

MQTT Diag 通訊規格

設備診斷與監控通訊協議規格書

適用範圍: WiFi 診斷事件、設備健康監控  
通訊協議: MQTT v3.1.1 / v5.0  
版本: v1.0

# 目錄

[目錄 2](#_Toc206018170)

[MQTT Diag 通訊協定規格 v1.0 (rtkMQTT) 8](#_Toc206018171)

[1. 術語定義 8](#_Toc206018172)

[2. 設計原則 8](#_Toc206018173)

[3. Topic 命名空間 8](#_Toc206018174)

[3.1 上行（Device → Controller） 8](#_Toc206018175)

[3.2 下行（Controller → Device） 9](#_Toc206018176)

[3.3 群組/廣播（可選） 9](#_Toc206018177)

[4. Device ID 規範 9](#_Toc206018178)

[5. 安全與存取控制 (Future Work) 9](#_Toc206018179)

[5.1 傳輸安全 (待實作) 9](#_Toc206018180)

[5.2 存取控制清單 (待實作) 9](#_Toc206018181)

[5.3 審計與監控 (待實作) 9](#_Toc206018182)

[6. 設備上下線偵測 10](#_Toc206018183)

[6.1 Last Will Testament (LWT) 機制 10](#_Toc206018184)

[6.2 LWT 設定要求 10](#_Toc206018185)

[6.3 上下線狀態管理 10](#_Toc206018186)

[7. 共通 Payload 格式 10](#_Toc206018187)

[7.1 什麼是共通 Payload 格式 10](#_Toc206018188)

[7.2 必要欄位說明 11](#_Toc206018189)

[7.3 選用欄位說明 11](#_Toc206018190)

[7.4 完整訊息範例 12](#_Toc206018191)

[7.5 版本相容性規則 12](#_Toc206018192)

[8. MQTT 使用時機 12](#_Toc206018193)

[8.1 發布頻率 12](#_Toc206018194)

[8.2 訂閱模式 12](#_Toc206018195)

[8.3 命令處理 13](#_Toc206018196)

[9. 上行結構定義（Device → Controller） 13](#_Toc206018197)

[9.1 `state`（retained） 13](#_Toc206018198)

[9.2 `telemetry/{metric}` 13](#_Toc206018199)

[9.3 `evt/{event\_type}`（事件/告警） 14](#_Toc206018200)

[9.4 `attr`（retained，裝置屬性） 15](#_Toc206018201)

[10. 下行命令（Controller → Device） 15](#_Toc206018202)

[10.1 `cmd/req`（Controller → Device） 15](#_Toc206018203)

[10.2 `cmd/ack`（Device → Controller） 16](#_Toc206018204)

[10.3 `cmd/res`（Device → Controller） 16](#_Toc206018205)

[11. 典型命令清單（建議命名） 17](#_Toc206018206)

[12. 診斷資料傳輸機制 17](#_Toc206018207)

[12.1 主動診斷事件傳輸 17](#_Toc206018208)

[12.2 被動詳細診斷請求 17](#_Toc206018209)

[12.3 診斷命令格式 17](#_Toc206018210)

[12.3 設備相依性 18](#_Toc206018211)

[12.4 常見診斷類型 18](#_Toc206018212)

[13. 錯誤碼建議 19](#_Toc206018213)

[14. 版本控管 19](#_Toc206018214)

[15. 順序、重送與冪等 19](#_Toc206018215)

[16. 監控與審計建議 19](#_Toc206018216)

[17. 測試案例（最低集合） 19](#_Toc206018217)

[18. JSON Schema（簡化示例） 20](#_Toc206018218)

[17.1 `state/1.0` 20](#_Toc206018219)

[17.2 `cmd.light.set/1.0` 20](#_Toc206018220)

[19. 實作指南（裝置端） 21](#_Toc206018221)

[20. 實作指南（Controller/後端） 21](#_Toc206018222)

[21. 範例訂閱樣式 21](#_Toc206018223)

[22. WiFi 診斷實際應用範例 22](#_Toc206018224)

[23.1 漫遊問題診斷範例 22](#_Toc206018225)

[23.2 連線失敗診斷範例 24](#_Toc206018226)

[23.3 ARP 遺失診斷範例 25](#_Toc206018227)

[23.4 時序圖與通訊流程 26](#_Toc206018228)

[Controller 全域監控 26](#_Toc206018229)

[特定場域監控 27](#_Toc206018230)

[設備類型監控 27](#_Toc206018231)

[23.5 診斷資料結構定義 27](#_Toc206018232)

[23.6 實作指南 28](#_Toc206018233)

[23. 變更紀錄（Changelog） 28](#_Toc206018234)

[附錄 29](#_Toc206018235)

[A. 系統架構與元件關係 29](#_Toc206018236)

[B. MQTT 通訊流程與時序圖 32](#_Toc206018237)

[MQTT WiFi 診斷通訊流程與時序圖 32](#_Toc206018238)

[1. 通用診斷流程時序圖 32](#_Toc206018239)

[2. 漫遊診斷完整流程 34](#_Toc206018240)

[3. 連線失敗診斷流程 36](#_Toc206018241)

[4. ARP 遺失診斷流程 37](#_Toc206018242)

[5. 訂閱模式與 Topic 路由 38](#_Toc206018243)

[5.1 Controller 訂閱策略 38](#_Toc206018244)

[6. 錯誤處理與恢復流程 38](#_Toc206018245)

[6.1 命令超時處理 38](#_Toc206018246)

[6.2 連線中斷恢復 39](#_Toc206018247)

[7. 效能最佳化建議 39](#_Toc206018248)

[7.1 訊息大小控制 39](#_Toc206018249)

[7.2 頻率控制 39](#_Toc206018250)

[7.3 批次處理 39](#_Toc206018251)

[C. WiFi 連線失敗診斷範例 40](#_Toc206018252)

[WiFi 連線失敗診斷完整 MQTT 範例 40](#_Toc206018253)

[情境描述 41](#_Toc206018254)

[MQTT 訊息流程 41](#_Toc206018255)

[1. 連線失敗事件觸發 (Device → Controller) 41](#_Toc206018256)

[2. Controller 請求詳細診斷 (Controller → Device) 42](#_Toc206018257)

[3. Device 命令確認 (Device → Controller) 42](#_Toc206018258)

[4. Device 回傳詳細連線失敗診斷 (Device → Controller) 42](#_Toc206018259)

[5. 狀態更新反映連線問題 (Device → Controller) 45](#_Toc206018260)

[診斷分析結果 46](#_Toc206018261)

[失敗原因分析 46](#_Toc206018262)

[建議修復動作 46](#_Toc206018263)

[Controller 監控建議 46](#_Toc206018264)

[D. ARP 遺失診斷範例 48](#_Toc206018265)

[ARP 遺失診斷完整 MQTT 範例 48](#_Toc206018266)

[情境描述 49](#_Toc206018267)

[MQTT 訊息流程 49](#_Toc206018268)

[1. ARP 遺失事件觸發 (Device → Controller) 49](#_Toc206018269)

[2. Controller 請求詳細網路診斷 (Controller → Device) 50](#_Toc206018270)

[3. Device 命令確認 (Device → Controller) 50](#_Toc206018271)

[4. Device 回傳網路診斷分析 (Device → Controller) 50](#_Toc206018272)

[5. 遙測資料持續監控 (Device → Controller) 54](#_Toc206018273)

[6. 狀態更新顯示網路品質改善 (Device → Controller) 54](#_Toc206018274)

[診斷分析結果 55](#_Toc206018275)

[根本原因 55](#_Toc206018276)

[即時處理動作 55](#_Toc206018277)

[持續監控策略 56](#_Toc206018278)

[E. WiFi 漫遊診斷範例 57](#_Toc206018279)

[漫遊問題診斷完整 MQTT 範例 57](#_Toc206018280)

[情境描述 57](#_Toc206018281)

[MQTT 訊息流程 57](#_Toc206018282)

[1. 事件觸發 (Device → Controller) 57](#_Toc206018283)

[2. Controller 請求詳細診斷 (Controller → Device) 58](#_Toc206018284)

[3. Device 命令確認 (Device → Controller) 58](#_Toc206018285)

[4. Device 回傳詳細診斷結果 (Device → Controller) 58](#_Toc206018286)

[5. 狀態更新 (Device → Controller) - 定期發送 60](#_Toc206018287)

[診斷分析結果 60](#_Toc206018288)

[根本原因分析 60](#_Toc206018289)

[建議動作 60](#_Toc206018290)

[Controller 後續動作建議 61](#_Toc206018291)

# MQTT Diag 通訊協定規格 v1.0 (rtkMQTT)

定義設備與控制器間的 MQTT 診斷通訊協定，包含狀態回報、遙測、事件與命令的訊息格式。適用於 IoT 裝置、伺服器、網路設備等各類設備的診斷狀態回報。

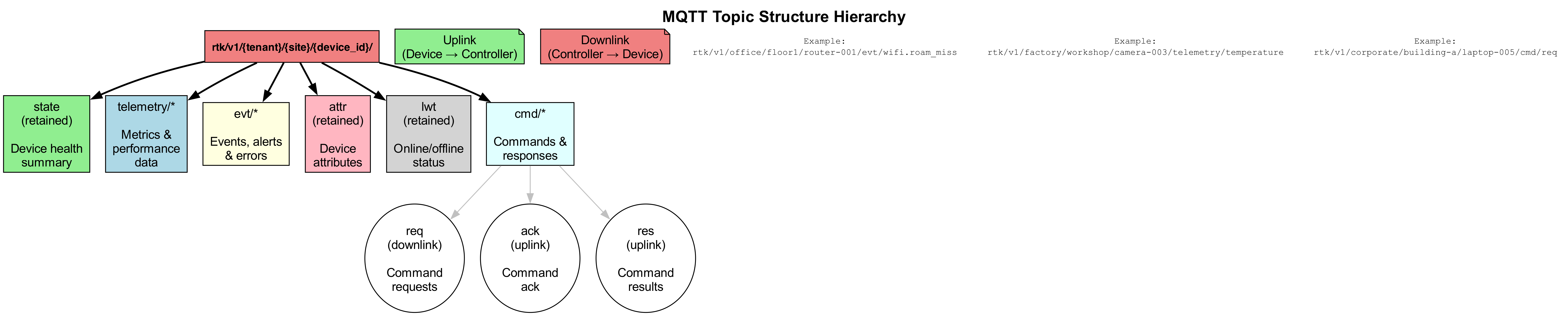
## 1. 術語定義

* **Device（設備）**: 連接 MQTT Broker 的設備，包含 IoT 裝置、伺服器、網路設備等
* **Controller（控制器）**: 發送命令並收集設備診斷資料的雲端或本地服務
* **Broker**: MQTT 訊息代理伺服器
* **Tenant/Site**: 租戶/場域，用於資料隔離與路由
* **Topic**: MQTT 主題路徑
* **LWT**: Last Will and Testament 遺囑訊息
* **Diagnosis（診斷）**: 設備健康狀態、效能指標、錯誤資訊等診斷資料

## 2. 設計原則

* **統一主題結構**: 以設備為中心的上下行訊息路徑設計
* **可擴充性**: 命令與 Schema 獨立演進，使用語義化版本控制
* **可觀測性**: 支援全域與範圍訂閱模式，便於監控與除錯
* **安全性**: TLS 加密、ClientID 認證與 ACL 存取控制 (這一個版本不需要)
* **診斷導向**: 專注於設備健康狀態、效能指標與故障診斷資訊的結構化傳輸，特別支援 WiFi 連線品質、漫遊事件、掃描結果等無線網路診斷

## 3. Topic 命名空間



根路徑採版本化：

rtk/v1/{tenant}/{site}/{device\_id}/...

