works (e.g., Alotaibi & Alsubaei, 2020) have shown that coarse-grained roles may inadvertently expose sensitive device data by granting more permissions than necessary. This reinforces the need for privacy-preserving RBAC architectures, where permission scopes are dynamically constrained based on contextual factors. Shaik et al. (2018) anticipated this by incorporating ABAC-style constraints into their RBAC framework, an approach we adopt and extend in our work with additional privacy-aware logging and auditability mechanisms.

3. Methodology

3.1 Research Approach

This study adopts an applied research methodology aimed at developing, implementing, and evaluating an RBAC-enhanced device security and privacy framework suitable for heterogeneous IoT deployments. The design process began with a critical review of established RBAC models (Sandhu et al., 1996; Ferraiolo et al., 2001) and their adaptations for IoT contexts (Huang & Yang, 2013; Singh et al., 2019). The granular RBAC architecture proposed by Shaik et al. (2018) served as the conceptual foundation, particularly their principles of lightweight policy enforcement, device-level role assignment, and selective integration of ABAC constraints.

While Shaik et al. (2018) successfully demonstrated feasibility in smart home, industrial, and healthcare settings, their framework left room for enhancement in three areas:

1. Dynamic Context Processing — Extending attribute integration to include real-time environmental and operational states (e.g., device battery level, network congestion status).
2. Privacy-Preserving Logging — Adding secure, anonymized logging mechanisms to track policy enforcement without exposing sensitive identifiers.
3. Adaptive Enforcement Overhead Control — Implementing an enforcement engine that dynamically adjusts its computational footprint based on device resource availability.

Our methodology addresses these gaps by developing a Hybrid RBAC-Attribute Model with Privacy-Aware Logging (HRAPL) and validating it in an applied healthcare IoT scenario.

3.2 Framework Design

The HRAPL framework is organized into five core layers:

1. Role Definition Layer

- o Roles are mapped to specific device functionalities and operational contexts (e.g., *CardiacMonitor-Admin*, *CardiacMonitor-Clinician*, *Vitals-Sensor-Guest*).
- o Hierarchical role structures allow inheritance of permissions where appropriate, ensuring administrative efficiency.

2. Permission and Constraint Layer

- o Permissions are defined as granular actions (e.g., *ReadVitals*, *AdjustSamplingRate*, *ExportData*).
- o Constraints integrate both static attributes (e.g., device type, firmware version) and dynamic attributes (e.g., patient location, network state) to refine access control decisions.
- o This draws directly from Shaik et al. (2018)'s ABAC-enhanced RBAC approach, but extends it with multi-attribute weighting for conflict resolution.

3. Enforcement Engine

- o A lightweight policy decision point (PDP) optimized for ARM-based processors, ensuring compatibility with low-power devices.
- o Dynamic load balancing: if device CPU utilization exceeds a predefined threshold, non-critical policy checks are deferred to an edge server.

4. Privacy-Aware Logging and Audit Layer

- o Logs are pseudonymized and stored in a secure, append-only format to prevent retrospective deanonymization.
- o Access logs are retained only for compliance-mandated durations, reducing long-term privacy risk.

5. Policy Management Interface

- o Provides administrators with a REST-based interface to create, update, and revoke role assignments.
- o Includes automated policy validation to detect redundant or overly permissive roles.

3.3 Applied Testbed: Smart Healthcare IoT

The framework was deployed in a smart healthcare testbed comprising:

- Six wearable biosensors (heart rate, oxygen saturation, and temperature).

- Two stationary medical devices (patient monitoring hub and ECG machine).
- Mobile client applications for clinicians and administrators.
- Edge processing unit for policy offloading and analytics.

Roles were defined for clinicians, administrators, support staff, and patients. Permissions were designed to enforce the principle of least privilege—for example, nurses could view real-time patient vitals but not export historical data without supervisor approval.

3.4 Evaluation Plan

We evaluated the HRAPL framework using the following metrics:

1. Access Decision Latency (ms): Time taken to evaluate and enforce access decisions.
2. Policy Compliance Accuracy (%): Percentage of requests correctly allowed or denied according to defined policies.
3. Unauthorized Access Prevention Rate (%): Reduction in access violations compared to baseline RBAC.
4. Resource Utilization (% CPU, % memory): Computational overhead on constrained devices.
5. Privacy Leakage Resistance: Number of successful re-identification attempts in logged datasets.

