Network programing

Tópicos de Informática para Automação

Mário Antunes

November 10, 2025

Universidade de Aveiro

Table of Contents i

A journey through modern communication protocols

Sockets: The Foundation i

A **socket** is an endpoint for communication. It's an abstraction (represented as a file descriptor) that your program can write to and read from.

- **Analogy:** A socket is like a "door" in your application. You give it a **port number** (the door number) on your machine's **IP address** (the street address).

Two main types for internet communication: **TCP** and **UDP**.

TCP vs. UDP: The Two Pillars i

Feature	TCP (Transmission Control Protocol)	UDP (User Datagram Protocol)
Connection	Connection-oriented (establishes a session)	Connectionless (fire and forget)
Reliability	**Reliable:** Guarantees delivery & order.	**Unreliable:** No guarantee of delivery or order.
Overhead	High (3-way handshake, ACKs, flow control)	Low (just a small header)
Speed	Slower, due to reliability checks	Faster, no connection setup or ACKs
Use Cases	Web (HTTP), Email (SMTP), File Transfer (FTP)	Streaming video, online gaming, DNS, VoIP
Python Module	`socket.SOCK_STREAM`	`socket.SOCK_DGRAM`

TCP Communication Pattern (Req/Rep)

TCP uses a **3-way handshake** to establish a reliable connection.

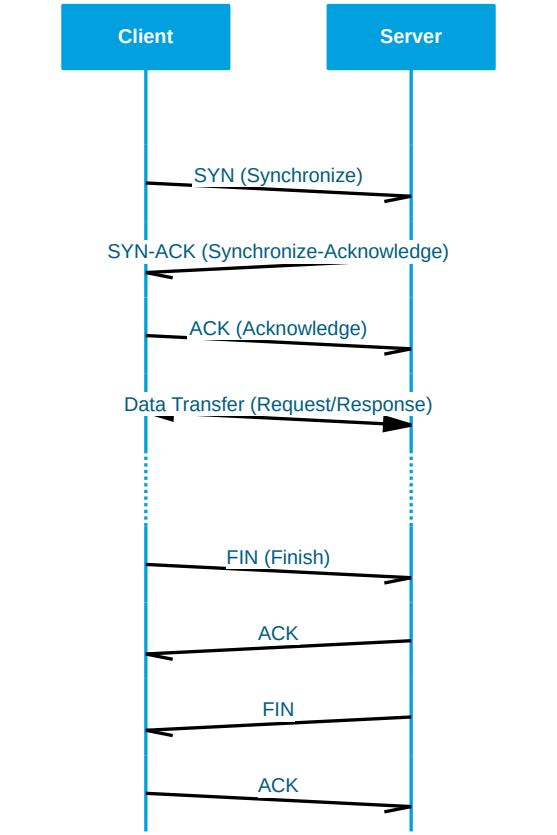


Figure 1: TCP 3-way handshake

Python TCP Server (Echo) i

```python
# tcp_server.py
import socket

HOST = '127.0.0.1'  # Standard loopback interface
PORT = 65432        # Port to listen on

# Use 'with' for automatic resource management
with socket.socket(socket.AF_INET, socket.SOCK_STREAM) as s:
    s.bind((HOST, PORT))
    s.listen()
    print(f"TCP server listening on {HOST}:{PORT}")
    # conn is a new socket object usable to send/recv data
    # addr is the address bound to the client
    conn, addr = s.accept()
    with conn:
        print(f"Connected by {addr}")
        while True:
            data = conn.recv(1024) # 1KB buffer
            if not data:
                break # Client closed connection
            print(f"Received: {data.decode()}")
            conn.sendall(data) # Echo back
```

Python TCP Client i

```python
# tcp_client.py
import socket

HOST = '127.0.0.1'  # The server's hostname or IP
PORT = 65432        # The port used by the server

with socket.socket(socket.AF_INET, socket.SOCK_STREAM) as s:
    s.connect((HOST, PORT))
    s.sendall(b'Hello, world') # Send as bytes
    data = s.recv(1024)
    print(f"Received echo: {data.decode()}")
```

UDP Communication Pattern (Datagram)

UDP is “fire and forget.” No connection is established.

