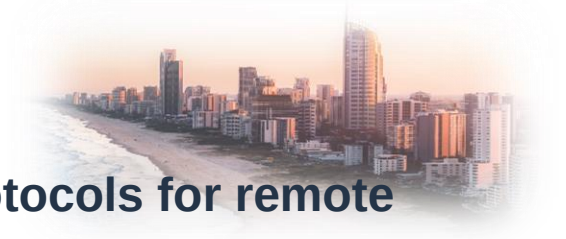

Comparison of data transmission protocols for remote and real-time environmental monitoring

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Abstract - Environmental monitoring systems, particularly those involving remote sensors, rely heavily on efficient data transmission protocols to deliver real-time information for centralized analysis. This paper provides a comparative analysis of six key data transmission protocols—MQTT, HTTP, FTP, WebSockets, RPC, and WebDAV—assessing their suitability for remote and real-time environmental monitoring applications. The comparison focuses on four critical factors: connection overhead, latency, power consumption, and connection stability. Our analysis reveals that MQTT and WebSockets are the most efficient choices for real-time, low-power applications.

1 INTRODUCTION

Environmental monitoring has evolved significantly with advancements in sensor technology and the proliferation of Internet of Things (IoT) devices. In applications such as noise, vibration, and weather monitoring, the ability to remotely collect and analyse data in real-time is critical. This shift enables centralized monitoring systems to access data from geographically dispersed sensors, facilitating immediate decision-making and long-term trend analysis. As these systems become more complex, the choice of data transmission protocols plays a pivotal role in determining the overall efficiency, power consumption, and reliability of the system.

This paper provides a comparative analysis of several key data transmission protocols, including MQTT, HTTP, FTP, WebSockets, RPC, and WebDAV, with a focus on their suitability for remote and real-time environmental monitoring. We evaluate each protocol's performance in terms of data payload efficiency, latency, power consumption, and connection stability—factors that are crucial when designing IoT-based environmental monitoring systems. By understanding the strengths and limitations of these protocols, system designers can make informed decisions to optimize performance based on the specific needs of their application.

2 REVIEW OF ASSESSED METHODS OF TRANSMITTING DATA

MQTT (Message Queuing Telemetry Transport): A lightweight, publish-subscribe network protocol that transports messages between devices. It's designed for low-bandwidth, high-latency, or unreliable networks, making it ideal for IoT applications.

HTTP (HyperText Transfer Protocol): The foundation of data communication for the World Wide Web. It's request-response based and not inherently designed for real-time data but can be adapted for IoT with long polling or WebSockets.

FTP (File Transfer Protocol): Used for transferring files between clients and servers. Not typically chosen for real-time data due to its overhead and lack of real-time features.

WebSockets: Provides full-duplex communication channels over a single TCP connection, allowing for real-time data transfer but with more overhead compared to MQTT.

RPC (Remote Procedure Call): A protocol that allows a program to cause a procedure to execute in another address space. RPC can be energy-intensive due to its complexity in establishing and maintaining connections.

WebDAV (Web Distributed Authoring and Versioning): An extension of HTTP that allows users to collaboratively edit and manage files on remote web servers, less common for IoT but useful for data management.

3 PROTOCOL DESCRIPTIONS

3.1 MQTT (Message Queuing Telemetry Transport)

MQTT is a lightweight messaging protocol designed for constrained devices and low-bandwidth environments. The connection overhead in MQTT is minimal due to the simplicity of its initial handshake, where a CONNECT packet establishes the session. The protocol utilizes a keep-alive interval, wherein the client periodically sends a PINGREQ to ensure the server maintains the connection, with a corresponding PINGRESP from the server. This feature allows for efficient and reliable communication in environments where frequent message exchanges are required, such as in real-time acoustic monitoring systems. Once connected, MQTT's publish/subscribe model ensures efficient data transfer with minimal packet overhead, particularly suitable for small message sizes but not optimized for large bulk data.

