White Paper: Dynamic Reverse SSH at Massive Scale Through MQTT and Sub-Domain Based Scaling

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Abstract

The rapid expansion of Internet of Things (IoT) deployments has given rise to an immediate necessity for scalable, secure, and efficient solutions for facilitating remote access to devices, especially those running behind Network Address Translation (NAT) or firewalls. Conventional SSH-based access cannot scale to millions of devices because of port constraints, server coordination issues, and the dynamic environment of IoT. This white paper introduces a revolutionary architecture for dynamic reverse SSH tunneling at huge scale, utilizing the lightweight MQTT protocol for messaging, a database-backed server registry for coordination, and sub-domain-based load balancing via an L4 proxy. Utilizing distinct server identifiers and dynamic port allocation among multiple server instances, this solution makes the most of more than 60,000 TCP ports, supporting millions of concurrent connections. The architecture ensures resilience, security, and flexibility, making it an ideal foundation for large-scale IoT ecosystems.

1. Introduction

The Internet of Things (IoT) has transformed industries, from smart homes and industrial automation to healthcare and agriculture, by connecting billions of devices to the internet. As of 2025, estimates suggest over 75 billion IoT devices are deployed globally, many operating in constrained environments behind NATs or firewalls. These conditions complicate direct remote access, which is critical for device management, diagnostics, and real-time interaction.

Reverse SSH tunneling, where a device initiates an outbound connection to a central server, is a proven method to bypass NATs and firewalls. However, traditional reverse SSH solutions face significant scalability barriers when applied to millions of devices. Key challenges include:

- **Port Limitations**: Each server can support only a finite number of TCP ports (approximately 60,000 usable ports), limiting the number of concurrent tunnels.
- **Server Coordination**: Managing multiple servers to handle device connections requires robust coordination to avoid port conflicts and ensure efficient load distribution.
- **Communication Overhead**: IoT devices often have limited bandwidth and processing power, necessitating lightweight communication protocols.
- **Security**: Ensuring secure authentication and encrypted communication across millions of connections is paramount.

This white paper introduces a distributed system that overcomes these challenges by integrating MQTT's light-weight publish-subscribe pattern, a centralized database or cache registry for server coordination, and sub-domain-based load balancing. The solution optimizes port utilization, provides high concurrency, and provides secure, reliable access to IoT devices, establishing a new standard for remote access in large-scale IoT deployments.

2. System Architecture

2.1 Overview

The proposed architecture is designed to scale reverse SSH tunneling to support millions of IoT devices while maintaining simplicity, security, and performance. It consists of three core components:

- **IoT Device Agent**: A lightweight software component running on IoT devices, responsible for establishing reverse SSH tunnels and forwarding traffic to local services.
- **Reverse SSH Server**: A server-side component that coordinates user requests, manages device connections, and facilitates SSH tunneling.
- **Load Balancer and Registry**: An L4 load balancer (e.g., HAProxy) routes traffic using sub-domain-based server identifiers, supported by a database or cache that stores server-to-IP mappings.

The system operates through a streamlined workflow:

- An IoT device receives a tunnel request via MQTT, specifying a local port on the device and a remote port on the server.
- The device connects to a reverse SSH server, selected randomly through an L4 load balancer.

- The server notifies the user of the assigned port and its unique server identifier via MQTT or an HTTP-based mechanism.
- Each server, upon startup, registers its unique identifier and IP address in a shared database or cache.
- The user connects to the load balancer's IP or domain, embedding the server's identifier in the hostname (e.g., `<server_id>.proxy_domain:port`).
- The load balancer queries the registry to resolve the server identifier to its IP and routes the connection to the appropriate server.

This approach leverages the full range of TCP ports (approximately 60,000 usable ports) across multiple servers, enabling massive scalability and efficient resource utilization.

2.2 Key Components

2.2.1 IoT Device Agent

The IoT device agent is a lightweight, resource-efficient component designed to run on constrained devices with limited CPU, memory, and bandwidth. Its primary responsibilities include:

- **Listening for Tunnel Requests**: Subscribes to a device-specific MQTT topic to receive tunnel requests, which include the local port (on the device) and the remote port (on the server).
- **Establishing Reverse SSH Tunnels**: Initiates secure SSH connections to a reverse SSH server, creating a tunnel that allows external access to local services.
- **Traffic Forwarding**: Forwards traffic between the server and local services (e.g., a web server or diagnostic interface) running on the device.
- **Connection Health Monitoring**: Monitors the health of SSH connections using keepalive mechanisms and gracefully handles disconnections or timeouts.
- **Resource Management**: Supports configurable connection limits to prevent resource exhaustion on the device.