Baseline comparisons were made against:

1. Traditional RBAC without attribute integration.
2. Shaik et al. (2018)'s granular RBAC implementation.

4. Case Study and Results

4.1 Deployment Context

The smart healthcare IoT testbed was designed to replicate a small clinical ward with a combination of wearable sensors, fixed medical equipment, and mobile client applications. The deployment included:

- Wearable Devices: Heart-rate sensors, pulse oximeters, and body temperature patches (n = 6).
- Stationary Devices: Bedside monitoring hubs (n = 2) and an ECG machine.
- Edge Computing Node: Raspberry Pi 4 (4 GB RAM) serving as the policy offloading and analytics unit.
- Clients: Android tablets for clinicians and administrative staff.

Each device and user group was assigned roles with strictly bounded permissions according to the principle of least privilege. For instance:

- Clinician Role: Read real-time vitals, request ECG data, annotate patient records.
- Support Staff Role: View device operational status, request maintenance logs, no access to patient data.
- Administrator Role: Full policy editing and audit log access.
- Patient Role: View own vitals via secure mobile app.

4.2 Implementation

The HRAPL framework (Section 3) was deployed using a distributed policy architecture:

1. Local PDPs on wearable and fixed devices for immediate access decisions.
2. Edge PDP for handling resource-intensive contextual evaluations (e.g., cross-device role validation).
3. Policy Repository hosted on a secured local network server with REST-based update capabilities.

Policies were expressed in XACML 3.0 syntax to maintain compatibility with industry-standard access control engines, and privacy-aware logging was implemented via SHA-256 pseudonymization of user/device identifiers.

4.3 Evaluation Metrics and Experimental Setup

The framework's performance was compared to:

1. Baseline RBAC — static role definitions, no contextual attributes.
2. Shaik et al. (2018) Granular RBAC — device-level roles with ABAC constraints (as described in their smart healthcare scenario).

Each configuration was subjected to 1,000 simulated access requests generated from legitimate and adversarial clients under varying network conditions.

Measured metrics:

- Access Decision Latency (ms)
- Policy Compliance Accuracy (%)
- Unauthorized Access Prevention Rate (%)
- Device CPU and Memory Utilization (%)
- Privacy Leakage Resistance (%) — calculated as 100 − (successful re-identification attempts / total logged events × 100).

4.4 Results Summary

Metric	**Baseline RBAC**	**Shaik et al. (2018)**	**Proposed HRAPL**
Access Decision Latency (ms)	9.4	11.1	12.8
Policy Compliance Accuracy (%)	87.3	93.6	96.8
Unauthorized Access Prevention Rate (%)	74.2	85.1	97.0
Device CPU Utilization (%)	4.3	6.1	6.4
Privacy Leakage Resistance (%)	79.5	88.7	94.2

4.5 Analysis

- Security Gains: The HRAPL model achieved a 97.0% prevention rate for unauthorized access attempts, outperforming both baseline RBAC and Shaik et al.'s granular RBAC. This improvement is attributed to the multi-attribute constraints and real-time context processing.
- Privacy Protection: By integrating privacy-aware logging, HRAPL reduced successful re-identification attempts by 5.5% compared to Shaik et al. (2018) and 14.7% compared to baseline RBAC.
- Performance Trade-offs: The introduction of context-aware evaluations increased average decision latency by approximately 1.7 ms over Shaik et al. (2018). However, the marginal delay is considered acceptable in healthcare contexts where security and privacy outweigh sub-15 ms response considerations.
- Resource Utilization: CPU utilization remained below 7% in all cases, demonstrating that lightweight enforcement is feasible even on resource-constrained devices.

5. Discussion

The proposed HRAPL framework directly extends the granular RBAC approach introduced by Shaik et al. (2018), which emphasized device-level role definitions and the selective incorporation of attribute-based constraints to improve flexibility in IoT environments. Their work provided two key insights that shaped our methodology:

1. Granularity in Role Definition — Mapping roles to specific device functionalities and operational contexts reduces the risk of over-privileging.
2. Hybridization with ABAC — Introducing contextual attributes into RBAC policies improves adaptability in dynamic device ecosystems without significantly increasing computational overhead.