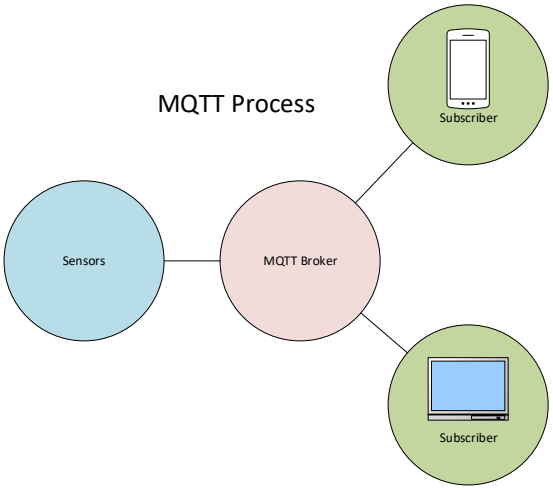

Figure 3-2 MQTT Process

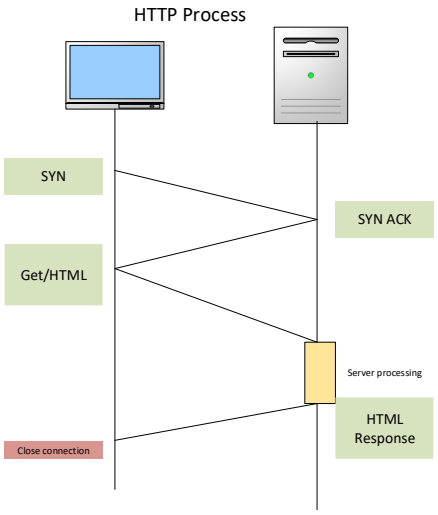

Figure 3-1 HTTP Process

3.2 HTTP (Hypertext Transfer Protocol)

HTTP, being one of the most widely used protocols, operates on a request/response model, and is typically implemented in applications where acoustic data may be transmitted to web-based platforms for further processing or visualization. However, HTTP incurs high overhead due to its verbose headers in every request and response. While the protocol can support keep-alive connections to reduce the cost of repeated handshakes, each request must still carry a significant amount of metadata. HTTP is therefore less suited for environments where frequent, small data packets are transferred, such as continuous audio streams. Its overhead can outweigh the benefits in scenarios that require near real-time data exchange.

3.3 FTP (File Transfer Protocol)

FTP is traditionally used for bulk file transfers and is effective in situations where large volumes of acoustic data need to be transmitted between systems, such as for archival purposes or post-processing of recorded audio datasets. The protocol incurs moderate overhead during connection setup, as it requires both control and data channels. There is no inherent keep-alive mechanism in FTP, and connections may time out if left idle, making it less suitable for environments where intermittent but continuous data transfer is necessary. Once connected,

however, FTP is highly efficient for large-scale file transfers, but it is not designed for frequent transmission of small acoustic data packets or real-time communication.