The agent is optimized for low overhead, ensuring compatibility with a wide range of IoT hardware, from Raspberry Pi to embedded microcontrollers.

2.2.2 Reverse SSH Server

The reverse SSH server is the central coordinator of the system, managing interactions between users and IoT devices. Its key functions include:

- **User Request Handling**: Receives user requests via MQTT, specifying the target device and desired local port.

- **Port Allocation**: Assigns a unique remote port for each tunnel, ensuring no conflicts across servers by consulting the registry.
- **Device Coordination**: Communicates with the IoT device via MQTT to initiate the reverse SSH tunnel.
- **User Notification**: Informs the user of the connection details, including the server's unique identifier and assigned remote port, using MQTT or HTTP.
- **Connection Management**: Tracks active tunnels, monitors their health, and cleans up expired or stale connections to free resources.
- **Server Registration**: Registers its unique identifier and IP address in the shared registry upon startup, enabling load balancer routing.

Each server operates independently but collaborates through the shared registry, ensuring distributed coordination and scalability.

2.2.3 Load Balancer and Registry

The load balancer and registry are critical for enabling dynamic routing and scalability:

- **L4 Load Balancer**: An L4 proxy (e.g., HAProxy) routes user connections to the correct server based on the hostname, which embeds the server's unique identifier (e.g., `<server_id>.proxy_domain:port`). The load balancer queries the registry to resolve the identifier to the server's IP address and forwards the connection.
- **Database/Cache Registry**: Stores mappings of server identifiers to IP addresses. Implemented as a high-availability database (e.g., PostgreSQL) or cache (e.g., Redis), the registry ensures fast, reliable lookups. Servers update their mappings on startup or IP changes, and the registry supports TTLs to handle server failures.

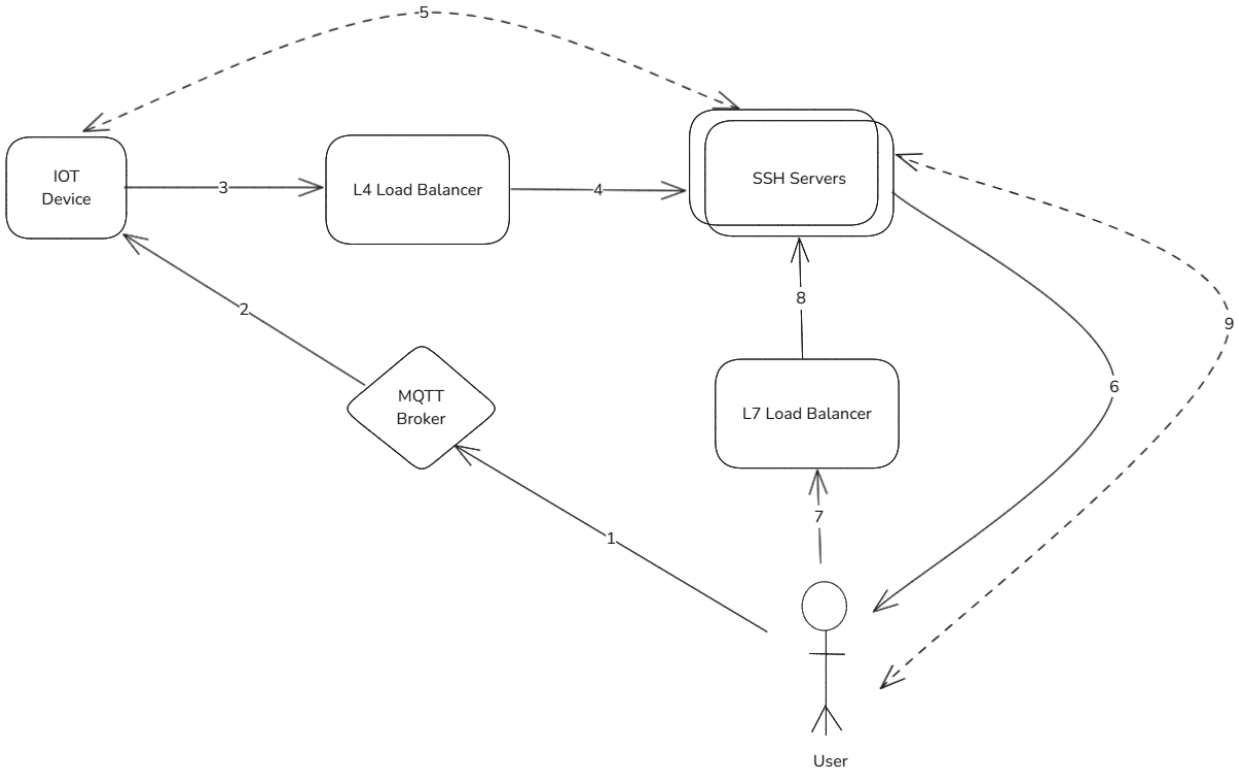
This combination enables dynamic, real-time routing without requiring static IP assignments or complex configuration.