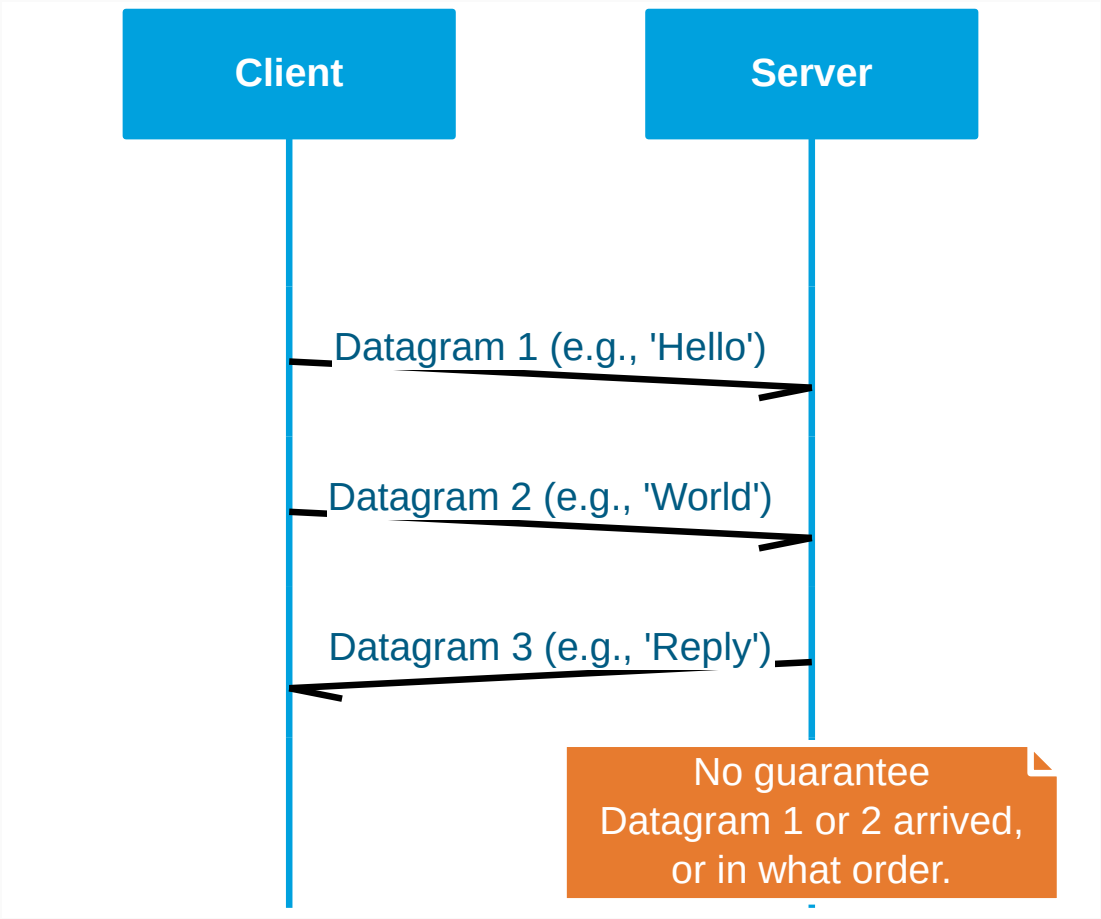


Figure 2: UDP - does not use session concepts

Python UDP Server (Echo) i

```python
# udp_server.py
import socket

HOST = '127.0.0.1'
PORT = 65432

with socket.socket(socket.AF_INET, socket.SOCK_DGRAM) as s:
    s.bind((HOST, PORT))
    print(f"UDP server listening on {HOST}:{PORT}")

    while True:
        # recvfrom returns data AND the address of the sender
        data, addr = s.recvfrom(1024)
        print(f"Received {data.decode()} from {addr}")

        if not data:
            break

        s.sendto(data, addr) # Echo back to the sender
```

Python UDP Client i

```python
# udp_client.py
import socket

HOST = '127.0.0.1'
PORT = 65432
MESSAGE = b'Hello, UDP!'

with socket.socket(socket.AF_INET, socket.SOCK_DGRAM) as s:
    s.sendto(MESSAGE, (HOST, PORT))

    data, addr = s.recvfrom(1024)
    print(f"Received echo: {data.decode()} from {addr}")
```

The Problem: Blocking I/O i

Traditional sockets are **blocking**.

- `s.accept()` **blocks** until a client connects.
- `conn.recv(1024)` **blocks** until data arrives.

If you are handling one client, all other clients must wait!

Traditional Solution: Multi-threading

- Creates one thread per client.
- **Complex:** Thread safety (locks, race conditions).
- **High Resource Use:** RAM, OS-level context switching.

The Problem: Blocking I/O ii

- **Python Issue (GIL):** The Global Interpreter Lock (GIL) in CPython prevents true parallel execution of Python code, limiting this approach.

The Solution: Async IO i

Asynchronous I/O (`asyncio` in Python) allows a single thread to manage many connections.