### 3.1 上行（Device → Controller）

* state：設備狀態摘要與診斷資訊（retained）
* telemetry/{metric}：遙測資料與效能指標，支援高頻分流
* evt/{event\_type}：事件、告警、錯誤與診斷事件
* attr：設備靜態屬性與規格資訊（retained）
* cmd/ack：命令接收確認
* cmd/res：命令結果回覆
* lwt：LWT 上下線通知（retained）

### 3.2 下行（Controller → Device）

* cmd/req：命令請求（統一路徑）。

### 3.3 群組/廣播（可選）

裝置可額外訂閱其所屬群組命令：

rtk/v1/{tenant}/{site}/group/{group\_id}/cmd/req

裝置對群組命令的 ack/res 仍回自己的裝置路徑，便於逐台追蹤。

## 4. Device ID 規範

* device\_id：全域唯一標識符，不可變更，格式：^[a-z0-9-]{20,40}$（建議使用 ULID/KSUID）
* MQTT clientId = device\_id
* 避免使用 MAC 或序號作為主鍵，此類資訊應存放於 /attr topic 或後端資料庫

## 5. 安全與存取控制 (Future Work)

此章節定義完整的安全機制與存取控制規範，包含：

### 5.1 傳輸安全 (待實作)

* TLS 加密設定
* Client certificate 認證
* Token-based 認證機制

### 5.2 存取控制清單 (待實作)

* 裝置端 Topic 發布/訂閱權限
* Controller 端權限管理
* 租戶間資料隔離

### 5.3 審計與監控 (待實作)

* 連線記錄與審計日誌
* 異常行為偵測
* 安全事件通報機制

**注意**: 目前開發版本暫不實作安全控制機制，所有連線預設為可信任環境。

## 6. 設備上下線偵測

### 6.1 Last Will Testament (LWT) 機制

LWT 是 MQTT 的內建機制，用於偵測設備異常斷線。當設備與 MQTT Broker 的連線意外中斷時（如網路故障、設備當機），Broker 會自動發布預先設定的「遺囑訊息」通知其他訂閱者。

### 6.2 LWT 設定要求

設備在建立 MQTT 連線時必須設定以下 LWT 參數：

* **LWT Topic**: rtk/v1/{tenant}/{site}/{device\_id}/lwt
* **LWT Payload**: {"status":"offline","ts":<timestamp>}
* **LWT Retained**: true

### 6.3 上下線狀態管理

**設備上線時**:

主動發布上線狀態到相同 topic：

{  
 "status": "online",  
 "ts": 1723526400000  
}

**設備正常下線時**:

發布離線狀態後再斷開連線：

{  
 "status": "offline",   
 "ts": 1723526500000,  
 "reason": "normal\_shutdown"  
}

**設備異常斷線時**:

MQTT Broker 自動發布預設的 LWT 訊息，讓 Controller 立即得知設備離線狀態。

## 7. 共通 Payload 格式

### 7.1 什麼是共通 Payload 格式

所有透過 MQTT 傳送的 JSON 訊息都應該包含一些共通欄位，這些欄位用於：

* **版本控制**: 確保不同版本的設備和系統能正確解析訊息
* **時間追蹤**: 記錄事件發生的精確時間
* **除錯追蹤**: 在複雜系統中追蹤訊息流向

無論是狀態回報、遙測資料、事件通知還是命令，都使用相同的基本結構。

### 7.2 必要欄位說明

#### `schema` (字串)

* **用途**: 標識訊息的類型和版本，讓接收端知道如何解析這個訊息
* **格式**: <訊息類型>/<版本號>
* **範例**:
* state/1.0 - 設備狀態訊息 v1.0
* evt.wifi.roam\_miss/1.0 - WiFi 漫遊失效事件 v1.0
* cmd.diagnosis.get/1.0 - 診斷資料請求命令 v1.0

#### `ts` (整數)

* **用途**: 記錄訊息產生或事件發生的時間，用於排序、關聯和分析
* **格式**: Unix timestamp 毫秒 (int64)
* **範例**: 1723526400000 (對應 2024-08-13 08:00:00 UTC)
* **注意**: 所有設備必須使用相同的時間基準

### 7.3 選用欄位說明

#### `trace` (物件，選用)

* **用途**: 在分散式系統中追蹤單一操作的完整流程
* **常用欄位**:
* req\_id: 請求唯一識別碼
* correlation\_id: 關聯多個相關訊息
* span\_id: 分散式追蹤的區段識別碼

**範例**:

{  
 "schema": "evt.wifi.connect\_fail/1.0",  
 "ts": 1723526400000,  
 "trace": {  
 "req\_id": "conn-retry-001",   
 "correlation\_id": "user-session-12345"  
 },  
 "severity": "error",  
 "connection\_info": {  
 "ssid": "OfficeWiFi"  
 }  
}

### 7.4 完整訊息範例

**設備狀態訊息**:

{  
 "schema": "state/1.0",  
 "ts": 1723526400000,  
 "health": "ok",  
 "cpu\_usage": 45.2,  
 "wifi\_stats": {  
 "rssi": -52,  
 "connected": true  
 }  
}

**診斷事件訊息**:

{  
 "schema": "evt.wifi.arp\_loss/1.0",   
 "ts": 1723526401000,  
 "trace": {  
 "correlation\_id": "network-issue-001"  
 },  
 "severity": "warning",  
 "arp\_statistics": {  
 "success\_rate": 0.6  
 }  
}

### 7.5 版本相容性規則

* **前向相容**: 實作必須忽略未知的 JSON 欄位
* **版本升級**:
* 小版本升級 (1.0 → 1.1): 新增欄位，不移除現有欄位
* 大版本升級 (1.x → 2.0): 可能移除或改變現有欄位
* **解析原則**: 如果 schema 版本不相容，應記錄警告但不中斷處理

## 8. MQTT 使用時機

### 8.1 發布頻率

* **狀態資料** (state): 每 30-60 秒或狀態改變時
* **遙測資料** (telemetry/\*): 每 10-60 秒，依重要性調整
* **事件資料** (evt/\*): 立即發布
* **設備屬性** (attr): 啟動時或屬性變更時

### 8.2 訂閱模式

* Controller 使用通配符訂閱: rtk/v1/+/+/+/state、rtk/v1/+/+/+/evt/#
* Device 只訂閱自己的命令: rtk/v1/{tenant}/{site}/{device\_id}/cmd/req

### 8.3 命令處理

* Device 收到 cmd/req 後立即回 cmd/ack (< 1 秒)
* 命令執行完成後發布 cmd/res，包含結果或錯誤

## 9. 上行結構定義（Device → Controller）

### 9.1 `state`（retained）

**Topic**

rtk/v1/{tenant}/{site}/{device\_id}/state

**Payload（範例）**

{  
 "schema": "state/1.0",  
 "ts": 1723526400,  
 "health": "ok",  
 "fw": "1.2.3",  
 "uptime\_s": 4567,  
 "cpu\_usage": 45.2,  
 "memory\_usage": 62.8,  
 "disk\_usage": 78.5,  
 "temperature\_c": 42.1,  
 "net": { "rssi": -62, "ip": "10.0.1.23", "bytes\_rx": 1048576, "bytes\_tx": 524288 },  
 "diagnosis": {  
 "last\_error": null,  
 "error\_count": 0,  
 "restart\_count": 3  
 }  
}

**欄位說明**

|  |  |  |
| --- | --- | --- |
| \* health: `ok | warn | error`，設備整體健康狀態 |

\* `cpu\_usage`: CPU 使用率百分比（0-100）

* memory\_usage: 記憶體使用率百分比（0-100）
* disk\_usage: 磁碟使用率百分比（0-100）
* temperature\_c: 設備溫度（攝氏度）
* net: 網路介面資訊與統計
* diagnosis: 診斷相關資訊，包含錯誤狀態與統計

### 9.2 `telemetry/{metric}`

**Topic**

rtk/v1/{tenant}/{site}/{device\_id}/telemetry/{metric}

**Payload（範例：wifi.scan\_result - 以 WiFi 設備為例）**

{  
 "schema": "telemetry.wifi.scan\_result/1.0",  
 "ts": 1723526400,  
 "scan\_info": {  
 "internal\_scan\_skip\_cnt": 10,  
 "environment\_scan\_ap\_number": 8,  
 "current\_bssid": "aa:bb:cc:dd:ee:ff",  
 "current\_rssi": -45  
 },  
 "roam\_candidates": [  
 {  
 "bssid": "11:22:33:44:55:66",  
 "rssi": -42,  
 "channel": 6,  
 "ap\_load": 30  
 },  
 {  
 "bssid": "77:88:99:aa:bb:cc",   
 "rssi": -48,  
 "channel": 11,  
 "ap\_load": 25  
 }  
 ],  
 "scan\_timing": {  
 "last\_scan\_time": 1723526395,  
 "last\_full\_scan\_complete\_time": 1723526380  
 }  
}

**常見 metric 類型:**

* **硬體診斷**: temperature, cpu\_usage, memory\_usage, disk\_usage, fan\_speed
* **網路診斷**: interface.eth0.rx\_bytes, interface.eth0.tx\_bytes, ping\_latency, bandwidth\_usage
* **WiFi 診斷**: wifi.scan\_result, wifi.roam\_candidate, wifi.connection\_quality, wifi.rssi, wifi.channel\_utilization
* **應用診斷**: response\_time, error\_rate, queue\_depth, connection\_count
* **IoT 特定**: battery\_voltage, humidity, power\_consumption, signal\_strength

高頻診斷資料應分 metric 發布以降低傳輸成本。

### 9.3 `evt/{event\_type}`（事件/告警）

**Topic**

rtk/v1/{tenant}/{site}/{device\_id}/evt/{event\_type}

**Payload（範例：system.error）**

{  
 "schema": "evt.system.error/1.0",  
 "ts": 1723526401,  
 "seq": 1023,  
 "severity": "warning",  
 "error\_code": "HIGH\_TEMPERATURE",  
 "message": "CPU temperature exceeded 80°C",  
 "source": "thermal\_monitor",  
 "details": {  
 "current\_temp": 82.5,  
 "threshold": 80.0,  
 "location": "cpu\_core\_0"  
 }  
}

**常見 event\_type 類型:**

* **系統診斷**: system.error, system.warning, system.recovery
* **硬體事件**: hardware.fault, hardware.overheat, power.failure
* **網路事件**: network.disconnected, network.latency\_high, interface.down
* **WiFi 事件**: wifi.roam\_triggered, wifi.scan\_failed, wifi.signal\_weak, wifi.ap\_changed
* **應用事件**: service.crashed, memory.low, disk.full