3. Operational Workflow

The system's workflow is designed for efficiency, scalability, and reliability:

- **Tunnel Request**: A user submits a request to access a specific IoT device, triggering an MQTT message that includes the desired local port (on the device) and a server-assigned remote port.
- **Device Connection**: The IoT device receives the MQTT message on its device-specific topic and establishes a reverse SSH tunnel to a server, selected randomly via the L4 load balancer.

- **User Notification**: The server sends the user the connection details, including its unique identifier and the assigned remote port, via MQTT or an HTTP endpoint.
- **Server Registration**: Upon startup, each server generates a unique identifier and registers it with its IP address in the database or cache, ensuring the load balancer can route traffic accurately.
- **User Connection**: The user connects to the load balancer's domain or IP, using a hostname that includes the server's identifier (e.g., `<server_id>.proxy_domain:port`).
- **Dynamic Routing**: The load balancer queries the registry to resolve the server identifier to its IP address and forwards the connection to the correct server, enabling the user to access the device's local service.



This workflow ensures seamless coordination between users, devices, and servers, even in deployments with millions of devices. The use of MQTT for asynchronous communication minimizes latency, while the registry-driven load balancing ensures accurate routing.

4. Scalability and Performance

4.1 Port Utilization

Each reverse SSH server can utilize approximately 60,000 TCP ports (excluding reserved ports below 1024 and other system-reserved ports). By deploying multiple server instances, the system scales linearly:

- **100 Servers**: Supports up to 6,000,000 concurrent tunnels.
- **1,000 Servers**: Supports up to 60,000,000 concurrent tunnels.

The system's scalability is driven by its ability to utilize the full range of TCP ports across multiple servers. Let's define the key parameters:

- **P**: Number of usable TCP ports per server (approximately 60,000, excluding reserved ports below 1024).
- **S**: Number of server instances.
- **C**: Total number of concurrent tunnels supported.

The total number of concurrent tunnels is given by:

$$C = P \times S$$

Examples:

- For $S = 100$ servers:

$$C = 60{,}000 \times 100 = 6{,}000{,}000 \text{ tunnels}$$

- For $S = 1{,}000$ servers:

$$C = 60{,}000 \times 1{,}000 = 60{,}000{,}000 \text{ tunnels}$$

This linear scalability assumes no port conflicts, which is ensured by the registry checking port availability across servers. The probability of a port conflict is minimized by the large port range and dynamic allocation:

$$\text{Probability of conflict} \approx \frac{\text{Number of allocated ports}}{\text{Total ports per server}} = \frac{N}{P}$$

For $N = 50{,}000$ allocated ports on a server:

$$\text{Probability} \approx \frac{50{,}000}{60{,}000} \approx 0.833$$

The registry reduces this to near zero by validating port assignments globally.

Dynamic port allocation, backed by the registry to prevent conflicts, ensures efficient use of the port space. The system checks for port availability across all servers, avoiding collisions and maximizing resource utilization.

4.2 Load Balancing

The L4 load balancer plays a pivotal role in scalability:

- **Device Connections**: The load balancer distributes device connections randomly across servers, ensuring even load distribution and preventing any single server from becoming a bottleneck.
- **User Connections**: Sub-domain-based routing allows users to connect to the correct server by embedding the server's unique identifier in the hostname. This eliminates the need for static IP assignments, as the load balancer dynamically resolves the identifier to the server's IP.

The L4 load balancer distributes device connections randomly across servers, ensuring even load distribution. The expected load per server is:

$$L = D / S$$

Where:

- **D**: Total number of devices.
- **S**: Number of servers.

For $D = 10,000,000$ devices and $S = 100$ servers:

$$L = 10,000,000 / 100 = 100,000 \text{ devices per server}$$

Sub-domain-based routing for user connections ensures zero overhead for IP resolution, as the load balancer queries the registry with a lookup time $T_{lookup} \approx 1\text{-}5$ ms (typical for Redis or PostgreSQL).

This approach supports seamless scaling by adding more server instances without requiring reconfiguration of the load balancer or clients. Health checks ensure that only operational servers receive traffic, enhancing reliability.