- It works for both **TCP** and **UDP** using an **event loop** to monitor sockets.
- When a socket is "ready" (e.g., has data), the loop runs the corresponding code.
- The `async` and `await` keywords "pause" a function, allowing the loop to work on other things, instead of blocking the whole thread.
  *This is **concurrency**, not parallelism. It's about waiting efficiently.*

Python `asyncio` TCP Server i

This server can handle thousands of clients concurrently.

```python
# asyncio_server.py
import asyncio

async def handle_client(reader, writer):
    """Callback for each new client connection"""
    addr = writer.get_extra_info('peername')
    print(f"Connected by {addr}")

    try:
        while True:
            data = await reader.read(1024)
            if not data:
                break

            message = data.decode()
            print(f"Received from {addr}: {message}")

            # Echo back
            writer.write(data)
            await writer.drain() # Wait until buffer is flushed
```

Python asyncio TCP Server ii

```
        except asyncio.CancelledError:
            print(f"Connection with {addr} cancelled.")
        finally:
            print(f"Closing connection with {addr}")
            writer.close()
            await writer.wait_closed()

async def main():
    server = await asyncio.start_server(
        handle_client, '127.0.0.1', 65432)

    addr = server.sockets[0].getsockname()
    print(f'Serving on {addr}')

    async with server:
        await server.serve_forever()

asyncio.run(main())
```

Python asyncio UDP Server i

AsyncIO also works for UDP, using a slightly different “Protocol” based approach.

```python
# asyncio_udp_server.py
import asyncio

class EchoServerProtocol(asyncio.DatagramProtocol):
    def connection_made(self, transport):
        self.transport = transport
        print("UDP Server (asyncio) started")

    def datagram_received(self, data, addr):
        message = data.decode()
        print(f"Received {message} from {addr}")
        self.transport.sendto(data, addr) # Echo back

async def main():
    loop = asyncio.get_running_loop()
    print("Starting UDP server on 127.0.0.1:65432")

    # Create the datagram endpoint
    transport, protocol = await loop.create_datagram_endpoint(
```

Python asyncio UDP Server ii

```
            lambda: EchoServerProtocol(),
            local_addr=('127.0.0.1', 65432))

        try:
            await asyncio.sleep(3600)  # Serve for 1 hour
        finally:
            transport.close()

    asyncio.run(main())
```

REST APIs: The Language of the Web

Sockets are powerful but low-level. Most modern web services don't expose sockets directly. They use **APIs** (Application Programming Interfaces).

REST (REpresentational State Transfer) is the most common architectural style for web APIs.

- It's **not a protocol**, but a set of rules.
- It builds *on top of* HTTP (which builds on top of TCP).
- It's **stateless**: Every request must contain all info needed to process it.

REST Communication Pattern (Req/Rep) i

Client-server communication over HTTP.

- **Resource:** An entity (e.g., `/users`, `/products/123`).
- **Verbs:** HTTP methods (GET, POST, PUT, DELETE).
- **Data:** Usually sent/received as **JSON**.