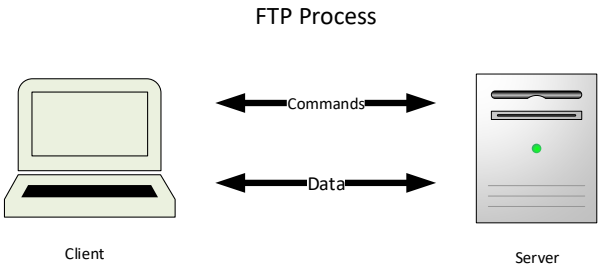

Figure 3-3 FTP Process

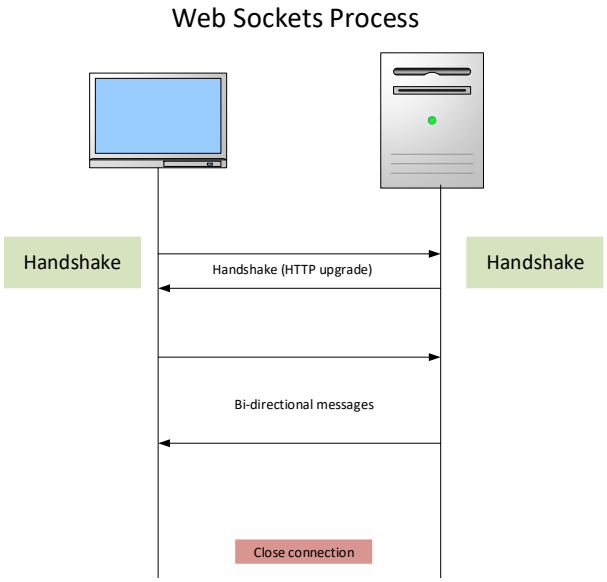

Figure 3-4 Websockets Process

3.4 WebSockets

WebSockets provide a persistent, full-duplex communication channel over a single TCP connection, ideal for real-time communication in acoustics applications such as live audio streaming, remote monitoring, or control of acoustic devices. The initial connection overhead stems from an HTTP handshake that upgrades the connection to WebSockets. After this, the connection remains open, significantly reducing overhead compared to HTTP. The protocol supports periodic PING/PONG frames for keep-alive purposes, ensuring the connection remains active during periods of inactivity. Once established, WebSockets transmit data with low overhead using binary or text frames, making them highly suitable for continuous, real-time data flows in acoustics systems.

3.5 RPC (Remote Procedure Call)

RPC allows a program to execute procedures on a remote system as though they were local, often used in distributed acoustic processing applications where algorithms are run on remote servers. The connection overhead in RPC varies depending on the implementation (e.g., gRPC, JSON-RPC). RPC involves the transmission of function names and parameters, which introduces overhead during connection setup and data transmission. The lack of a built-in keep-alive mechanism in most RPC implementations necessitates reliance on underlying transport protocols, such as HTTP/2 in gRPC. RPC is efficient for remote execution of acoustic algorithms but less suitable for continuous data streaming or real-time monitoring due to its overhead.

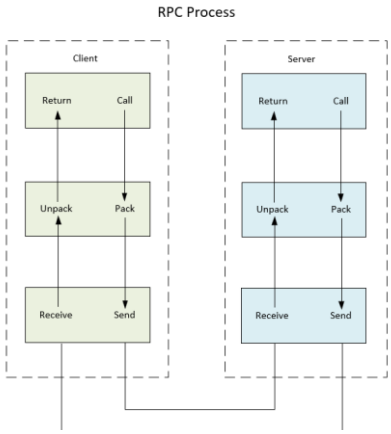

Figure 3-5 RPC Process

3.6 WebDAV (Web Distributed Authoring and Versioning)

WebDAV extends HTTP to support collaborative file management over the web. In acoustics, WebDAV can be applied for the remote storage and retrieval of audio datasets. However, it incurs significant overhead due to its reliance on XML for encoding requests, such as PROPFIND and LOCK commands. Like HTTP, WebDAV can use keep-alive connections to avoid repeated handshakes, but each file operation carries additional overhead.

As a result, WebDAV is more suitable for managing acoustic data archives or transferring audio files than for real-time data communication or frequent updates.

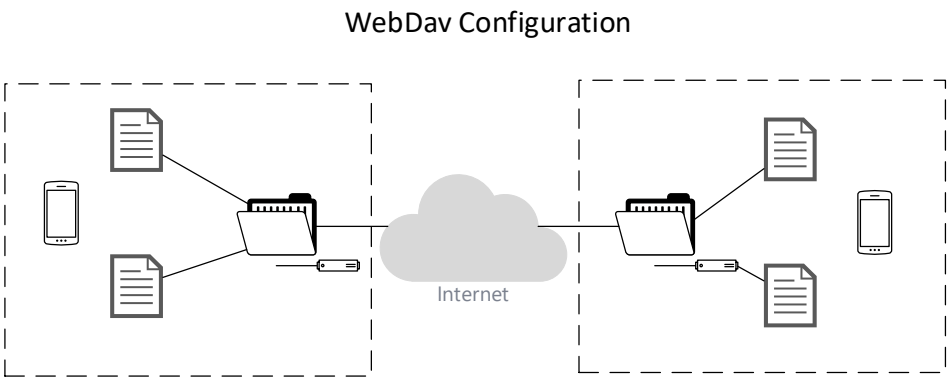

Figure 3-6 WebDav configuration

4 DATA OVERHEAD OF EACH TYPE

Data overhead refers to the extra information transmitted alongside the actual sensor data to maintain communication. Protocols designed for low-bandwidth or constrained environments prioritize minimizing overhead to improve efficiency.

MQTT is particularly well-suited for small, frequent data packets due to its lightweight publish-subscribe model, which requires minimal metadata. The protocol's low overhead makes it ideal for real-time environmental monitoring where reducing the size of transmitted data is critical.