### 9.4 `attr`（retained，裝置屬性）

**Topic**

rtk/v1/{tenant}/{site}/{device\_id}/attr

**Payload（範例）**

{  
 "schema": "attr/1.0",  
 "model": "TB-Hub-8K",  
 "sn": "A1B2C3",  
 "hw": "revC",  
 "schema\_state": "1.0",  
 "cap": { "light": true, "ports": 8 }  
}

**欄位說明**

* schema: 訊息格式版本標識（必要的共通欄位）
* model: 設備型號，用於識別硬體規格和相容性
* sn: 設備序號，用於保固查詢和硬體追蹤
* hw: 硬體版本，如 PCB 版本，用於韌體相容性判斷
* schema\_state: 此設備支援的 state 訊息格式版本
* cap: 設備能力描述，讓 Controller 知道設備支援哪些功能
* light: 是否支援燈控功能
* ports: 設備的埠數量

## 10. 下行命令（Controller → Device）

所有命令統一走 cmd/req，裝置收到即回 cmd/ack，完成後回 cmd/res。

### 10.1 `cmd/req`（Controller → Device）

**Topic**

rtk/v1/{tenant}/{site}/{device\_id}/cmd/req

**Payload**

{  
 "id": "c-1001",  
 "op": "light.set",  
 "schema": "cmd.light.set/1.0",  
 "args": { "on": true, "brightness": 80 },  
 "timeout\_ms": 5000,  
 "expect": "result",   
 "reply\_to": null,  
 "ts": 1723526400  
}

* id：命令唯一識別，去重與關聯 ack/res。
* op：命令名稱（資源導向，如 device.reboot、net.wifi.config）。

|  |  |  |
| --- | --- | --- |
| \* expect：`ack | result | none`。 |

\* `reply\_to`：如需回到不同 topic 可覆寫（一般為空）。

### 10.2 `cmd/ack`（Device → Controller）

**Topic**

rtk/v1/{tenant}/{site}/{device\_id}/cmd/ack

**Payload**

{  
 "id": "c-1001",  
 "ts": 1723526401,  
 "accepted": true,  
 "err": null  
}

### 10.3 `cmd/res`（Device → Controller）

**Topic**

rtk/v1/{tenant}/{site}/{device\_id}/cmd/res

**Payload（成功）**

{  
 "id": "c-1001",  
 "ts": 1723526403,  
 "ok": true,  
 "result": { "on": true, "brightness": 80 },  
 "progress": null,  
 "err": null  
}

**Payload（失敗）**

{  
 "id": "c-1001",  
 "ts": 1723526403,  
 "ok": false,  
 "result": null,  
 "err": { "code": "E\_UNSUPPORTED", "msg": "capability not available" }  
}

* 長任務可在處理期間定期發布含 progress 的 res（0\~100 或階段字串），最後再送最終 res。

## 11. 典型命令清單（建議命名）

|  |  |  |  |
| --- | --- | --- | --- |
| op | 說明 | args 範例 | 結果 result 範例 |
| light.set | 設定燈狀態 | { "on": true, "brightness": 80, "color": "#ffaa00" } | { "on": true, "brightness": 80 } |
| device.reboot | 重新啟動 | {} | { "uptime\_s": 0 } |
| report.push | 立即回報特定資料 | { "what": ["state", "telemetry.temperature"] } | { "pushed": ["state", "telemetry.temperature"] } |
| diagnosis.get | 取得診斷資料 | { "type": "wifi", "detail\_level": "full" } | 設備相依的診斷資料結構 |
| fw.update | 韌體更新 | { "version": "1.2.4", "url": "https://...", "sha256": "..." } | { "phase": "done", "version": "1.2.4" } |
| net.wifi.config | 設定 Wi‑Fi | { "ssid": "x", "psk": "y" } | { "connected": true, "ip": "..." } |

命令的實際清單由各產品線維護，並以 schema 版本化。

## 12. 診斷資料傳輸機制

### 12.1 主動診斷事件傳輸

設備在檢測到異常狀況時，會主動透過 evt/{event\_type} 發送診斷事件，包含：

* 觸發條件與嚴重程度
* 初步診斷資訊與環境參數
* 建議後續動作

### 12.2 被動詳細診斷請求

Controller 可透過 diagnosis.get 命令主動請求設備回報特定類型的詳細診斷資料。設備收到診斷命令後，應立即透過 cmd/res 回傳當前的完整診斷狀態。

### 12.3 診斷命令格式

**Command Request:**

{  
 "id": "diag-001",  
 "op": "diagnosis.get",  
 "schema": "cmd.diagnosis.get/1.0",  
 "args": {  
 "type": "wifi",  
 "detail\_level": "full",  
 "include\_history": false  
 },  
 "timeout\_ms": 10000,  
 "expect": "result",  
 "ts": 1723526400  
}

**Command Response (範例 - WiFi 設備):**

{  
 "id": "diag-001",  
 "ts": 1723526401,  
 "ok": true,  
 "result": {  
 "diagnosis\_type": "wifi",  
 "device\_type": "wifi\_router",  
 "data": {  
 "current\_connection": {  
 "bssid": "aa:bb:cc:dd:ee:ff",  
 "rssi": -45,  
 "channel": 6,  
 "link\_speed": 150  
 },  
 "scan\_results": [  
 {  
 "bssid": "11:22:33:44:55:66",  
 "ssid": "AP\_Name\_1",  
 "rssi": -42,  
 "channel": 6  
 }  
 ],  
 "roam\_history": [  
 {  
 "timestamp": 1723526300,  
 "from\_bssid": "ff:ee:dd:cc:bb:aa",  
 "to\_bssid": "aa:bb:cc:dd:ee:ff",  
 "reason": "signal\_weak"  
 }  
 ]  
 }  
 }  
}

### 12.3 設備相依性

* **診斷資料內容**: 每種設備類型的診斷資料結構完全不同
* **支援的診斷類型**: 各設備根據硬體能力支援不同的 type 參數
* **回應時間**: 複雜診斷可能需要較長處理時間，建議設定適當的 timeout\_ms

### 12.4 常見診斷類型

* wifi: WiFi 連線狀態、掃描結果、漫遊記錄
* network: 網路介面統計、路由表、連線狀態
* system: CPU、記憶體、磁碟使用狀況
* hardware: 硬體感測器資料、溫度、風扇轉速
* application: 應用程式狀態、服務運行情況

## 13. 錯誤碼建議

|  |  |
| --- | --- |
| 代碼 | 說明 |
| E\_TIMEOUT | 命令處理逾時 |
| E\_UNSUPPORTED | 裝置不支援該 op 或參數 |
| E\_BUSY | 裝置忙碌，無法處理 |
| E\_INVALID\_ARGS | 參數格式錯誤 |
| E\_FORBIDDEN | 權限不足或 ACL 拒絕 |
| E\_INTERNAL | 內部錯誤 |

## 14. 版本控管

* **Topic 版本**：rtk/v1/...；破壞式變更升 v2。
* **Schema 版本**：每種 payload schema 採語意化版本（SemVer）。
* **相容原則**：
* 裝置/後端對未知欄位需忽略。
* 新增欄位為不破壞性；移除/改義需升大版並逐步淘汰。

## 15. 順序、重送與冪等

* **命令去重**：裝置應以 id 做去重，對重複 id 只執行一次，重傳先回覆既有結果。
* **超時與重試**：Controller 端可在 timeout\_ms 到期後重試；重試必須沿用同一個 id。
* **送達順序**：MQTT 僅保證同一連線與同一 topic 的消息順序；跨 topic 需以 ts/seq 校正。

## 16. 監控與審計建議

* 監控訂閱：rtk/v1/+/+/+/cmd/#、rtk/v1/+/+/+/evt/#、rtk/v1/+/+/+/lwt。
* 寫入審計：所有 cmd 的 req/ack/res 需落庫（含 tenant/site/device\_id/id/op/ts）。
* 異常告警：
* 同一 device\_id 多重連線（疑似複製）。
* 過久未更新 state 或頻繁 offline。

## 17. 測試案例（最低集合）

1. **裝置上線／下線**：

* 上線發布 lwt: online（retained），Broker 斷線自動發布 offline。

1. **狀態 retained**：

* 新訂閱者立即收到最後一筆 state/attr。

1. **命令 RPC**：

* Controller 發 cmd/req → 裝置回 ack → 完成回 res（成功/失敗皆測）。

1. **重試與冪等**：

* Controller 重送相同 id，裝置不得重複執行，需回覆既有結果。

1. **群組命令**（如使用）：

* 群組下發 → 裝置各自回到自身 ack/res。

1. **ACL 驗證**：

* 裝置嘗試超權限 publish/subscribe 應被拒絕。

## 18. JSON Schema（簡化示例）

下列為示例片段，實務可拆成多檔版本化維護。

### 17.1 `state/1.0`

{  
 "$schema": "https://json-schema.org/draft/2020-12/schema",  
 "title": "state/1.0",  
 "type": "object",  
 "required": ["schema", "ts", "health"],  
 "properties": {  
 "schema": {"const": "state/1.0"},  
 "ts": {"type": "number"},  
 "health": {"enum": ["ok", "warn", "error"]},  
 "fw": {"type": "string"},  
 "uptime\_s": {"type": "number"},  
 "battery\_v": {"type": "number"},  
 "net": {  
 "type": "object",  
 "properties": {  
 "rssi": {"type": "number"},  
 "ip": {"type": "string"}  
 },  
 "additionalProperties": true  
 }  
 },  
 "additionalProperties": true  
}

### 17.2 `cmd.light.set/1.0`

{  
 "$schema": "https://json-schema.org/draft/2020-12/schema",  
 "title": "cmd.light.set/1.0",  
 "type": "object",  
 "required": ["id", "op", "schema", "args"],  
 "properties": {  
 "id": {"type": "string"},  
 "op": {"const": "light.set"},  
 "schema": {"const": "cmd.light.set/1.0"},  
 "args": {  
 "type": "object",  
 "properties": {  
 "on": {"type": "boolean"},  
 "brightness": {"type": "number", "minimum": 0, "maximum": 100},  
 "color": {"type": "string"}  
 },  
 "additionalProperties": false  
 },  
 "timeout\_ms": {"type": "number"},  
 "expect": {"enum": ["ack", "result", "none"]},  
 "reply\_to": {"type": ["string", "null"]},  
 "ts": {"type": "number"}  
 },  
 "additionalProperties": true  
}

## 19. 實作指南（裝置端）

1. 以 clientId=device\_id 連線 Broker，設置 LWT offline（retained）。
2. 上線後發布 lwt=online 與最新 attr/state。
3. 訂閱 cmd/req（以及群組 req，如有）。
4. 收到命令：

* 解析 payload → 立刻回 ack（含 id）。
* 執行命令；長任務定期回 res（含 progress）。
* 完成後回最終 res（ok=true/false）。