REST Communication Pattern (Req/Rep) ii

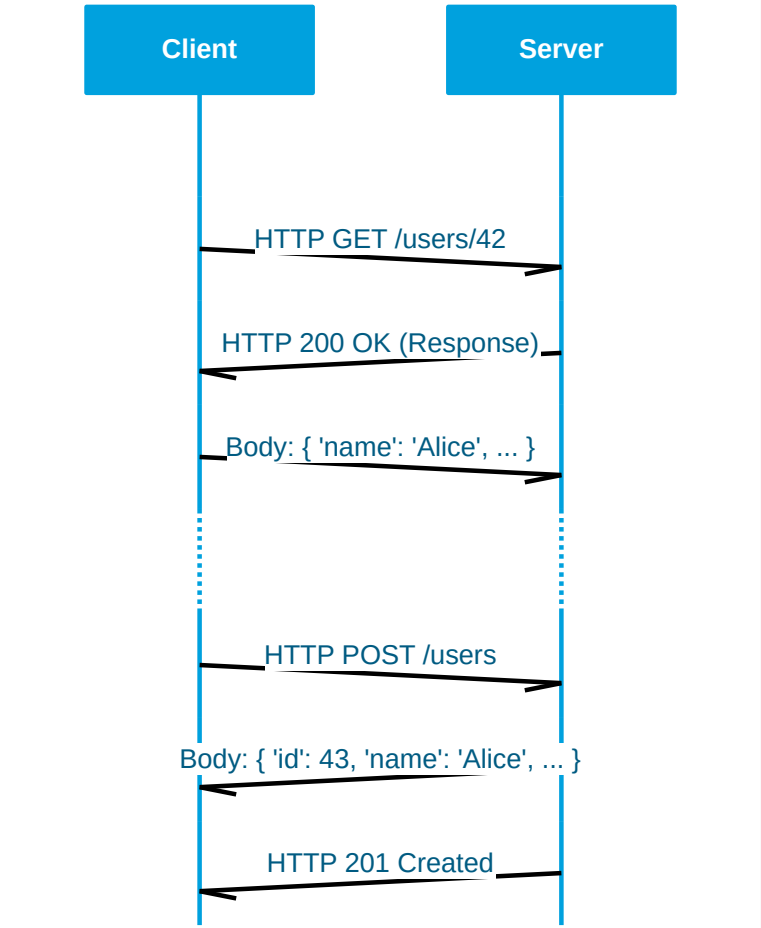


Figure 3: HTTP comunication

Data Format: JSON

JSON (JavaScript Object Notation) is the *de facto* standard for data exchange in REST APIs.

- Lightweight and human-readable.
- Easy for machines to parse and generate.
- Based on JavaScript object syntax.

Example:

```
{
  "id": 123,
  "username": "api_user",
  "isActive": true,
  "roles": ["admin", "editor"],
  "lastLogin": {
    "date": "2025-11-07",
    "ip": "192.0.2.1"
  }
}
```

Example: FastAPI (Python) i

FastAPI is a modern, high-performance Python web framework for building APIs. It's built on `asyncio`.

1. Install: `pip install fastapi "uvicorn[standard]"`
2. Save as `main.py`:

```python
# main.py
from fastapi import FastAPI

app = FastAPI()

# In-memory "database"
items = {
    1: {"name": "Laptop", "price": 1200},
    2: {"name": "Mouse", "price": 50}
}

@app.get("/")
```

Example: FastAPI (Python) ii

```
def read_root():
    return {"message": "Hello, API!"}

@app.get("/items/{item_id}")
def read_item(item_id: int):
    if item_id in items:
        return items[item_id]
    return {"error": "Item not found"}
```

3. Run: `uvicorn main:app --reload`
4. Access in browser:
   `http://127.0.0.1:8000/items/1`

Sockets vs. REST APIs i

Feature	Raw Sockets	REST APIs
Level	**Low-level** (OS-level)	**High-level** (Application-level)
Protocol	TCP, UDP (custom protocol)	HTTP/HTTPS (standardized)
State	Can be stateful	**Stateless** by design
Data Format	Anything (binary, custom text)	Usually JSON
Use When...	Custom protocol, high-speed, games, persistent connection.	Web services, mobile apps, public APIs, interoperability.

Sockets vs. REST APIs ii

Key takeaway: *You could build a REST API on raw sockets... but you'd just be re-inventing HTTP. REST gives you a massive head start with standardization, security (HTTPS), and tooling.*

WebSockets: The Real-Time Channel i

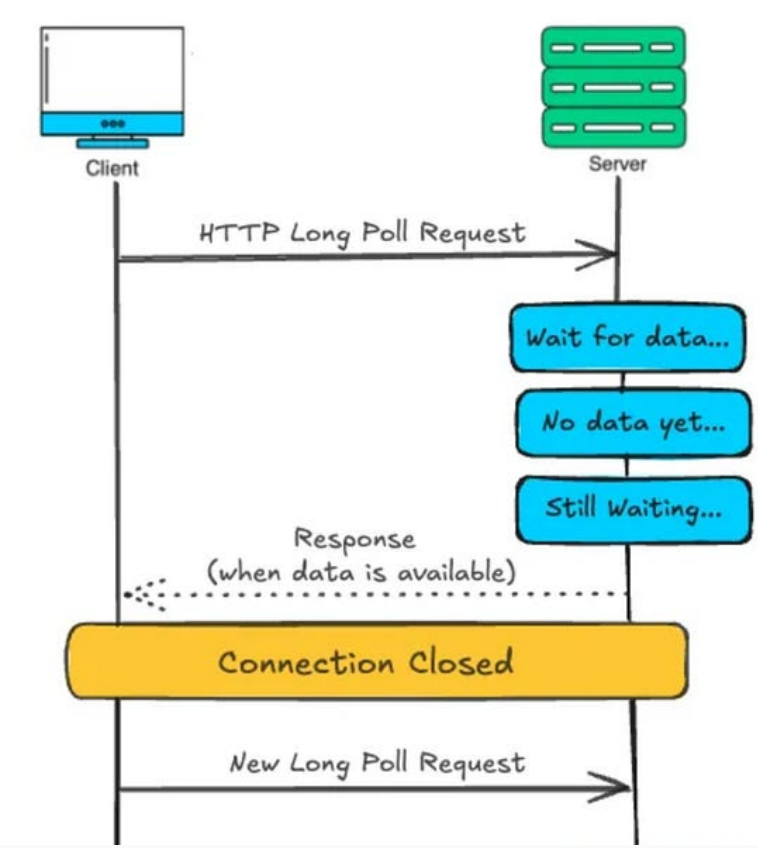
What if REST is too slow? What if the server needs to push data to the client *without* being asked?

