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

By: **Ben Meehan**
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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 follows a streamlined, scalable workflow designed for efficiency and resilience. When an IoT device receives a tunnel request via MQTT, it includes both the local port to expose and the remote port to be opened on the server. The device then initiates a reverse SSH connection to one of the available servers, selected at random through an L4 load balancer. Once the connection is established, the server informs the user, via MQTT or an HTTP-based mechanism of the assigned remote port and the server’s unique identifier. Each server, when it starts up, registers its unique ID and current IP address in a shared

registry (such as a database or cache). When a user wants to access the device, they connect to the load balancer's domain using a specially crafted hostname that includes the server ID (e.g., `<server_id>.proxy_domain:port`). The load balancer consults the registry to resolve this identifier to the correct server IP and forwards the connection accordingly. This design makes use of the full range of available TCP ports—up to around 60,000 per server—and distributes the load across multiple servers, enabling massive scalability and efficient use of system resources.

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. It 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. Upon receiving a request, the agent establishes secure reverse SSH tunnels to a central server, enabling external access to local services such as web servers or diagnostic interfaces. It efficiently forwards traffic between the server and the device's local services, monitors SSH connection health using keepalive mechanisms, and gracefully handles disconnections or timeouts. To prevent resource exhaustion, the agent includes configurable connection limits and is optimized for minimal overhead, ensuring broad compatibility across diverse IoT hardware, from Raspberry Pi to embedded microcontrollers.

2.2.2 Reverse SSH Server

The reverse SSH server acts as the central coordinator of the system, managing interactions between users and IoT devices. It handles user requests received via MQTT, which specify the target device and desired local port, and assigns a unique remote port for each tunnel by consulting a shared registry to avoid conflicts across servers. Upon processing a request, it communicates with the appropriate IoT device via MQTT to initiate the reverse SSH tunnel and then notifies the user of the connection details—including the server's unique identifier and assigned remote port, via MQTT or HTTP. The server continuously manages active tunnels by monitoring their health and cleaning up expired or stale connections to conserve resources. Additionally, each server registers its unique identifier and IP address in the shared registry upon startup, enabling proper routing through a load balancer. While each server operates independently, they coordinate through the shared registry to ensure distributed functionality and system scalability.

2.2.3 Load Balancer and Registry

The load balancer and registry are critical components for enabling dynamic routing and system scalability. An L4 load balancer, such as HAProxy, routes user connections to the appropriate server based on the hostname, which includes the server's unique identifier (e.g., `<server_id>.proxy_domain:port`). To determine the correct routing, the load balancer queries a central registry that maps server identifiers to IP addresses and forwards the connection accordingly. This registry is implemented as a high-availability database like PostgreSQL or a fast in-memory cache like Redis, providing reliable and low-latency lookups. Servers update their mappings in the registry during startup or when their IP changes, and TTLs are used to expire stale entries and gracefully handle server failures. Together, the load balancer and registry allow for real-time, dynamic routing without relying on static IPs or complex configurations, supporting scalable and resilient system architecture.