1. 週期性發布 state 與必要 telemetry，異常以 evt/\* 通報。

## 20. 實作指南（Controller/後端）

1. 封裝 sendCommand(op, args, device\_id, timeout)：

* 產生 id → 發布 cmd/req。
* 等待 ack，超時重試（同 id）。
* 視 expect 等待 res，處理超時與最終態。

1. 日誌/審計：完整記錄 req/ack/res 與錯誤碼。
2. 指標/告警：命令成功率、延遲分佈、裝置上線率、事件頻度等。

## 21. 範例訂閱樣式

* 全租戶所有命令流：rtk/v1/+/+/+/cmd/#
* 某站台所有裝置狀態：rtk/v1/{tenant}/{site}/+/state
* 某裝置所有遙測：rtk/v1/{tenant}/{site}/{device\_id}/telemetry/#

## 22. WiFi 診斷實際應用範例

本章節基於真實的 WiFi 診斷資料，展示完整的 MQTT 診斷通訊流程，涵蓋漫遊問題、連線失敗、網路異常等典型場景。

### 23.1 漫遊問題診斷範例

#### 情境描述

辦公室 AP office-ap-001 檢測到 RSSI 降至 -75dBm 持續 10 秒，但未觸發漫遊機制。

#### 完整 MQTT 流程

**步驟 1: 事件觸發**

Topic: rtk/v1/office/floor1/office-ap-001/evt/wifi.roam\_miss

{  
 "schema": "evt.wifi.roam\_miss/1.0",  
 "ts": 1723526401000,  
 "severity": "warning",  
 "trigger\_info": {  
 "rssi\_threshold": -70,  
 "duration\_ms": 10000,  
 "cooldown\_ms": 300000  
 },  
 "diagnosis": {  
 "internal\_scan\_skip\_count": 3,  
 "environment\_ap\_count": 8,  
 "candidate\_ap\_count": 2,  
 "current\_bssid": "aa:bb:cc:dd:ee:ff",  
 "current\_rssi": -75,  
 "candidates": {  
 "5g": {  
 "bssid": "11:22:33:44:55:66",  
 "rssi": -42,  
 "channel": 36  
 },  
 "6g": {  
 "bssid": "77:88:99:aa:bb:cc",  
 "rssi": -48,  
 "channel": 37  
 }  
 },  
 "scan\_timing": {  
 "last\_scan\_time": 1723526395000,  
 "last\_full\_scan\_complete\_time": 1723526380000  
 }  
 }  
}

**步驟 2: Controller 請求詳細診斷**

Topic: rtk/v1/office/floor1/office-ap-001/cmd/req

{  
 "id": "roam-diag-001",  
 "op": "diagnosis.get",  
 "schema": "cmd.diagnosis.get/1.0",  
 "args": {  
 "type": "wifi.roaming",  
 "detail\_level": "full",  
 "include\_history": true,  
 "include\_rf\_stats": true  
 },  
 "timeout\_ms": 15000,  
 "expect": "result",  
 "ts": 1723526402000  
}

**步驟 3: Device 回傳詳細診斷結果**

Topic: rtk/v1/office/floor1/office-ap-001/cmd/res

{  
 "id": "roam-diag-001",  
 "ts": 1723526403500,  
 "ok": true,  
 "result": {  
 "diagnosis\_type": "wifi.roaming",  
 "data": {  
 "roaming\_analysis": {  
 "trigger\_reasons": ["poor\_signal\_quality", "scan\_skip\_detected"],  
 "skip\_analysis": {  
 "total\_skips\_10sec": 3,  
 "skip\_reasons": ["scan\_in\_progress", "channel\_switch\_delay"],  
 "last\_successful\_scan": 1723526395000  
 }  
 },  
 "current\_connection": {  
 "bssid": "aa:bb:cc:dd:ee:ff",  
 "ssid": "OfficeWiFi-5G",  
 "rssi": -75,  
 "channel": 149,  
 "bandwidth": "80MHz",  
 "connection\_duration\_ms": 1847500  
 },  
 "roam\_candidates": [  
 {  
 "band": "5G",  
 "bssid": "11:22:33:44:55:66",  
 "rssi": -42,  
 "channel": 36,  
 "load\_percentage": 25,  
 "roam\_score": 85  
 },  
 {  
 "band": "6G",   
 "bssid": "77:88:99:aa:bb:cc",  
 "rssi": -48,  
 "channel": 37,  
 "load\_percentage": 15,  
 "roam\_score": 92  
 }  
 ],  
 "rf\_statistics": {  
 "interference\_level": "moderate",  
 "channel\_utilization\_percent": 45,  
 "retry\_rate\_percent": 12.5  
 }  
 }  
 }  
}

### 23.2 連線失敗診斷範例

#### 情境描述

筆記型電腦 laptop-005 嘗試連線企業 WiFi 時在 WPA3 SAE 認證階段失敗。

**事件觸發**

Topic: rtk/v1/corporate/building-a/laptop-005/evt/wifi.connect\_fail

{  
 "schema": "evt.wifi.connect\_fail/1.0",  
 "ts": 1723526501000,  
 "severity": "error",  
 "connection\_info": {  
 "role\_type": "STA",  
 "target\_bssid": "cc:dd:ee:ff:00:11",  
 "ssid": "CorporateNet-5G",  
 "security\_type": "WPA3\_SAE"  
 },  
 "failure\_details": {  
 "join\_status": "AUTH\_TIMEOUT",  
 "tx\_fail\_category": "AUTH",  
 "auth\_mode": "WPA3SAE",  
 "auth\_algo": "SAE",  
 "response\_status\_code": 0,  
 "failure\_stage": "authentication"  
 }  
}

**診斷結果** (簡化)

Topic: rtk/v1/corporate/building-a/laptop-005/cmd/res

{  
 "id": "connect-diag-002",  
 "ok": true,  
 "result": {  
 "data": {  
 "connection\_stages": {  
 "authentication": {  
 "status": "timeout",  
 "duration\_ms": 2500,  
 "sae\_exchange": {  
 "commit\_sent": true,  
 "commit\_response\_received": false  
 }  
 }  
 },  
 "failure\_analysis": {  
 "primary\_cause": "sae\_timeout",  
 "contributing\_factors": ["ap\_sae\_processing\_delay", "possible\_ap\_overload"],  
 "recommendations": ["retry\_with\_different\_ap", "check\_ap\_load\_balance"]  
 }  
 }  
 }  
}

### 23.3 ARP 遺失診斷範例

#### 情境描述

智能攝影機 smart-camera-003 偵測到連續 2 次 ARP response 未收到。

**事件觸發**

Topic: rtk/v1/factory/workshop/smart-camera-003/evt/wifi.arp\_loss

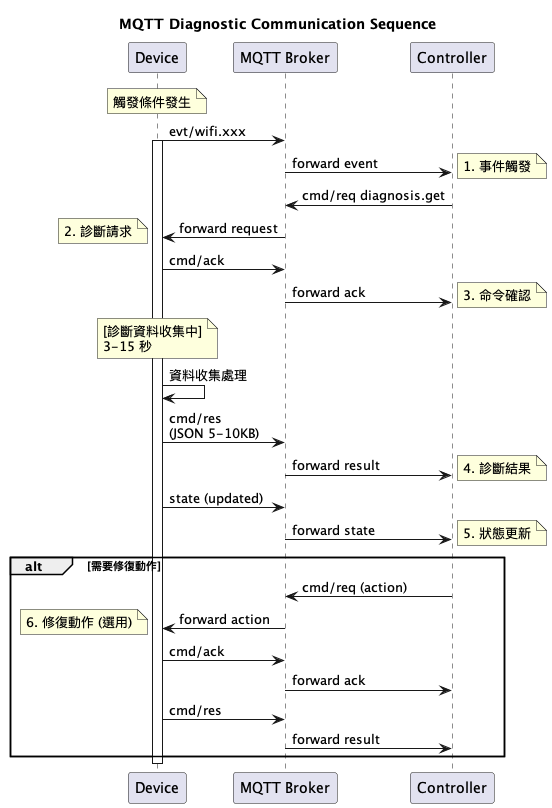
{  
 "schema": "evt.wifi.arp\_loss/1.0",  
 "ts": 1723526601000,  
 "severity": "warning",  
 "trigger\_info": {  
 "consecutive\_loss\_count": 2,  
 "cooldown\_ms": 300000  
 },  
 "network\_info": {  
 "current\_bssid": "bb:cc:dd:ee:ff:00",  
 "current\_rssi": -67,  
 "channel\_hw\_match": true,  
 "scan\_in\_progress": false  
 },  
 "arp\_statistics": {  
 "source\_ip": "192.168.10.203",  
 "destination\_ip": "192.168.10.1",  
 "req\_tx\_fail\_count": 2,  
 "req\_count": 5,  
 "rsp\_count": 3,  
 "success\_rate": 0.6  
 }  
}

**診斷分析結果** (簡化)

{  
 "result": {  
 "data": {  
 "root\_cause\_analysis": {  
 "primary\_causes": ["channel\_interference", "ap\_load\_fluctuation"],  
 "probability\_scores": {  
 "rf\_interference": 0.8,  
 "ap\_overload": 0.6,  
 "network\_congestion": 0.7  
 }  
 },  
 "rf\_diagnostics": {  
 "channel\_analysis": {  
 "channel\_utilization": 65,  
 "interference\_sources": [  
 {  
 "type": "industrial\_equipment",  
 "strength": "moderate",  
 "estimated\_impact": "medium"  
 }  
 ]  
 }  
 }  
 }  
 }  
}

### 23.4 時序圖與通訊流程

#### 典型診斷流程



#### 訂閱模式建議

# Controller 全域監控

rtk/v1/+/+/+/evt/wifi.# # 所有 WiFi 事件

rtk/v1/+/+/+/lwt # 設備上下線狀態

rtk/v1/+/+/+/state # 設備健康狀態

# 特定場域監控

rtk/v1/office/+/+/evt/# # 辦公室所有事件

rtk/v1/factory/+/+/evt/wifi.# # 工廠 WiFi 事件

# 設備類型監控

rtk/v1/+/+/smart-camera-+/evt/# # 智能攝影機事件

### 23.5 診斷資料結構定義

#### WiFi 漫遊候選 AP 結構

{  
 "wifi\_roam\_candidate": {  
 "bssid": "string (MAC address format)",  
 "rssi": "integer (-100 to 0)",  
 "channel": "integer (1-165)",  
 "load\_percentage": "integer (0-100)",  
 "roam\_score": "integer (0-100)"  
 }  
}

#### 連線失敗分析結構

{  
 "connection\_failure\_analysis": {  
 "primary\_cause": "enum [auth\_timeout, assoc\_timeout, key\_install\_fail]",  
 "failure\_stage": "enum [beacon\_detection, authentication, association, four\_way\_handshake]",  
 "contributing\_factors": ["array of strings"],  
 "recommendations": ["array of strings"]  
 }  
}

#### ARP 統計結構

{  
 "arp\_statistics": {  
 "source\_ip": "string (IPv4)",  
 "destination\_ip": "string (IPv4)",  
 "req\_count": "integer",  
 "rsp\_count": "integer",   
 "success\_rate": "number (0-1)",  
 "avg\_response\_time\_ms": "number"  
 }  
}