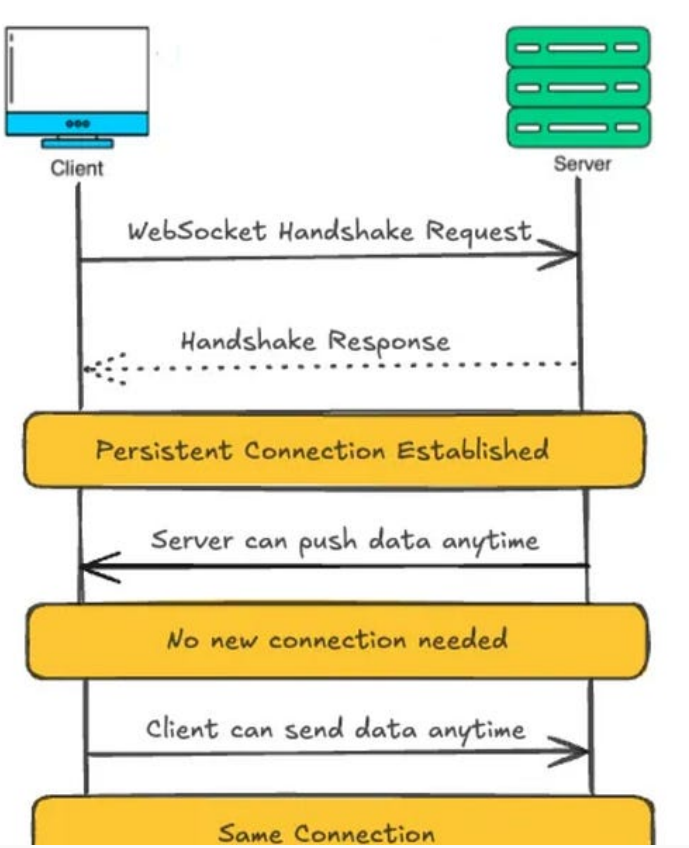
- HTTP is a client-pull (Req/Rep) model.
- Inefficient "polling" (asking "any updates?" every 2 seconds) is a common, bad workaround.

Solution: WebSockets

- A **persistent, full-duplex** (bidirectional) connection.
- Starts as a standard HTTP "Upgrade" request.
- Once established, it's a "raw" TCP-like channel for sending messages.