3. Operational Workflow

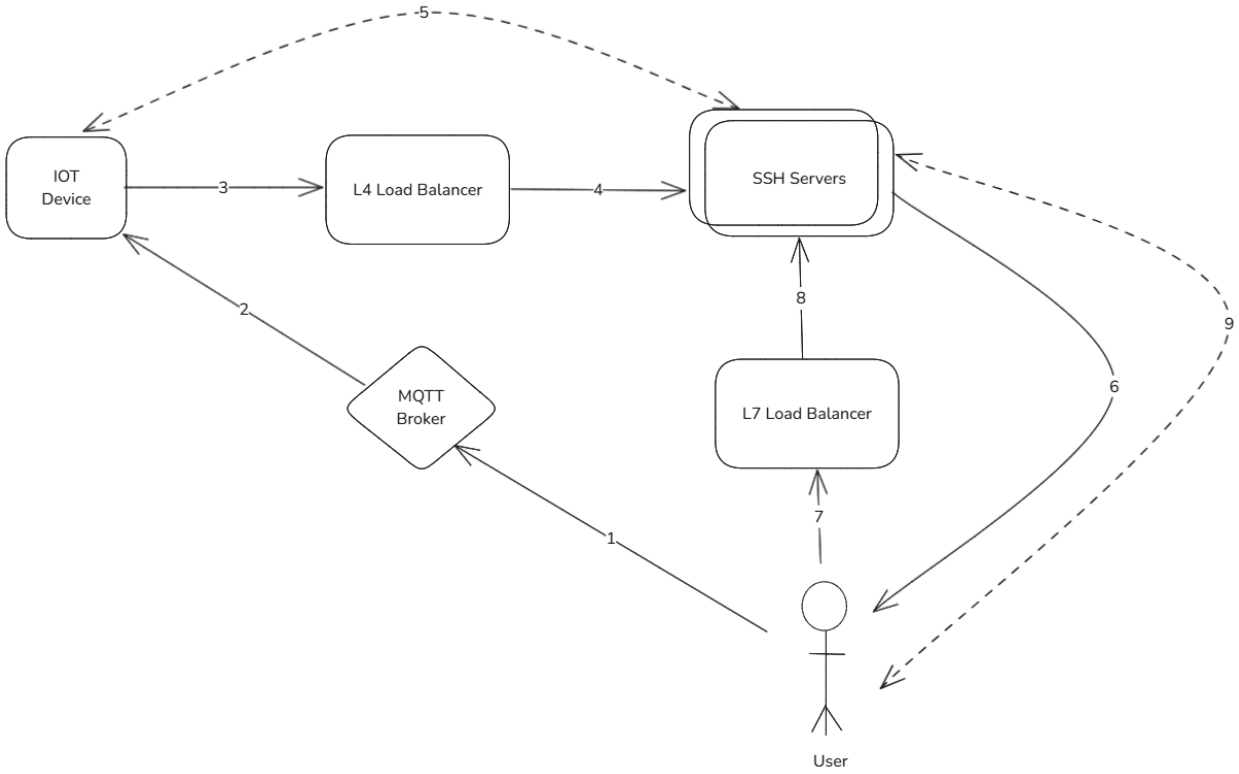
The system's workflow is thoughtfully designed to balance efficiency, scalability, and reliability, making it well-suited for managing large numbers of IoT devices and user connections. It begins when an IoT device receives a tunnel request through MQTT, containing details about which local port should be exposed and which remote port the server should open. The device then establishes a reverse SSH connection to a server behind an L4 load balancer. This server is chosen at random by the load balancer, ensuring even distribution of connections and reducing the risk of overload on any single node.

Once the tunnel is established, the server notifies the user, either through MQTT or a lightweight HTTP-based API, providing the assigned remote port and the server's unique identifier. This allows the user to know exactly where and how to connect. To support this dynamic environment, each server registers itself with a shared registry (backed by a fast, highly available database or cache such as PostgreSQL or Redis) at startup, storing its unique identifier and IP address. The registry is continuously updated to reflect changes in server IPs and supports automatic cleanup of stale entries using TTLs, which helps maintain reliability in the face of network issues or server failures.

When the user initiates a connection, they use the load balancer's domain or IP along with a specially formatted hostname that embeds the server's unique ID, for example, `<server_id>.proxy_domain:port`. The load balancer then queries the registry to resolve the server ID to the correct IP address and routes the incoming traffic to the appropriate server. This approach allows for dynamic, real-time routing without the need for static IPs or manual configuration, and by leveraging the full range of TCP ports across

multiple servers, the system can scale to handle tens of thousands of simultaneous connections with minimal overhead.

- **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 large-scale deployments involving millions of IoT devices. By using MQTT for asynchronous communication, the system maintains low latency and efficient message delivery, enabling quick tunnel setup and responsiveness even on constrained networks. The integration of a centralized registry with the load balancer allows for dynamic, real-time routing based on server identifiers, ensuring that each connection is accurately directed to the correct server without requiring static IPs or complex network configurations. This combination of lightweight messaging and registry-driven routing provides the foundation for a robust, scalable platform that can adapt to varying workloads while maintaining reliable and consistent connectivity across the entire system.

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:

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

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

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

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 $F = 0.1\ requests/second$:

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

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, designed to address the unique challenges of IoT deployments at scale. Devices and servers authenticate using SSH public key authentication, with password-based and keyboard-interactive methods disabled to prevent brute-force attacks. All SSH traffic is encrypted to ensure data confidentiality and integrity, while MQTT connections are secured using TLS and authenticated access to restrict topic-level operations. To prevent spoofing, the load balancer validates server identifiers embedded in hostnames, and DNS records for the proxy domain are secured

with DNSSEC. User access is tightly controlled—requests are verified to ensure they target only authorized devices, and connection details are shared exclusively with authenticated users via secure channels such as TLS-protected MQTT or HTTPS. The shared registry, which maps server identifiers to IPs, is protected through strict access controls, encryption at rest, and network isolation to guard against unauthorized modifications. Additionally, the system logs all critical events, including connection attempts, tunnel setups, and registry changes, ensuring full auditability and supporting regulatory compliance. These comprehensive security measures collectively safeguard both IoT devices and user access against a wide range of threats.