### 23.6 實作指南

#### Device 端實作要點

1. **事件觸發條件**: 依據個別單位資料中的觸發條件實作
2. **診斷資料收集**: 結合 RF 統計、流量分析、環境掃描
3. **冷卻機制**: 5 分鐘內相同事件不重複發送
4. **資料結構**: 遵循 JSON Schema 定義

#### Controller 端實作要點

1. **智能診斷請求**: 根據事件類型請求相應的診斷資料
2. **根因分析**: 利用診斷結果進行自動化分析
3. **修復建議**: 提供可執行的修復動作命令
4. **趨勢監控**: 追蹤診斷事件的模式和頻率

## 23. 變更紀錄（Changelog）

* **1.0**：首版，定義統一路徑、RPC 命令模型、Retained/LWT、安全與 ACL、群組命令與 Shadow 選項、JSON Schema 範例、WiFi 診斷實際應用範例。

# 附錄

## A. 系統架構與元件關係

*系統整體架構圖，說明 Device、Controller、MQTT Broker 之間的關係與資料流向*

MQTT Diag System Architecture Diagram

=========================================

![MQTT Diag System Architecture](system\_architecture\_complete.png)

## 系統架構與元件關係

MQTT Diag 系統採用中心化的訊息代理架構，由以下核心元件組成：

### 核心元件

1. \*\*Controller (控制器)\*\*

- 雲端或本地部署的控制服務

- 負責發送診斷命令與收集診斷資料

- 監控設備健康狀態與事件

2. \*\*MQTT Broker (訊息代理)\*\*

- 中央訊息路由器

- 處理 retained 訊息機制

- 管理 LWT (Last Will Testament) 訊息

3. \*\*各類診斷設備\*\*

- WiFi 路由器：提供 WiFi 診斷、漫遊事件

- 伺服器：系統指標、效能資料

- IoT 感測器：環境資料、電池狀態

- 網路交換器：埠統計、連線事件

### 訊息流向

1. \*\*上行通訊 (Device → Controller)\*\*

- state: 設備狀態摘要

- telemetry: 遙測資料與效能指標

- evt: 事件、告警、診斷事件

- attr: 設備屬性資訊

2. \*\*下行通訊 (Controller → Device)\*\*

- cmd/req: 診斷命令請求

3. \*\*命令回應 (Device → Controller)\*\*

- cmd/ack: 命令接收確認

- cmd/res: 命令執行結果

Topic Structure:

rtk/v1/{tenant}/{site}/{device\_id}/

├── state (retained)

├── telemetry/

│ ├── wifi.scan\_result

│ ├── cpu\_usage

│ └── temperature

├── evt/

│ ├── wifi.roam\_triggered

│ ├── system.error

│ └── hardware.fault

├── attr (retained)

├── cmd/

│ ├── req (downlink)

│ ├── ack (uplink)

│ └── res (uplink)

└── lwt (retained)

Key Components:

===============

1. MQTT Broker:

- Central message router

- Handles retained messages

- Manages LWT messages

2. Controller (Cloud/Local):

- Sends diagnosis commands

- Collects diagnostic data

- Monitors device health

3. Devices (Various Types):

- WiFi Router: WiFi diagnostics, roaming events

- Server: System metrics, performance data

- IoT Sensor: Environmental data, battery status

- Network Switch: Port statistics, link events

4. Message Types:

- state: Device health summary

- telemetry: Metrics and performance data

- evt: Events, alerts, errors

- attr: Device attributes and capabilities

- cmd: Command request/acknowledgment/response

- lwt: Last Will Testament for online/offline status

Communication Patterns:

======================

1. Periodic Reporting:

Devices regularly publish state and telemetry data

2. Event-Driven:

Devices publish events when specific conditions occur

3. On-Demand Diagnosis:

Controller requests specific diagnostic data using diagnosis.get command

4. Device Lifecycle:

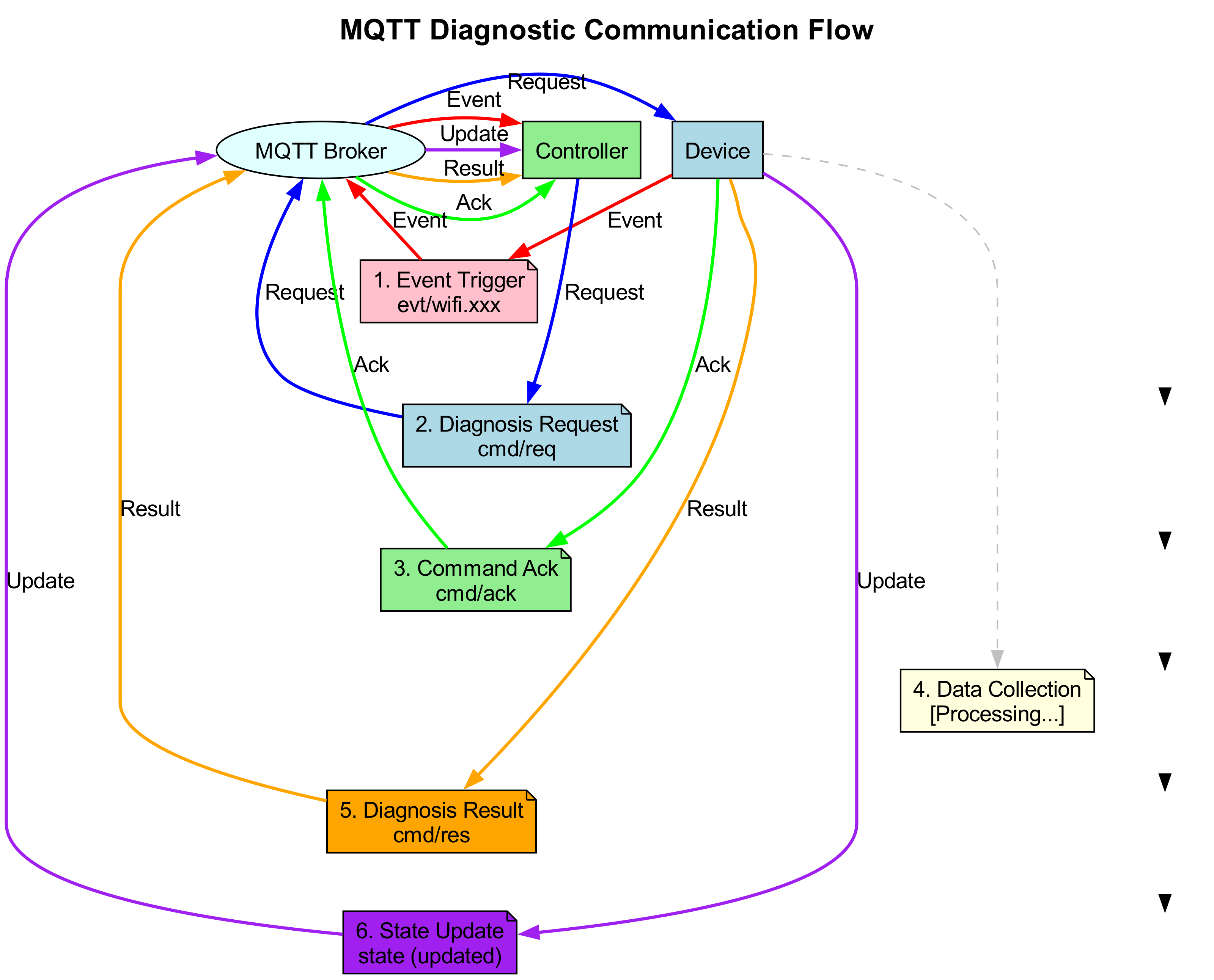
LWT messages track device online/offline status