WebSockets: The Real-Time Channel ii





WebSocket Communication Pattern

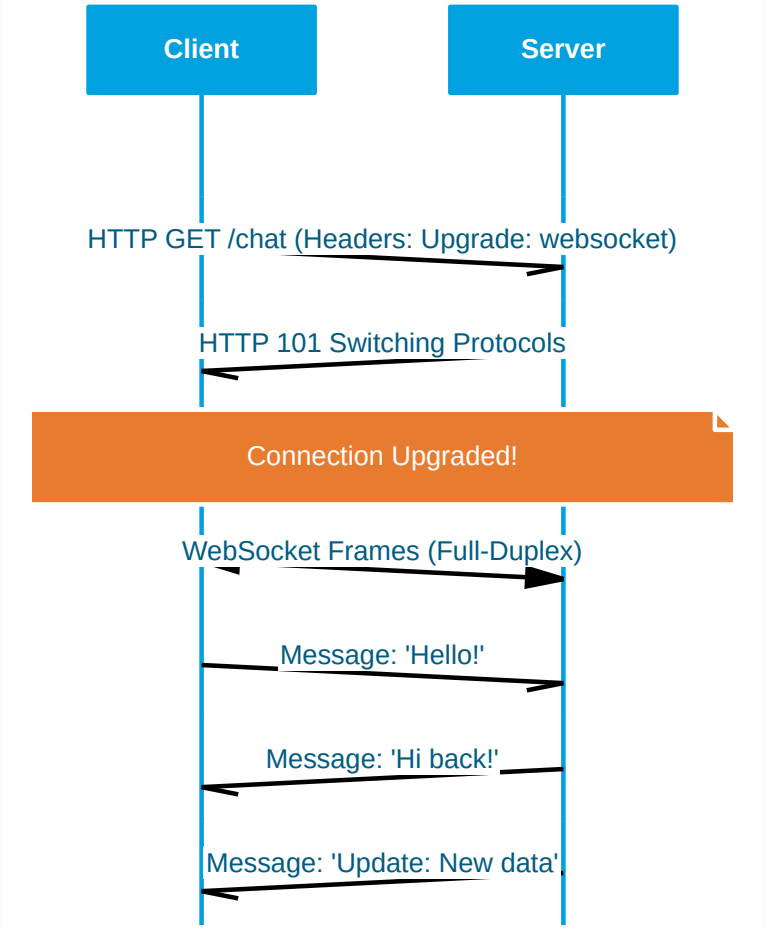


Figure 4: WebSocket Communication

WebSocket Example: JavaScript Client i

The browser is the *native* platform for WebSockets.

```
<!DOCTYPE html>
<html>
<head><title>WebSocket Chat</title></head>
<body>
    <ul id="messages"></ul>
    <input id="messageBox" type="text" />
    <button id="sendButton">Send</button>

    <script>
        const ws = new WebSocket("ws://localhost:8765"); // Connect
        const messages = document.getElementById("messages");
        const messageBox = document.getElementById("messageBox");
        const sendButton = document.getElementById("sendButton");

        // Listen for messages from server
        ws.onmessage = (event) => {
            const li = document.createElement("li");
            li.textContent = `Server: ${event.data}`;
            messages.appendChild(li);
        };
```

WebSocket Example: JavaScript Client ii

```
        // Send message to server
        sendButton.onclick = () => {
            const message = messageBox.value;
            ws.send(message);
            const li = document.createElement("li");
            li.textContent = `Client: ${message}`;
            messages.appendChild(li);
            messageBox.value = "";
        };

        ws.onopen = () => console.log("Connected to server");
        ws.onclose = () => console.log("Disconnected");
    </script>
</body>
</html>
```

WebSocket Example: Python Server i

Using the `websockets` library: `pip install websockets`

```python
# ws_server.py
import asyncio
import websockets

connected_clients = set()

async def chat_handler(websocket, path):
    # Register new client
    connected_clients.add(websocket)
    print(f"Client connected: {websocket.remote_address}")

    try:
        # Iterate over messages
        async for message in websocket:
            print(f"Received from {websocket.remote_address}: {message}")

            # Broadcast message to all other clients
            for client in connected_clients:
                if client ≠ websocket:
                    await client.send(f"[{websocket.remote_address[1]}]: {message}")
```

WebSocket Example: Python Server ii

```
        except websockets.ConnectionClosed:
            print(f"Client disconnected: {websocket.remote_address}")
        finally:
            # Unregister client
            connected_clients.remove(websocket)

async def main():
    print("Starting WebSocket server on ws://localhost:8765")
    async with websockets.serve(chat_handler, "localhost", 8765):
        await asyncio.Future()  # Run forever

if __name__ == "__main__":
    asyncio.run(main())
```

Advantages & When to Use i

Why WebSockets?

- **Low Latency:** No HTTP overhead for each message.
- **Real-Time:** Server can push data *instantly*.
- **Efficient:** Replaces constant polling, saving bandwidth and server load.

When to Use?

- Real-time chat applications
- Live sports tickers or stock feeds
- Multiplayer online games
- Collaborative editing (like Google Docs)

Advantages & When to Use ii

Advantage of Browser as Platform

- **Rich UI:** HTML & CSS provide a powerful rendering engine.
- **Powerful Logic:** JavaScript is a mature, high-performance language.
- **Ubiquity:** Runs on every desktop, laptop, and phone.
- **Integrated APIs:** Access to graphics (WebGL), audio, storage, and more.

MQTT: The IoT Protocol i

What if you have thousands of tiny, battery-powered devices on an unreliable network?

- TCP is too heavy.
- HTTP is *way* too heavy.
- They might not even have a stable IP address.

MQTT (Message Queuing Telemetry Transport)

- A lightweight, **publish/subscribe** protocol.
- Designed for constrained devices (IoT) and low-bandwidth networks.
- Minimal overhead (can be a 2-byte header).

Communication Pattern: Publish/Subscribe i

This is a fundamental shift from Request/Response.

- **Publisher:** Sends messages on a **Topic** (e.g., `home/livingroom/temp`). It doesn't know *who* is listening.
- **Subscriber:** Listens to one or more **Topics**. It doesn't know *who* published the message.
- **Broker:** The central server that receives *all* messages and routes them to the correct subscribers.