6. Advantages

The proposed architecture delivers a range of compelling advantages that make it highly suitable for large-scale, modern IoT deployments. It achieves unprecedented scalability by utilizing the full spectrum of TCP ports across multiple servers, enabling support for millions of simultaneous tunnels without bottlenecks. Its dynamic and flexible design, featuring subdomain-based routing and registry-driven load balancing, allows infrastructure to scale effortlessly and adapt to changes in real time. Communication is highly efficient thanks to MQTT's lightweight and asynchronous messaging model, which minimizes bandwidth and processing overhead, making it ideal for resource-constrained devices and variable network conditions. The system is built with resilience in mind, incorporating automatic cleanup of stale tunnels, continuous server health monitoring, and centralized coordination through the registry to maintain robust operations even under failure conditions. It also offers versatility in how users receive connection details, supporting both MQTT and HTTP to cater to a wide range of clients, from command-line tools to modern web interfaces. Finally, the architecture emphasizes cost efficiency, relying on commodity hardware and open-source components like MQTT brokers and HAProxy to deliver high performance without excessive infrastructure investment. Collectively, these strengths position the system as a powerful, scalable, and cost-effective solution for IoT providers, enterprises, and service operators looking to enable secure, remote access at scale.

7. Use Cases

The architecture is well-suited to a broad range of IoT use cases, offering secure, scalable, and efficient remote access across various industries. In industrial IoT, it enables remote maintenance of factory equipment like PLCs or robotic arms, even when located behind strict corporate firewalls. In smart home environments, it provides secure access to devices such as cameras, thermostats, and home automation systems for troubleshooting and configuration. In healthcare, the system supports real-time monitoring and management of medical devices, including wearable sensors and diagnostic equipment, both in clinical

settings and at home. For smart city applications, it facilitates the remote administration of distributed infrastructure such as traffic sensors, lighting systems, and environmental monitors. In agriculture, it allows farmers and technicians to access IoT-enabled equipment like irrigation controllers or soil sensors to support precision farming. Across all these scenarios, the system's robust architecture ensures reliable connectivity, strong security, and low overhead, ultimately improving operational efficiency and the overall user experience.

8. Potential Enhancements

While the proposed architecture is already robust, several enhancements could further elevate its capabilities. Implementing automated key management with key rotation and integration with secrets management systems like HashiCorp Vault would improve SSH security and streamline the key lifecycle process, reducing the risk of outdated or compromised keys. Connection throttling, with configurable per-device or per-user limits, would help prevent resource exhaustion and ensure equitable resource distribution in multi-tenant environments. Intelligent load balancing, based on real-time metrics such as server CPU load, memory usage, or connection latency, could optimize the distribution of traffic, ensuring better performance under varying system loads. Comprehensive monitoring tools like Prometheus and Grafana would enable real-time tracking of connection counts, port usage, system health, and latency, providing proactive insights for early issue detection and troubleshooting. Failover mechanisms could be developed to automatically reassign active tunnels to healthy servers during failures, minimizing downtime and ensuring continuous service. Expanding the system to support additional protocols like HTTP/3 or WebSocket would broaden its applicability, catering to a wider range of client connections. Finally, a geo-distributed deployment with regional load balancers and registries would reduce latency and address data sovereignty concerns, making the system more suitable for global use cases. These enhancements would further reinforce the system’s scalability, reliability, and adaptability, making it even more effective for a wide array of IoT use cases.

9. Challenges and Mitigation Strategies

Deploying a system at this scale involves overcoming several key challenges, each of which can be mitigated with strategic measures to maintain performance, security, and reliability. One of the primary concerns is network congestion, as high volumes of MQTT and SSH traffic could strain network infrastructure. To mitigate this, traffic shaping can be implemented to prioritize critical traffic, and content delivery networks (CDNs) can be leveraged for load balancer endpoints to distribute traffic more efficiently. Registry bottlenecks could occur if the database or cache becomes overloaded, potentially slowing down lookup performance. To address this, a distributed cache with read replicas can be

employed, alongside query optimization techniques such as indexing, to enhance speed and availability.

Device heterogeneity is another challenge, as IoT devices come in various shapes and sizes with differing hardware and software capabilities. The solution here is to design the agent with portability in mind, using modular components and offering configurable resource limits to ensure compatibility with a wide array of devices. Security threats, including sophisticated attacks like DDoS or key compromises, could jeopardize the integrity of the system. Mitigation strategies include implementing rate limiting, deploying intrusion detection systems (IDS), and conducting regular security audits to identify and address vulnerabilities proactively.

Finally, regulatory compliance presents a challenge, as IoT deployments must comply with data protection regulations, such as the GDPR, depending on their location. To mitigate this, the system should ensure data is encrypted both in transit and at rest, employ anonymization where necessary, and adhere to regional privacy laws to maintain legal and ethical standards.

By addressing these challenges with the proposed mitigation strategies, the system can maintain high performance, security, and regulatory compliance, ensuring reliability and effectiveness in large-scale, real-world IoT 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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