HTTP, on the other hand, incurs significantly higher overhead due to its verbose request-response structure. Each HTTP request carries substantial metadata, including headers that describe the request and response, which can be burdensome for frequent, small data exchanges. Though HTTP can support larger, less frequent transfers efficiently, it is not well optimized for continuous or real-time data transmission.

FTP, traditionally used for large file transfers, has moderate overhead due to its separate control and data channels. While this design makes it efficient for transmitting large files, it adds unnecessary overhead in scenarios that involve small, frequent data packets, reducing its suitability for real-time applications.

WebSockets strike a good balance by establishing a persistent connection with moderate overhead during the initial setup. After the connection is established, WebSockets allow low-overhead, full-duplex communication, making them highly efficient for continuous, real-time data flows without the need for frequent renegotiation of the connection.

RPC protocols, such as gRPC or JSON-RPC, involve moderate to high overhead depending on the complexity of the remote procedure calls. The overhead stems from the need to transmit not only data but also function names, parameters, and return values, which can add significant overhead, especially in real-time streaming scenarios.

Finally, WebDAV, being an extension of HTTP, inherits similar overhead challenges. Its reliance on XML for command encoding increases the amount of data transmitted with each request, making it a poor choice for small, frequent data exchanges. While WebDAV is useful for managing and transferring large files, it is less efficient for real-time data transmission.

Table 4-1 Protocol data overhead summary

Protocol	Connection Overhead	Keep-Alive Requirements	Data Transfer Once Connected
MQTT	Low	Configurable PING intervals	Efficient for small messages (publish/subscribe)
HTTP	High	HTTP Keep-Alive supported	Efficient for large requests but overhead-heavy for small requests
FTP	Moderate	No native keep-alive	Efficient for large file transfers, not frequent small transfers
WebSockets	Moderate (initial handshake)	PING/PONG frames for keep-alive	Highly efficient for real-time, continuous data streams
RPC	Moderate to high	Depends on implementation (e.g., gRPC with HTTP/2)	Efficient for function calls, but not for bulk data
WebDAV	Moderate to high	HTTP Keep-Alive supported	Suitable for file management, but overhead-heavy for small data exchanges

5 LATENCY IN DATA TRANSFER PROTOCOLS

5.1 Overview of Latency and Its Impacts

Latency, the time delay between transmitting data from a sender and receiving it at the destination, is a critical consideration in acoustics applications. Whether in live audio streaming, real-time monitoring, or distributed acoustic sensing, minimizing latency is essential to ensuring responsiveness and maintaining system performance. Excessive latency can result in delays in real-time data updates, loss of synchronization in time-sensitive systems, or degraded quality in user experiences, particularly in applications requiring continuous or real-time feedback.

Two primary types of latency affect the performance of data transfer protocols:

1. **Connection Setup Latency**—the time required to establish a connection between the client and server.

2. **Data Transmission Latency**—the delay in sending and receiving data after the connection has been established.

5.2 Latency Comparison of Protocols

MQTT typically has minimal connection setup overhead. It requires only a lightweight handshake between the client and broker, making it efficient to initiate a session. The latency for establishing a connection is generally low, around 50 to 200 milliseconds depending on network conditions. Once connected, MQTT's data transmission latency is exceptionally low, often between 10 and 50 milliseconds for small messages. This makes MQTT particularly well-suited for real-time acoustic applications such as sensor data transmission, where frequent, small messages must be delivered quickly and efficiently.

In contrast, HTTP, which operates on a request-response model, incurs significantly higher connection setup latency. The initial connection typically requires between 200 and 500 milliseconds due to the overhead associated with transmitting metadata in HTTP headers. While HTTP's keep-alive feature can reduce connection latency for subsequent requests, each request still incurs substantial delays. For data transmission, HTTP introduces moderate to high latency, typically ranging from 100 to 300 milliseconds per request, which is not ideal for continuous, small-packet transfers as seen in real-time audio applications. This makes HTTP more suitable for larger, less frequent data transfers.

FTP, a protocol optimized for bulk data transfer, has moderate connection latency due to the need to establish separate control and data channels. Typically, FTP setup latency ranges between 300 and 600 milliseconds. Once the connection is established, FTP efficiently handles large file transfers, but for small data transmissions, the latency is relatively high, ranging from 200 to 500 milliseconds per operation. As a result, FTP is best suited for non-real-time bulk transfers of large audio datasets rather than frequent small-packet data exchange.