This fully decouples clients from each other.

MQTT (Pub/Sub)

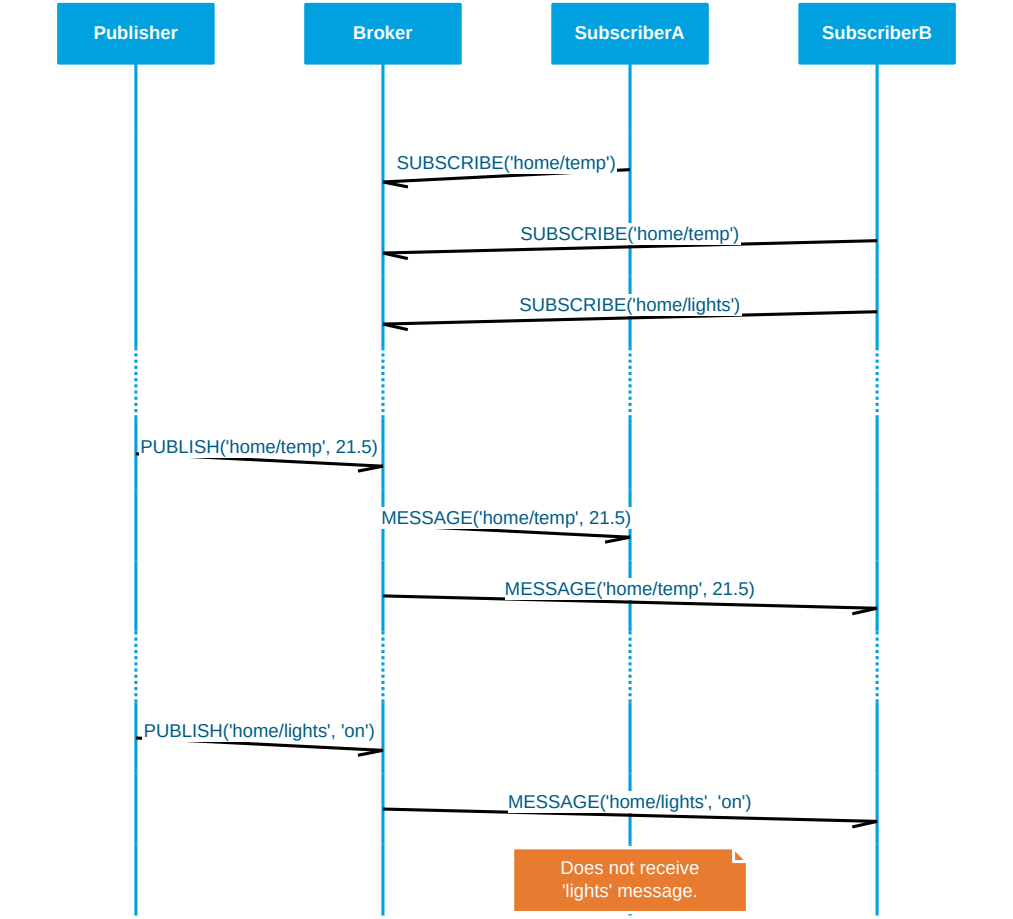


Figure 5: MQTT Pub/Sub pattern

MQTT Protocol Details i

- **Topics:** Hierarchical strings (e.g., `building/floor1/room102/light`).
  - Subscribers can use wildcards:
    - +: Single-level (e.g., `building/+/room102/light`)
    - #: Multi-level (e.g., `building/floor1/#`)
- **Quality of Service (QoS):**
  - **QoS 0:** At most once. (Fire and forget, like UDP)
  - **QoS 1:** At least once. (Guarantees delivery, may have duplicates)
  - **QoS 2:** Exactly once. (Guarantees delivery, no duplicates. Slowest)

MQTT Protocol Details ii

- **Last Will & Testament (LWT):** A message the broker sends *on behalf of* a client if it disconnects ungracefully. (e.g., `device/123/status` -> “offline”)

Python Publisher Example i

Using the `paho-mqtt` library: `pip install paho-mqtt`

```python
# publisher.py
import paho.mqtt.client as mqtt
import time
import random

def on_connect(client, userdata, flags, rc):
    print(f"Connected with result code {rc}")

client = mqtt.Client()
client.on_connect = on_connect

# Connect to a public broker (test.mosquitto.org)
client.connect("test.mosquitto.org", 1883, 60)
client.loop_start() # Start a background thread for handling network

try:
    while True:
        temperature = round(random.uniform(20.0, 25.0), 2)
        print(f"Publishing: {temperature}")

        # Publish message
```