## B. MQTT 通訊流程與時序圖

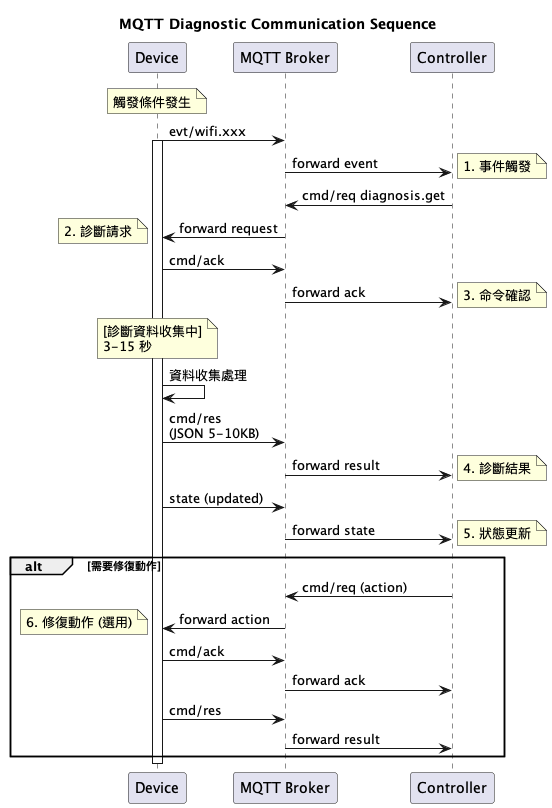
*詳細的 MQTT 訊息交換時序圖，包含各種診斷場景的完整通訊流程*

# MQTT WiFi 診斷通訊流程與時序圖

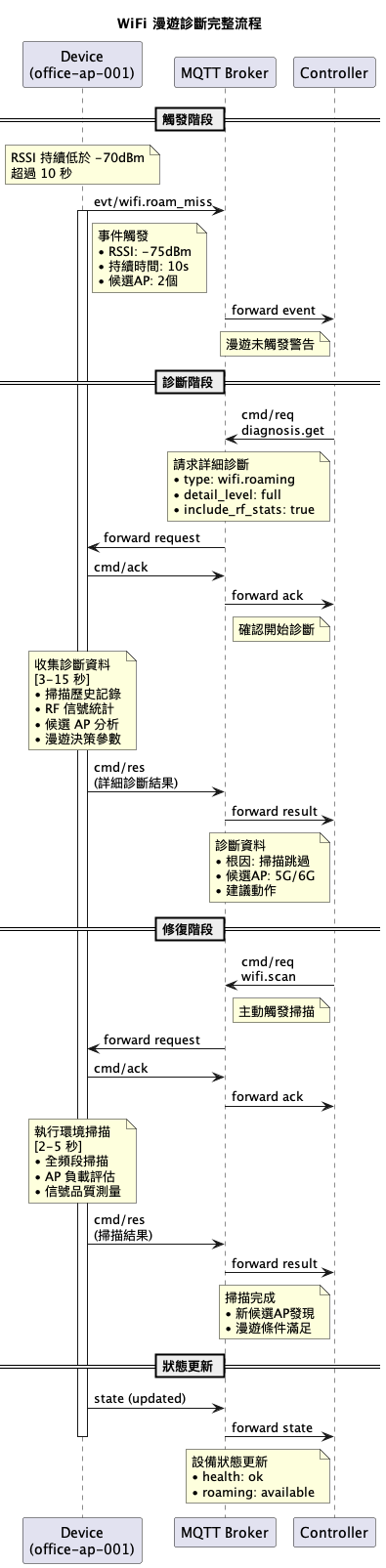
## 1. 通用診斷流程時序圖



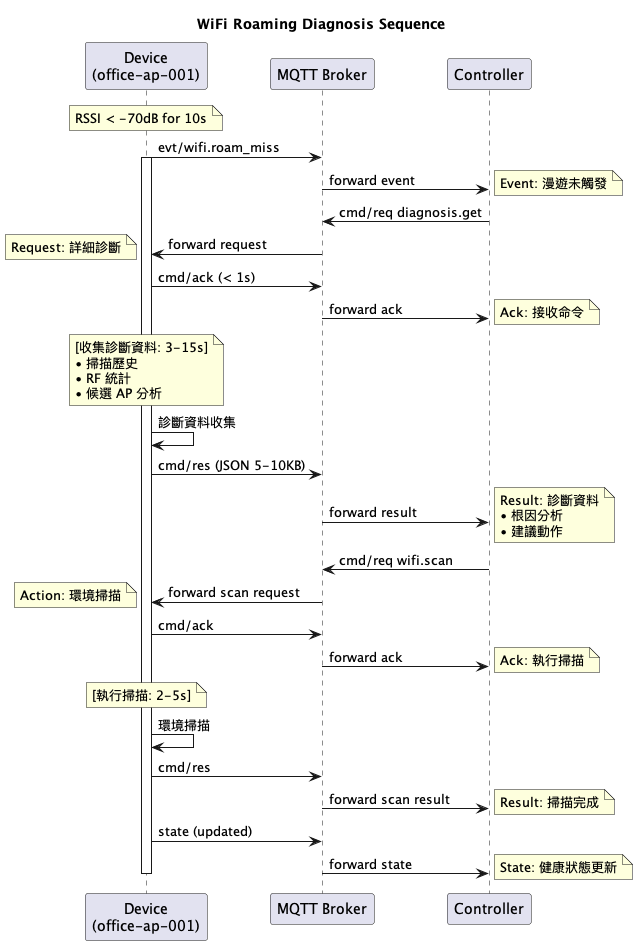
**詳細序列圖**：



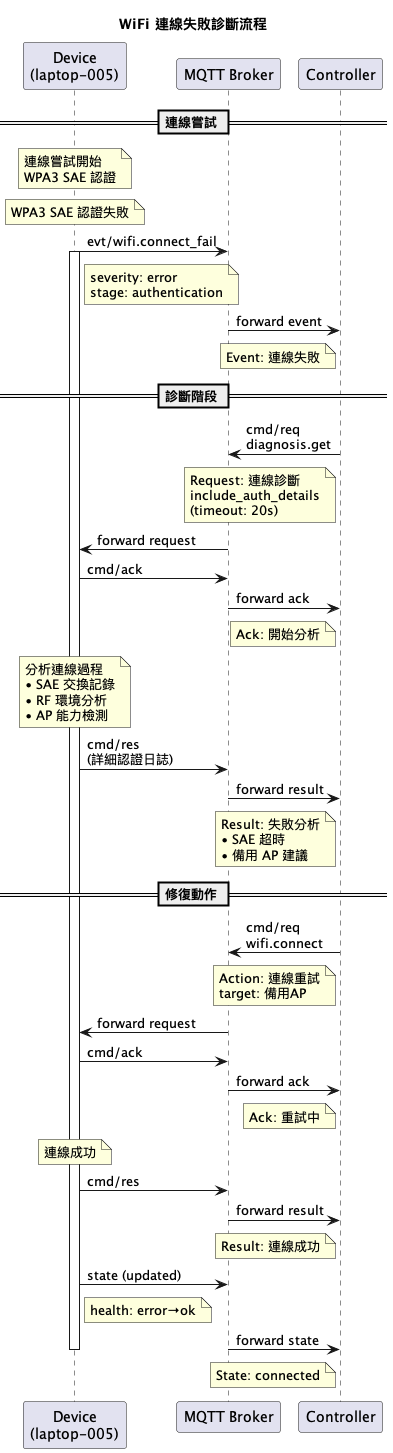
## 2. 漫遊診斷完整流程



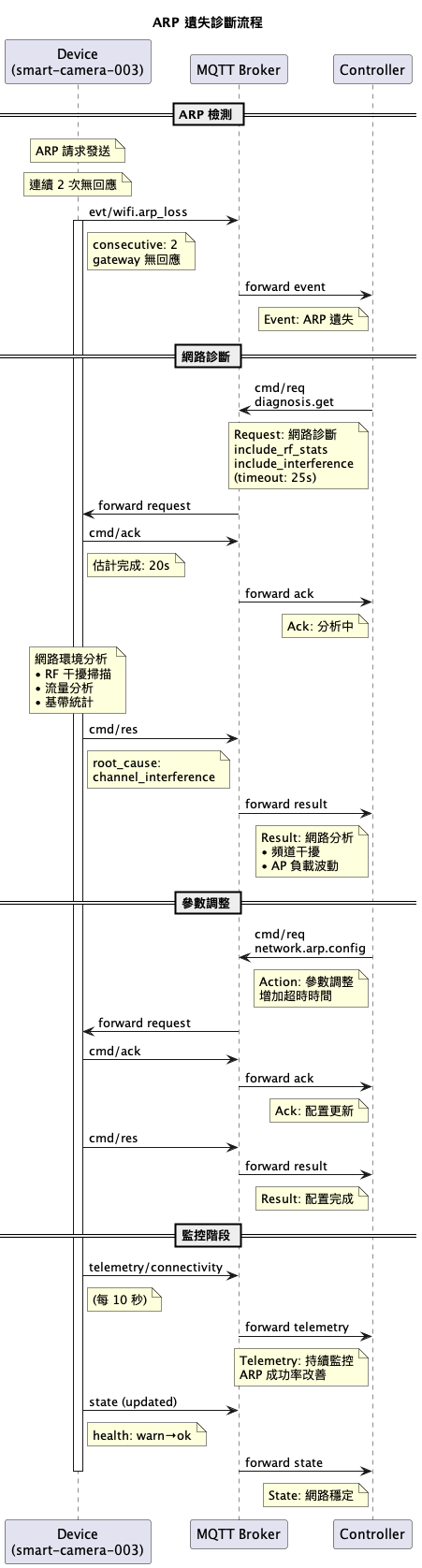
**詳細序列圖**：



## 3. 連線失敗診斷流程



## 4. ARP 遺失診斷流程



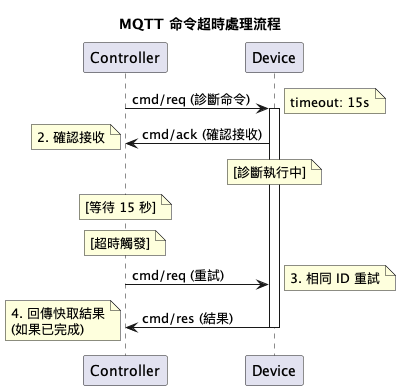
## 5. 訂閱模式與 Topic 路由

### 5.1 Controller 訂閱策略

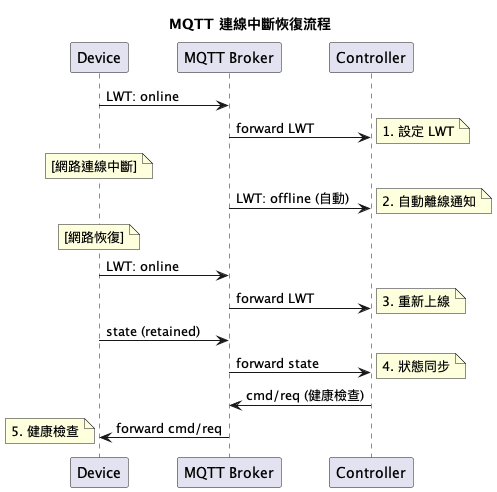
全域監控:  
├── rtk/v1/+/+/+/evt/# # 所有事件  
├── rtk/v1/+/+/+/lwt # 設備上下線  
└── rtk/v1/+/+/+/state # 設備狀態  
  
特定場域監控:  
├── rtk/v1/office/+/+/evt/# # 辦公室事件  
├── rtk/v1/factory/+/+/evt/wifi.# # 工廠 WiFi 事件  
└── rtk/v1/corporate/+/+/cmd/ack # 企業命令確認  
  
設備類型監控:  
├── rtk/v1/+/+/smart-camera-+/evt/# # 智能攝影機  
├── rtk/v1/+/+/laptop-+/evt/wifi.# # 筆記型電腦 WiFi  
└── rtk/v1/+/+/office-ap-+/telemetry/# # 辦公室 AP 遙測

## 6. 錯誤處理與恢復流程

### 6.1 命令超時處理



### 6.2 連線中斷恢復



## 7. 效能最佳化建議

### 7.1 訊息大小控制

* **Event 訊息**: < 1KB (關鍵資訊)
* **Diagnostic 結果**: < 10KB (詳細分析)
* **Telemetry**: < 500B (定期指標)
* **State**: < 2KB (完整狀態)

### 7.2 頻率控制

* **Events**: 立即發送 + 5分鐘冷卻期
* **Diagnostics**: 按需請求，最大 1 次/分鐘
* **Telemetry**: 10-60 秒間隔
* **State**: 30-60 秒或狀態變更時

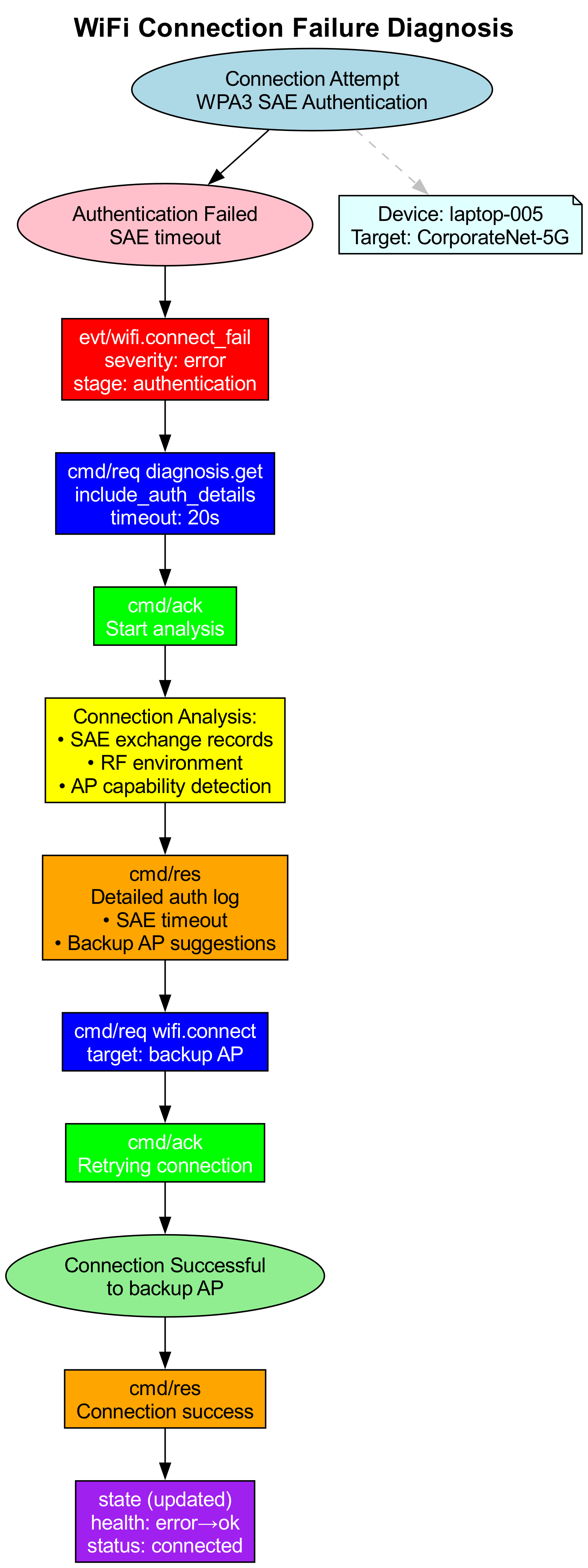
### 7.3 批次處理

{  
 "id": "batch-diag-001",  
 "op": "diagnosis.batch\_get",  
 "args": {  
 "types": ["wifi.roaming", "wifi.interference", "wifi.performance"],  
 "correlation\_id": "network\_issue\_001"  
 }  
}