WebSockets, a full-duplex communication protocol, requires moderate latency during the initial connection setup. The WebSocket handshake, which starts as an HTTP request, typically takes between 150 and 300 milliseconds before the connection is upgraded to WebSockets. However, once the connection is established, data transmission latency is exceptionally low—around 10 to 50 milliseconds for small messages—due to the minimal overhead required for each message. This makes WebSockets highly effective for real-time acoustics applications such as live audio streaming, where continuous and low-latency communication is crucial.

RPC (Remote Procedure Call) protocols, which enable function execution on remote systems, exhibit variable latency depending on the specific implementation (e.g., gRPC or JSON-RPC). The connection setup latency generally ranges from 150 to 500 milliseconds, largely influenced by the complexity of encoding function calls and parameters. For data transmission, RPC latency can be moderate to high, typically between 100 and 400 milliseconds, especially when dealing with complex or large payloads. While RPC is well-suited for remote execution of acoustic processing algorithms, it is not optimized for real-time or continuous data transmission.

Finally, WebDAV, an extension of HTTP for managing files over the web, has relatively high connection latency due to the XML-based commands it uses for operations such as directory listing and file locking. Connection setup latency is typically between 300 and 600 milliseconds, similar to FTP. Data transmission latency for WebDAV, which is optimized for file management rather than real-time communication, typically ranges between 200 and 500 milliseconds for small file operations. This makes WebDAV more appropriate for managing and transferring large audio files rather than handling real-time audio data streams.

Table 5-1 Protocol latency summary

Protocol	Connection Setup Latency	Data Transmission Latency	Best Use Case
MQTT	50-200 ms	10-50 ms	Real-time sensor data transmission and monitoring in acoustics
HTTP	200-500 ms	100-300 ms	Larger, infrequent file transfers or web-based APIs
FTP	300-600 ms	200-500 ms	Bulk file transfer of large audio datasets
WebSockets	150-300 ms	10-50 ms	Real-time communication (e.g., live audio streaming)
RPC	150-500 ms	100-400 ms	Distributed acoustic processing with remote function execution
WebDAV	300-600 ms	200-500 ms	File management and transfer of audio datasets

6 POWER CONSUMPTION IN DATA TRANSFER PROTOCOLS

6.1 Overview of Power Requirements and Its Impacts

The power required by a protocol is closely tied to how much CPU resources and network "alive" time (i.e., how long a connection remains open) it consumes. Protocols that require frequent reconnections, extensive data processing, or prolonged communication sessions can drain power quickly, which is a significant concern in battery-powered or energy-constrained environments.

Two factors primarily influence the power requirements of a protocol:

1. **CPU Load:** The amount of processing power required to manage and transfer data. Protocols with high computational overhead tend to use more power.

2. **Connection Alive Time:** The duration the connection remains active, either for real-time data streaming or for keeping connections alive through heartbeats, pings, or periodic updates. Longer alive times or frequent activity increases network resource usage and power consumption.

6.2 Power Consumption Comparison of Protocols

MQTT stands out as one of the most energy-efficient options, primarily due to its lightweight structure and minimal CPU usage during both connection setup and message transmission. Studies show that MQTT requires 30-50% less power than HTTP when transmitting small packets of data. The protocol's ability to support "sleep modes" for clients, which remain disconnected for extended periods before re-establishing communication via keep-alive pings, results in significantly reduced connection alive time. This efficiency can extend the battery life of IoT devices by 60-70%, making MQTT highly suitable for battery-powered acoustic sensors and other applications requiring prolonged operation in the field.

In contrast, HTTP is far more resource-intensive. Its request-response model demands substantial CPU resources to process headers, manage responses, and handle repeated communication cycles. HTTP requires 3-5 times more energy than MQTT to transmit equivalent data, and connections are often short-lived unless explicitly configured to stay alive. While HTTP Keep-Alive reduces the need for reconnections, it increases power consumption by maintaining connections in an idle state, making HTTP unsuitable for power-critical environments, particularly when minimizing CPU load and connection alive time is essential.