4.3 MQTT Efficiency

MQTT's publish-subscribe model is inherently scalable, supporting millions of topics and clients with minimal overhead. Key features include:

- **Device-Specific Topics**: Each device subscribes to a unique topic (e.g., `device/<device_id>`), ensuring precise communication without topic collisions.
- **Shared Subscriptions**: User requests are processed through shared MQTT subscriptions, distributing the load across server instances and preventing bottlenecks.
- **Low Overhead**: MQTT's lightweight protocol is ideal for IoT environments, where devices may have limited bandwidth or processing power.

MQTT's publish-subscribe model supports high throughput. The system's MQTT broker handles:

- **User Requests**: Shared subscriptions distribute requests across servers.
- **Device Messages**: Device-specific topics ensure precise communication.

The message rate for tunnel requests is:

$$R = U \times F$$

Where:

- **U**: Number of users.
- **F**: Frequency of requests per user (e.g., requests per second).

For $U = 100,000$ users and $F = 0.1$ requests/second:

$$R = 100,000 \times 0.1 = 10,000 \text{ messages/second}$$

Modern MQTT brokers (e.g., Mosquitto, EMQX) can handle millions of messages per second, ensuring scalability.

The asynchronous nature of MQTT reduces latency and ensures that devices and servers can operate independently, improving overall system performance.

4.4 Registry Performance

The database or cache registry is optimized for high-throughput, low-latency lookups:

- **Caching Layer**: A cache like Redis stores server mappings with TTLs, reducing database load and ensuring rapid resolution of server identifiers. TTLs also handle server failures by expiring stale mappings.

- **Database Backend**: For durability, a high-availability database (e.g., PostgreSQL with replication) stores persistent mappings, ensuring data integrity in case of cache failures.
- **Scalability**: The registry supports horizontal scaling through clustering (e.g., Redis Sentinel) or sharding, accommodating the needs of large-scale deployments.

The registry's lookup performance is critical for load balancing. The expected lookup time is:

$$T_{total} = T_{cache} + P_{miss} \times T_{db}$$

Where:

- T_{cache}: Cache lookup time (≈ 1 ms).
- P_{miss}: Cache miss probability (≈ 0.01).
- T_{db}: Database lookup time (≈ 10 ms).

For typical values:

$$T_{total} = 1 + 0.01 \times 10 = 1.1 \text{ ms}$$

This ensures low-latency routing even under heavy load.

This combination ensures that the load balancer can resolve server identifiers in milliseconds, maintaining low latency even under heavy load.

5. Security Considerations

Security is a cornerstone of the proposed architecture, addressing the unique challenges of IoT deployments:

- **Secure Authentication**: Devices and servers use public key authentication for SSH, ensuring only authorized entities can establish tunnels. Password-based and keyboard-interactive authentication are disabled to mitigate brute-force risks.
- **Encrypted Communication**: All SSH traffic is encrypted, protecting data confidentiality and integrity. MQTT connections utilize TLS and authentication mechanisms to secure topic access and prevent unauthorized subscriptions or publications.
- **Sub-Domain Validation**: The load balancer validates server identifiers in hostnames to prevent spoofing attempts. DNS records for the proxy domain are secured with DNSSEC to ensure trustworthiness.
- **Access Control**: User requests are validated to ensure they target authorized devices, and connection details are delivered only to authenticated users through secure channels (e.g., TLS-protected MQTT or HTTPS).

- **Registry Security**: The database or cache is protected with strict access controls, encryption at rest, and network-level isolation to prevent unauthorized modifications to server mappings.
- **Auditability**: All connection attempts, tunnel establishments, and registry updates are logged, enabling forensic analysis and compliance with regulatory requirements.

These measures ensure that the system remains secure even in the face of sophisticated attacks, protecting both the IoT devices and the users accessing them.

6. Advantages

The proposed architecture offers several key advantages:

- **Unprecedented Scalability**: By leveraging the full range of TCP ports across multiple servers, the system supports millions of concurrent tunnels, meeting the needs of the largest IoT deployments.
- **Dynamic Flexibility**: Sub-domain-based routing and registry-driven load balancing enable seamless scaling and server management, accommodating dynamic changes in infrastructure.
- **Efficient Communication**: MQTT's lightweight, asynchronous model minimizes overhead, making it ideal for resource-constrained IoT devices and high-latency networks.
- **Resilience**: Automated cleanup of expired tunnels, health checks for servers, and registry-based coordination ensure system stability and handle failures gracefully.
- **Versatility**: Support for both MQTT and HTTP for user notifications accommodates diverse client requirements, from command-line tools to web-based dashboards.
- **Cost Efficiency**: The use of commodity hardware for servers, combined with open-source technologies like MQTT and HAProxy, reduces deployment costs while maintaining high performance.