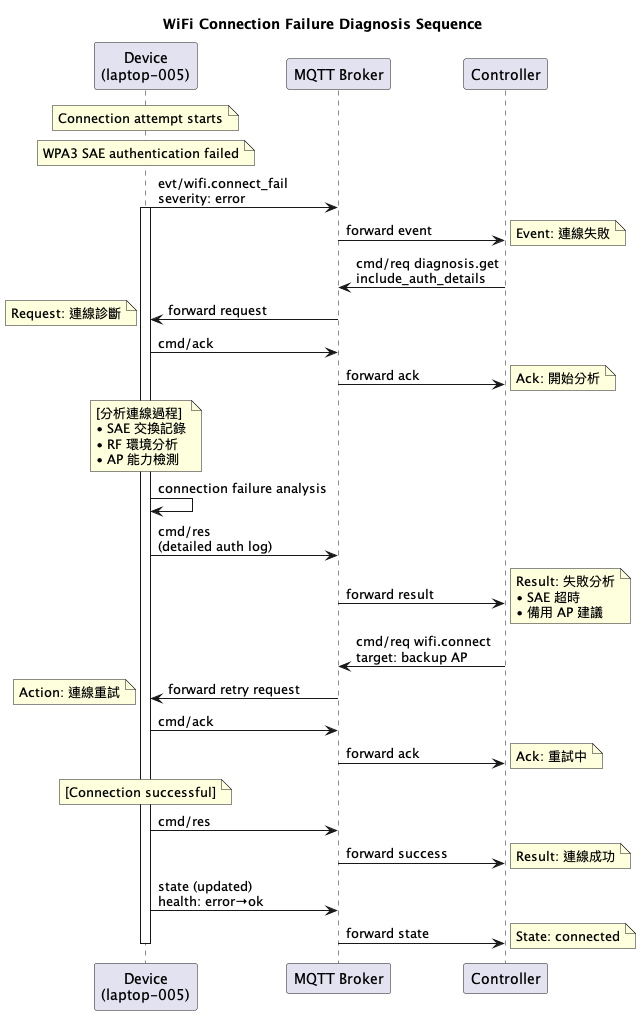
## C. WiFi 連線失敗診斷範例

*最常見的連線問題診斷，包含認證失敗、超時等處理流程*

# WiFi 連線失敗診斷完整 MQTT 範例



**詳細序列圖**：



## 情境描述

用戶設備 laptop-005 嘗試連接到企業 WiFi CorporateNet-5G，但在 WPA3 認證階段失敗。

## MQTT 訊息流程

### 1. 連線失敗事件觸發 (Device → Controller)

**Topic**: rtk/v1/corporate/building-a/laptop-005/evt/wifi.connect\_fail

**Retained**: false

{  
 "schema": "evt.wifi.connect\_fail/1.0",  
 "ts": 1723526501000,  
 "severity": "error",  
 "connection\_info": {  
 "role\_type": "STA",  
 "target\_bssid": "cc:dd:ee:ff:00:11",  
 "ssid": "CorporateNet-5G",  
 "security\_type": "WPA3\_SAE"  
 },  
 "failure\_details": {  
 "join\_status": "AUTH\_TIMEOUT",   
 "join\_rx\_count": 18,  
 "tx\_fail\_category": "AUTH",  
 "auth\_mode": "WPA3SAE",  
 "auth\_algo": "SAE",  
 "four\_way\_status": 0,  
 "response\_status\_code": 0,  
 "failure\_stage": "authentication"  
 },  
 "environment": {  
 "rssi": -52,  
 "channel": 44,  
 "bandwidth": "80MHz",  
 "interference\_level": "low"  
 }  
}

### 2. Controller 請求詳細診斷 (Controller → Device)

**Topic**: rtk/v1/corporate/building-a/laptop-005/cmd/req

{  
 "id": "connect-diag-002",  
 "op": "diagnosis.get",  
 "schema": "cmd.diagnosis.get/1.0",  
 "args": {  
 "type": "wifi.connection",  
 "detail\_level": "full",  
 "include\_auth\_details": true,  
 "include\_rf\_analysis": true,  
 "target\_bssid": "cc:dd:ee:ff:00:11"  
 },  
 "timeout\_ms": 20000,  
 "expect": "result",  
 "ts": 1723526502000  
}

### 3. Device 命令確認 (Device → Controller)

**Topic**: rtk/v1/corporate/building-a/laptop-005/cmd/ack

{  
 "id": "connect-diag-002",  
 "ts": 1723526502150,  
 "accepted": true,  
 "err": null  
}

### 4. Device 回傳詳細連線失敗診斷 (Device → Controller)

**Topic**: rtk/v1/corporate/building-a/laptop-005/cmd/res

{  
 "id": "connect-diag-002",  
 "ts": 1723526503800,  
 "ok": true,  
 "result": {  
 "diagnosis\_type": "wifi.connection",  
 "device\_type": "laptop\_client",  
 "collection\_time": 1723526503000,  
 "data": {  
 "connection\_attempt": {  
 "start\_time": 1723526498000,  
 "end\_time": 1723526501000,  
 "total\_duration\_ms": 3000,  
 "attempt\_count": 1,  
 "retry\_count": 0  
 },  
 "target\_ap\_info": {  
 "bssid": "cc:dd:ee:ff:00:11",  
 "ssid": "CorporateNet-5G",  
 "rssi": -52,  
 "channel": 44,  
 "bandwidth": "80MHz",  
 "band": "5G",  
 "security": {  
 "type": "WPA3\_SAE",  
 "akm\_suite": "SAE\_SHA256",  
 "pairwise\_cipher": "CCMP\_128",  
 "group\_cipher": "CCMP\_128",  
 "mgmt\_group\_cipher": "BIP\_CMAC\_128"  
 },  
 "capabilities": {  
 "ht\_supported": true,  
 "vht\_supported": true,  
 "he\_supported": true,  
 "mfp\_capable": true,  
 "mfp\_required": true  
 }  
 },  
 "connection\_stages": {  
 "beacon\_detection": {  
 "status": "success",  
 "duration\_ms": 200,  
 "beacons\_received": 3,  
 "probe\_responses\_received": 2  
 },  
 "authentication": {  
 "status": "timeout",  
 "duration\_ms": 2500,  
 "auth\_algorithm": "SAE",  
 "auth\_transactions": [  
 {  
 "sequence": 1,  
 "timestamp": 1723526498500,  
 "direction": "tx",   
 "status": "sent",  
 "tx\_attempts": 3,  
 "ack\_received": true  
 },  
 {  
 "sequence": 2,  
 "timestamp": 0,  
 "direction": "rx",  
 "status": "timeout",  
 "expected": true,  
 "received": false  
 }  
 ],  
 "sae\_exchange": {  
 "commit\_sent": true,  
 "commit\_response\_received": false,  
 "confirm\_sent": false,  
 "confirm\_response\_received": false,  
 "pwd\_id": null,  
 "rejected\_groups": []  
 }  
 },  
 "association": {  
 "status": "not\_attempted",  
 "reason": "authentication\_failed"  
 },  
 "four\_way\_handshake": {  
 "status": "not\_attempted",  
 "reason": "authentication\_failed"  
 }  
 },  
 "failure\_analysis": {  
 "primary\_cause": "sae\_timeout",  
 "contributing\_factors": [  
 "ap\_sae\_processing\_delay",  
 "possible\_ap\_overload"  
 ],  
 "recommendations": [  
 "retry\_with\_different\_ap",  
 "check\_ap\_load\_balance",  
 "verify\_sae\_configuration"  
 ]  
 },  
 "rf\_environment": {  
 "channel\_info": {  
 "primary\_channel": 44,  
 "secondary\_channel": 48,  
 "center\_frequency": 5230,  
 "bandwidth": "80MHz"  
 },  
 "signal\_quality": {  
 "rssi": -52,  
 "snr": 28,  
 "noise\_floor": -95,  
 "signal\_strength": "good"  
 },  
 "interference": {  
 "level": "low",  
 "sources": ["microwave"],  
 "channel\_utilization": 25,  
 "adjacent\_channel\_interference": false  
 }  
 },  
 "device\_state": {  
 "wifi\_driver\_version": "22.140.1",  
 "firmware\_version": "ucode-36.177a0a2c",  
 "regulatory\_domain": "TW",  
 "power\_management": "disabled",  
 "roaming\_enabled": true,  
 "sae\_h2e\_enabled": true,  
 "pmf\_enabled": true  
 },  
 "network\_scan\_results": [  
 {  
 "bssid": "cc:dd:ee:ff:00:11",  
 "ssid": "CorporateNet-5G",  
 "rssi": -52,  
 "channel": 44,  
 "security": "WPA3\_SAE",  
 "load": "medium"  
 },  
 {  
 "bssid": "cc:dd:ee:ff:00:22",   
 "ssid": "CorporateNet-5G",  
 "rssi": -58,  
 "channel": 48,  
 "security": "WPA3\_SAE",  
 "load": "low"  
 },  
 {  
 "bssid": "cc:dd:ee:ff:00:33",  
 "ssid": "CorporateNet-2G",  
 "rssi": -45,  
 "channel": 6,  
 "security": "WPA2\_PSK",  
 "load": "high"  
 }  
 ]  
 }  
 },  
 "err": null  
}