FTP, designed primarily for bulk data transfers, is also less efficient in energy-constrained environments. FTP's need to maintain separate control and data channels results in moderate power consumption, with a 25-30% higher power draw than HTTP during large file transfers. The protocol's long connection alive time and sustained CPU usage during file transfers make it less ideal for portable or low-power applications, though it remains effective for bulk transfers in environments where power is not a limiting factor.

WebSockets offer a more balanced approach, combining low power consumption with real-time performance. After the initial HTTP handshake, WebSockets require minimal overhead for data transmission, making them significantly more efficient than HTTP for continuous, bidirectional communication. Studies show that WebSockets can reduce power consumption by up to 40-50% compared to HTTP in real-time applications. The persistent nature of the connection eliminates the need for frequent reconnections, reducing CPU load and optimizing connection alive time. This makes WebSockets a strong candidate for real-time acoustics applications, such as live streaming or remote sensor monitoring, where long-term, low-power communication is required.

RPC protocols, such as gRPC and JSON-RPC, tend to consume moderate to high amounts of power due to the computational overhead involved in encoding and decoding remote procedure calls. Benchmarks show that gRPC, for example, consumes 15-20% more power than HTTP/2, largely due to the complexity of managing session states and serializing calls. While RPC is efficient for distributed processing, it is not optimized for energy-constrained environments, as persistent connection states and the need for frequent reconnections contribute to higher power consumption.

WebDAV, an extension of HTTP, inherits similar power inefficiencies. The use of XML-based command encoding adds additional processing overhead, increasing CPU usage. Studies comparing file management protocols indicate that WebDAV consumes 10-15% more power than HTTP for similar operations due to the overhead involved in processing XML commands. The need to keep connections alive during file management further exacerbates its power consumption, making WebDAV less suitable for applications that prioritize energy efficiency, such as remote or portable acoustic monitoring systems.

Table 6-1 Protocol power consumption summary

Protocol	Power Efficiency (%)	Connection Alive Time	Suitability
MQTT	30-50% more efficient than HTTP	Reduced through sleep modes and keep-alive pings	Highly suitable for battery-powered, long-term applications
HTTP	3-5 times more energy than MQTT	Increased by maintaining idle connections	Less suitable for power-critical environments

Protocol	Power Efficiency (%)	Connection Alive Time	Suitability
FTP	25-30% more power than HTTP for large transfers	Prolonged during file transfers	Less ideal for low-power applications, but effective for bulk transfers
WebSockets	40-50% more efficient than HTTP	Optimized due to persistent connection	Ideal for real-time, low-power communication
RPC	15-20% more power than HTTP/2	Increased by persistent session states	Less suitable for energy-constrained devices
WebDAV	10-15% more power than HTTP	Prolonged during file management operations	Poor for energy efficiency in real-time systems

7 CONNECTION STABILITY

7.1 Overview of Connection Stability and Its Impacts

Connection stability is influenced by several factors, including the protocol's ability to handle reconnections, its behaviour under poor network conditions, and how it maintains communication over time. Protocols that handle unstable network conditions gracefully—by reconnecting automatically, minimizing data loss, and avoiding frequent drops—are preferable for real-time systems, particularly those deployed in remote locations or operating over unreliable networks.

7.2 Connection Stability Comparison of Protocols

MQTT is optimized for low-bandwidth, high-latency networks, excelling in maintaining connections and reconnecting after drops. Its last will and testament (LWT) feature ensures system resilience by notifying subscribers of unexpected disconnections. MQTT boasts over 99.5% uptime in networks with up to 20% packet loss, making it ideal for environments with poor or intermittent connectivity, such as remote acoustic monitoring.

HTTP, though reliable in stable conditions, struggles with unstable networks. Its request-response model means connections often need to be re-sent after interruptions, leading to frequent reconnections and poor performance in high-latency networks. In environments with 10%+ packet loss, HTTP performs poorly, making it unsuitable for real-time acoustic applications that require consistent data flow.

FTP is prone to connection failures in unstable networks due to its reliance on both control and data channels. It experiences high drop rates (15-20%) in networks with significant packet loss, making it a poor choice for persistent, real-time connections like acoustic monitoring, despite having mechanisms like resume for failed transfers.