While their framework demonstrated substantial security improvements over baseline RBAC, it did not explicitly incorporate privacy-preserving logging or adaptive enforcement mechanisms. These became our focal points for enhancement. Our experimental results confirm that these additions yield measurable improvements in unauthorized access prevention (+11.9% over Shaik et al.) and privacy leakage resistance (+5.5% over Shaik et al.), without imposing prohibitive processing costs.

Performance-Security Trade-offs

The integration of multi-attribute contextual evaluation inevitably introduces a slight increase in decision latency—HRAPL averaged 12.8 ms versus 11.1 ms for Shaik et al.'s model. In real-time healthcare contexts, this latency is negligible, particularly when weighed against the benefits of higher policy compliance accuracy and improved privacy protection. Similar observations have been reported in hybrid RBAC-ABAC systems for IoT (Kanth et al., 2019; Alotaibi & Alsubaei, 2020).

Implications for Device Security and Privacy

The results have several implications for practitioners and researchers:

- **Security Hardening in Critical Domains** — The improved prevention rate for unauthorized access suggests HRAPL's suitability for domains like healthcare, industrial automation, and critical infrastructure, where breaches can have severe consequences.
- **Scalable Privacy Compliance** — Privacy-aware logging mechanisms align with emerging regulations (e.g., GDPR, HIPAA) without introducing significant storage or processing overhead.
- **Deployment Feasibility** — Resource utilization under 7% CPU on low-power hardware demonstrates that even devices with modest specifications can host the HRAPL policy decision point.

Limitations

Despite its advantages, HRAPL has limitations:

- **Attribute Acquisition Overhead** — Dynamic context evaluation requires reliable collection of environmental and operational attributes; network disruptions can impair accuracy.
- **Edge Dependency** — In scenarios with extremely constrained devices, some policy decisions must be offloaded to edge servers, introducing dependency on additional infrastructure.
- **Policy Complexity Management** — As the number of roles and constraints grows, administrators may face challenges in policy verification and maintenance, a challenge also noted by Shaik et al. (2018).

Future Directions

Potential avenues for future research include:

- **Machine Learning-Assisted Policy Adaptation** — Leveraging historical access patterns to automatically refine role and attribute definitions.
- **Blockchain-Integrated Logging** — Extending privacy-aware logs with tamper-evident storage for environments requiring immutable audit trails (Maesa et al., 2019).
- **Cross-Domain RBAC Federation** — Developing standardized interfaces for policy enforcement across heterogeneous administrative domains.

6. Conclusion

The rapid expansion of IoT ecosystems, encompassing both consumer and mission-critical domains, demands access control mechanisms that are granular, adaptive, and privacy-conscious. While traditional Role-Based Access Control (RBAC) remains a proven model for scalable privilege management, its direct application to resource-constrained, dynamic device environments introduces operational and privacy challenges.

This research presented the Hybrid RBAC-Attribute Model with Privacy-Aware Logging (HRAPL**)**, an applied framework that builds directly upon the granular RBAC approach proposed by Shaik et al. (2018)**.** By incorporating multi-attribute contextual evaluation**,** lightweight enforcement**, and** privacy-preserving logging**,** HRAPL addresses limitations in both baseline RBAC and Shaik et al.'s original implementation.

Evaluation in a smart healthcare IoT testbed demonstrated that HRAPL:

- Reduced unauthorized access attempts by 97.0%**,** outperforming both traditional RBAC and Shaik et al.'s model.
- Achieved a 94.2% privacy leakage resistance rate through pseudonymized, compliance-aligned logging.
- Maintained low computational overhead (<7% CPU usage), confirming feasibility for constrained devices.

These results underscore HRAPL's applicability in privacy-sensitive, multi-device environments, particularly where regulatory compliance and real-time decision-making are critical. The modest trade-off in decision latency is outweighed by substantial gains in security and privacy.

In the broader research landscape as of 2022, this work contributes a deployable, standards-compatible RBAC enhancement that bridges the gap between theoretical access control models and the operational realities of IoT security. Future research should explore machine learning-driven policy adaptation**,** blockchain-enabled immutable logging, and federated RBAC architecture**s** to further strengthen security and privacy in distributed device ecosystems.

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