These advantages make the system a compelling solution for IoT providers, enterprises, and service providers seeking to enable remote access at scale.

7. Use Cases

The architecture is applicable to a wide range of IoT use cases:

- **Industrial IoT**: Remote maintenance of factory equipment, such as PLCs or robotic arms, behind corporate firewalls.

- **Smart Homes**: Secure access to home automation devices, such as cameras or thermostats, for troubleshooting or configuration.
- **Healthcare IoT**: Real-time monitoring and management of medical devices, such as wearable sensors or diagnostic equipment, in hospitals or homes.
- **Smart Cities**: Remote administration of infrastructure, such as traffic sensors or environmental monitors, deployed across urban environments.
- **Agriculture**: Access to IoT-enabled farming equipment, such as irrigation controllers or soil sensors, for precision agriculture.

In each case, the system's scalability, security, and efficiency ensure reliable access to devices, enhancing operational efficiency and user experience.

8. Potential Enhancements

While the proposed architecture is robust, several enhancements could further improve its capabilities:

- **Automated Key Management**: Implement automated key rotation and integration with secrets management systems (e.g., HashiCorp Vault) to enhance SSH security and simplify key lifecycle management.
- **Connection Throttling**: Introduce per-device or per-user connection limits to prevent resource exhaustion and ensure fair resource allocation in multi-tenant environments.
- **Intelligent Load Balancing**: Use metrics such as server CPU load, memory usage, or connection latency to optimize load distribution, improving performance under varying conditions.
- **Comprehensive Monitoring**: Deploy monitoring tools (e.g., Prometheus and Grafana) to track connection counts, port usage, latency, and system health in real time, enabling proactive issue detection.
- **Failover Mechanisms**: Develop automated failover for servers, reassigning active tunnels to healthy instances during failures to minimize downtime.
- **Multi-Protocol Support**: Extend the system to support additional protocols (e.g., HTTP/3 or WebSocket) for user connections, broadening its applicability.
- **Geo-Distributed Deployment**: Optimize the architecture for global deployments by introducing regional load balancers and registries to reduce latency and comply with data sovereignty regulations.

These enhancements would further strengthen the system's scalability, reliability, and adaptability to diverse use cases.

9. Challenges and Mitigation Strategies

Deploying a system at this scale presents several challenges, each with corresponding mitigation strategies:

- **Network Congestion**: High volumes of MQTT and SSH traffic could strain network infrastructure. **Mitigation**: Deploy traffic shaping, prioritize critical traffic, and use content delivery networks (CDNs) for load balancer endpoints.
- **Registry Bottlenecks**: Heavy load on the database or cache could impact lookup performance. **Mitigation**: Use a distributed cache with read replicas and optimize query performance through indexing.
- **Device Heterogeneity**: IoT devices vary widely in hardware and software capabilities. **Mitigation**: Design the agent to be highly portable, with modular components and configurable resource limits.
- **Security Threats**: Sophisticated attacks, such as DDoS or key compromise, could disrupt operations. **Mitigation**: Implement rate limiting, intrusion detection, and regular security audits to maintain system integrity.
- **Regulatory Compliance**: IoT deployments may be subject to data protection regulations (e.g., GDPR). **Mitigation**: Ensure data encryption, anonymization, and compliance with regional privacy laws.

By proactively addressing these challenges, the system can maintain high performance and reliability in real-world deployments.

10. Conclusion

The proposed architecture for dynamic reverse SSH tunneling at large scale represents a paradigm shift in remote access for devices in the IoT ecosystem by utilizing the lightweight form of communication in MQTT, a robust database or cache registry, and using sub-domain based load balancing. The system can support millions of concurrent connections and is not limited to the scalability of a traditional SSH solution. The system utilizes the entire TCP port range across distributed servers with dynamically routed connections and secure authentication to provide unparalleled flexibility, security, and performance.

The architecture is suitable for a wide variety of IoT applications ranging from smart cities to industrial automation, providing seamless device management through real-time interaction. The system is also resilient to failures, it makes efficient use of resources, and it can support various notification systems - making it an incredibly versatile solution for enterprises and service providers. Future improvements to key management, monitoring,

and failover will enhance the architecture's standing as a robust framework for enabling IoT remote access.

As IoT deployments continue to proliferate the proposed architecture has established a scalable, secure, efficient connectivity standard that empowers organizations to realize the potential of the Internet of Things.

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