Python Publisher Example ii

```
            client.publish("myhome/livingroom/temperature", payload=temperature, qos=0)

            time.sleep(5)
    except KeyboardInterrupt:
        print("Publishing stopped")
        client.loop_stop()
```

Python Subscriber Example i

```python
# subscriber.py
import paho.mqtt.client as mqtt

# Callback when connecting
def on_connect(client, userdata, flags, rc):
    print(f"Connected with result code {rc}")
    # Subscribe to the topic once connected
    client.subscribe("myhome/livingroom/temperature")
    print("Subscribed to 'myhome/livingroom/temperature'")

# Callback when a message is received
def on_message(client, userdata, msg):
    print(f"Topic: {msg.topic} | Message: {msg.payload.decode()}")

client = mqtt.Client()
client.on_connect = on_connect
client.on_message = on_message

client.connect("test.mosquitto.org", 1883, 60)

# Blocking call that processes network traffic, dispatches callbacks,
# and handles reconnecting.
client.loop_forever()
```

Other Communication Patterns i

Sockets, REST, WebSockets, and MQTT cover most cases, but other powerful patterns exist.

We'll look at two major examples:

- **Message Brokers (e.g., RabbitMQ):**
  - **Smart server, dumb clients.**
  - Manages complex routing, persistence, and delivery guarantees.
- **Brokerless Sockets (e.g., ZeroMQ):**
  - **Smart clients, no server.**
  - A library that provides high-level patterns (Pub/Sub, Push/Pull) over raw sockets.

Pattern: Message Broker (RabbitMQ) i

Uses the **AMQP** protocol (or others). It's a server that acts as a post office.

- **Producer:** Sends a message to an `Exchange`.
- **Exchange:** Routes the message to one or more `Queues` based on rules ("routing key").
- **Queue:** A durable buffer that holds messages.
- **Consumer:** Pulls messages from a `Queue`.

Advantages:

- **Reliability:** Queues can persist messages to disk.
- **Decoupling:** Producer and Consumer don't know about each other.

Pattern: Message Broker (RabbitMQ) ii

- **Complex Routing:** Fanout (broadcast), topic, and direct routing.
- **Load Balancing:** Multiple consumers can read from one queue.

Use Case: Microservice backends, task queues (e.g., Celery), financial transactions.

Pattern: Brokerless (ZeroMQ / ØMQ) i

ZeroMQ is **not** a broker. It's a **socket library on steroids.** It gives you patterns, not just a raw data stream.

- **How it works:** You import `zmq` and create sockets with *patterns*.
- **Common Patterns:**
  - `REQ/REP`: Like REST, but faster and bi-directional.
  - `PUB/SUB`: Like MQTT, but *without a central broker*. (Subscribers connect directly to Publisher).
  - `PUSH/PULL`: Distributes work to a pool of "worker" nodes.

Advantages:

Pattern: Brokerless (ZeroMQ / ØMQ) ii

- **Blazing Fast:** Can use in-process, IPC, or TCP communication.
- **Lightweight:** No single point of failure (broker).
- **Simple:** Easy to embed in any application.

Use Case: High-speed data (HPC), financial trading, inter-process communication.

Summary: Choosing the Right Tool i

- **Raw Sockets (TCP/UDP):**
  - **Use:** Custom protocols, high-performance needs, games.
  - **Pattern:** Request/Response (or custom).
- **REST API (HTTP):**
  - **Use:** Standard web services, public APIs, mobile app backends.
  - **Pattern:** Request/Response.
- **WebSockets:**
  - **Use:** Real-time web (chat, live feeds, collaborative editing).
  - **Pattern:** Full-Duplex / Bidirectional.
- **MQTT:**
  - **Use:** IoT, constrained devices, unreliable networks.

Summary: Choosing the Right Tool ii

    - **Pattern:** Publish/Subscribe (via Broker).
- **RabbitMQ (Broker):**
    - **Use:** Reliable microservice communication, task queues.
    - **Pattern:** Queues & Exchanges.
- **ZeroMQ (Brokerless):**
    - **Use:** High-speed, low-latency messaging.
    - **Pattern:** Various (Pub/Sub, Push/Pull, etc.).

📚 Further Resources i

Python Docs

- `socket` — Low-level networking interface
- `asyncio` — Asynchronous I/O

Frameworks & Libraries

- FastAPI
- `websockets` library
- Paho-MQTT Client
- RabbitMQ (and Python tutorial)
- ZeroMQ (and Python guide)

📚 Further Resources ii

Protocols & Concepts

- MQTT Standard
- WebSocket (MDN)
- The Global Interpreter Lock (GIL)