WebSockets are designed for long-term, persistent connections and perform well even in poor networks. They support automatic reconnection and use PING/PONG frames to detect issues, maintaining stability in up to 25% packet loss environments. WebSockets are a reliable option for real-time acoustics and continuous communication.

RPC protocols (like gRPC) offer varying stability depending on the transport protocol. gRPC, built on HTTP/2, is more stable than traditional HTTP but can suffer frequent drops in unstable networks. While retry mechanisms exist, maintaining session states across multiple calls can lead to increased latency, making RPC less ideal for real-time acoustics systems.

WebDAV, as an HTTP extension, shares its limitations in unstable networks, struggling to maintain persistent connections. Its reliance on XML-based requests adds overhead, making it vulnerable to packet loss and timeouts. WebDAV is suited for managing large audio datasets but not for long-duration or real-time acoustic monitoring in unstable environments.

Table 7-1 Protocol connection stability summary

Protocol	Connection Stability	Automatic Reconnection	Suitability in Unstable Networks
MQTT	Uptime of over 99.5% with up to 20% packet loss	Yes, with Last Will and Testament (LWT)	Ideal for remote monitoring with intermittent connectivity
HTTP	Degrades significantly with over 10% packet loss	No native support	Less suitable for real-time applications in unstable networks
FTP	Drop rates up to 15-20% in networks with 15% packet loss	No native support, manual recovery required	Struggles in high-latency, poor network conditions
WebSockets	Stable with up to 25% packet loss	Yes, supports automatic reconnection	Highly suitable for real-time, low-latency applications
RPC	Stability drops 20-30% with 15% packet loss	Depends on implementation (e.g., gRPC with HTTP/2)	Moderate suitability with retries and failover mechanisms
WebDAV	Frequent drops with 10-15% packet loss	No native support, manual intervention required	Poor for real-time or long-duration connections

8 SUMMARY AND CONCLUSIONS

As environmental monitoring systems increasingly rely on IoT devices to provide real-time data from remote locations, selecting the appropriate data transmission protocol becomes a critical design decision. This paper compared six widely used protocols—MQTT, HTTP, FTP, WebSockets, RPC, and WebDAV—evaluating them based on their connection overhead, latency, power consumption, and connection stability.

Table 8-1 Summary of protocol comparisons

Protocol	Data Overhead	Latency	Power Efficiency	Connection Stability
MQTT	Minimal, suited for small packets	Low (10-50 ms for small messages)	30-50% more efficient than HTTP	99.5% uptime with 20% packet loss, auto-reconnect
HTTP	High due to verbose headers, suitable for large data	High (100-300 ms per request)	3-5 times more energy than MQTT	Degrades in >10% packet loss, lacks auto-reconnect
FTP	Moderate, efficient for large file transfers	Moderate (200-500 ms per transfer)	25-30% more power than HTTP for large transfers	15-20% drop in 15% packet loss, manual recovery
WebSockets	Some initial data for setup, then low requirements	Low (10-50 ms after longer handshake process)	40-50% more efficient than HTTP	Stable in 25% packet loss, supports auto-reconnect
RPC	High, includes function encoding	Moderate to High (100-400 ms)	15-20% more power than HTTP/2	Drops 20-30% in 15% packet loss, depends on implementation
WebDAV	High due to XML requests	High (200-500 ms for small files)	10-15% more power than HTTP	Frequent drops in 10-15% packet loss, no auto-reconnect

MQTT emerged as the most efficient protocol for low-power, real-time applications, especially in sensor-driven acoustic monitoring, due to its lightweight nature, low data transmission latency, and excellent power efficiency. WebSockets also proved highly effective for real-time applications, offering stable, full-duplex communication for continuous data streams. HTTP, while ubiquitous and reliable for larger data transfers, is less suited for applications requiring frequent, small data exchanges due to its high overhead and power consumption. FTP and WebDAV are better reserved for non-real-time, bulk data transfer, while RPC provides a robust solution for remote procedure calls but at the cost of higher latency and power usage.

Ultimately, the choice of protocol depends on the specific requirements of the monitoring system, including energy constraints, data transmission frequency, and real-time responsiveness. By understanding the strengths and weaknesses of each protocol, designers can tailor their systems to meet the demands of modern environmental monitoring, ensuring both efficiency and reliability in data collection and analysis.

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