### 5. 狀態更新反映連線問題 (Device → Controller)

**Topic**: rtk/v1/corporate/building-a/laptop-005/state

**Retained**: true

{  
 "schema": "state/1.0",  
 "ts": 1723526504000,  
 "health": "error",  
 "fw": "ucode-36.177a0a2c",  
 "uptime\_s": 8923,  
 "cpu\_usage": 15.3,  
 "memory\_usage": 68.4,  
 "temperature\_c": 45.2,  
 "wifi\_stats": {  
 "connection\_status": "disconnected",  
 "last\_connected\_ssid": "HomeWiFi",  
 "last\_disconnect\_time": 1723523891000,  
 "connection\_attempts": 1,  
 "connection\_failures": 1,  
 "last\_failure\_reason": "auth\_timeout"  
 },  
 "net": {  
 "interface": "wlan0",  
 "ip": null,  
 "connection\_type": "wifi",  
 "connected": false  
 },  
 "diagnosis": {  
 "last\_event": "wifi.connect\_fail",  
 "last\_event\_time": 1723526501000,  
 "error\_count": 1,  
 "warning\_count": 0,  
 "connectivity\_status": "no\_internet"  
 }  
}

## 診斷分析結果

### 失敗原因分析

1. **SAE 認證超時**: AP 未在預期時間內回應 SAE commit 訊息
2. **AP 負載問題**: 可能的 AP 處理延遲或過載
3. **配置相容性**: SAE 參數設定可能存在不相容

### 建議修復動作

#### 立即動作

1. **嘗試連線備用 AP**:

{  
 "id": "auto-retry-001",  
 "op": "wifi.connect",  
 "schema": "cmd.wifi.connect/1.0",  
 "args": {  
 "ssid": "CorporateNet-5G",  
 "bssid": "cc:dd:ee:ff:00:22",  
 "security": "WPA3\_SAE",  
 "priority": "high",  
 "timeout\_ms": 30000  
 }  
}

#### 長期解決方案

1. **SAE 參數調整**: 檢查 H2E (Hash-to-Element) 設定
2. **AP 負載平衡**: 建議 IT 部門檢查 AP 負載分佈
3. **韌體更新**: 確認裝置與 AP 韌體相容性

### Controller 監控建議

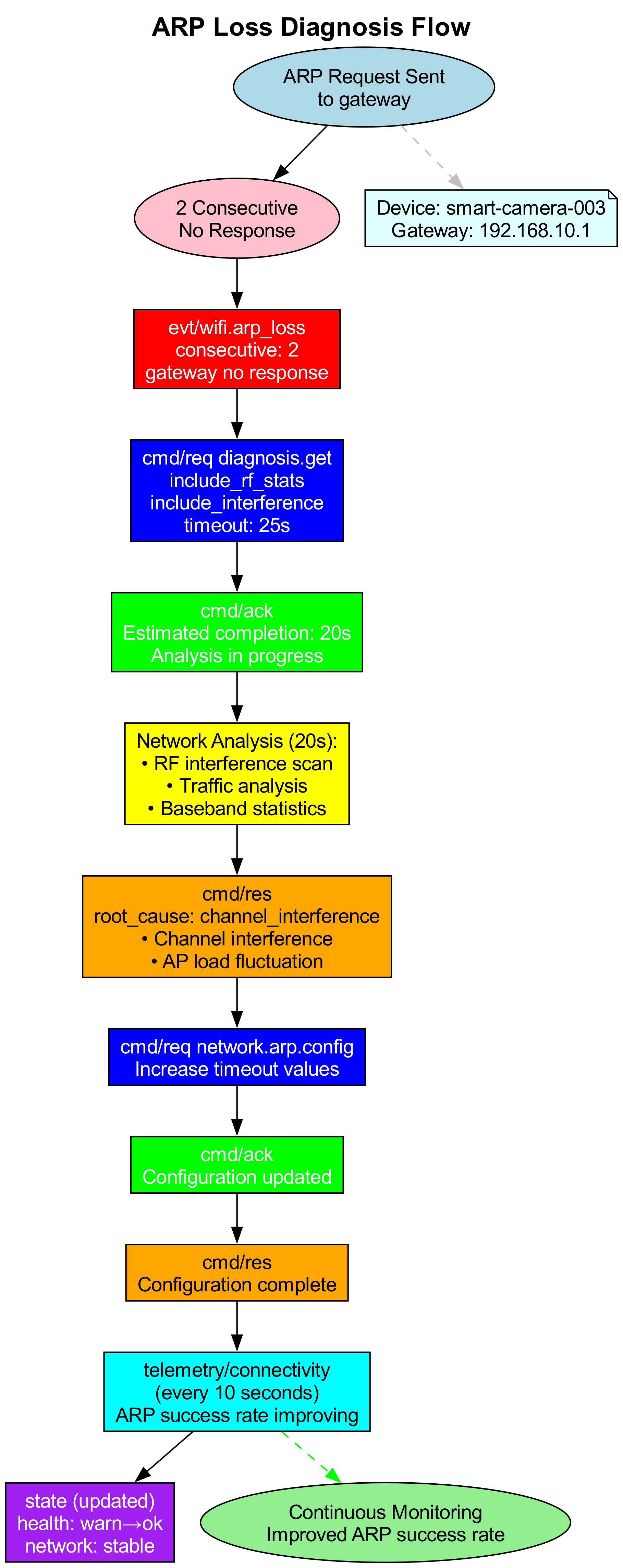
**設定連線重試策略**:

{  
 "id": "retry-policy-001",  
 "op": "policy.set",  
 "schema": "cmd.policy.set/1.0",  
 "args": {  
 "policy\_type": "connection\_retry",  
 "max\_retries": 3,  
 "retry\_interval\_ms": 5000,  
 "fallback\_security": "WPA2\_PSK",  
 "prefer\_less\_loaded\_ap": true  
 }  
}

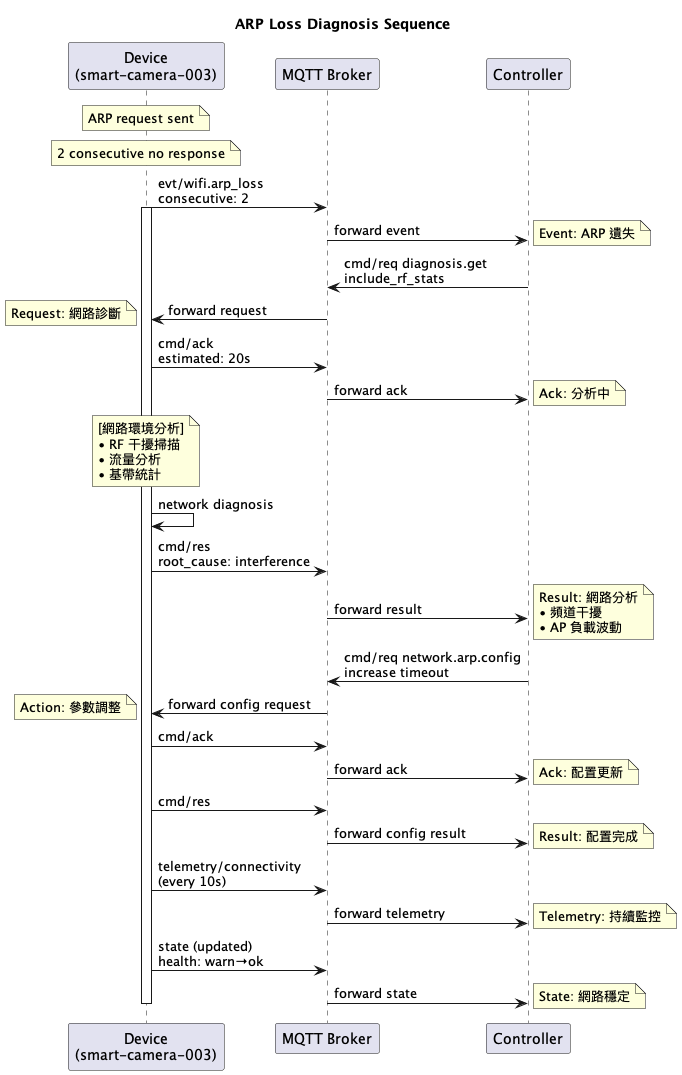
## D. ARP 遺失診斷範例

*網路連線品質診斷，包含封包遺失檢測與網路環境分析*

# ARP 遺失診斷完整 MQTT 範例



**詳細序列圖**：



## 情境描述

IoT 設備 smart-camera-003 在監控網路環境中，連續2次 ARP response 未收到，可能導致網路連線中斷。

## MQTT 訊息流程

### 1. ARP 遺失事件觸發 (Device → Controller)

**Topic**: rtk/v1/factory/workshop/smart-camera-003/evt/wifi.arp\_loss

**Retained**: false

{  
 "schema": "evt.wifi.arp\_loss/1.0",  
 "ts": 1723526601000,  
 "severity": "warning",  
 "trigger\_info": {  
 "consecutive\_loss\_count": 2,  
 "cooldown\_ms": 300000,  
 "detection\_window\_ms": 15000  
 },  
 "network\_info": {  
 "current\_bssid": "bb:cc:dd:ee:ff:00",  
 "current\_rssi": -67,  
 "channel\_hw\_match": true,  
 "scan\_in\_progress": false,  
 "link\_quality": "degraded"  
 },  
 "arp\_statistics": {  
 "source\_ip": "192.168.10.203",  
 "destination\_ip": "192.168.10.1",  
 "req\_tx\_fail\_count": 2,  
 "req\_count": 5,  
 "rsp\_count": 3,  
 "success\_rate": 0.6  
 },  
 "immediate\_indicators": {  
 "packet\_loss\_detected": true,  
 "latency\_increase": true,  
 "throughput\_degraded": false  
 }  
}

### 2. Controller 請求詳細網路診斷 (Controller → Device)

**Topic**: rtk/v1/factory/workshop/smart-camera-003/cmd/req

{  
 "id": "arp-diag-003",  
 "op": "diagnosis.get",  
 "schema": "cmd.diagnosis.get/1.0",  
 "args": {  
 "type": "wifi.network",  
 "detail\_level": "full",  
 "include\_rf\_stats": true,  
 "include\_traffic\_analysis": true,  
 "include\_interference\_scan": true,  
 "analysis\_window\_sec": 60  
 },  
 "timeout\_ms": 25000,  
 "expect": "result",   
 "ts": 1723526602000  
}

### 3. Device 命令確認 (Device → Controller)

**Topic**: rtk/v1/factory/workshop/smart-camera-003/cmd/ack

{  
 "id": "arp-diag-003",  
 "ts": 1723526602300,  
 "accepted": true,  
 "estimated\_completion\_ms": 20000,  
 "err": null  
}

### 4. Device 回傳網路診斷分析 (Device → Controller)

**Topic**: rtk/v1/factory/workshop/smart-camera-003/cmd/res

{  
 "id": "arp-diag-003",  
 "ts": 1723526606500,  
 "ok": true,  
 "result": {  
 "diagnosis\_type": "wifi.network",  
 "device\_type": "smart\_camera",  
 "collection\_time": 1723526606000,  
 "analysis\_window": {  
 "start\_time": 1723526546000,  
 "end\_time": 1723526606000,  
 "duration\_sec": 60  
 },  
 "data": {  
 "network\_connectivity": {  
 "gateway\_ip": "192.168.10.1",  
 "dns\_servers": ["192.168.10.10", "8.8.8.8"],  
 "dhcp\_server": "192.168.10.1",  
 "subnet\_mask": "255.255.255.0",  
 "connection\_uptime\_sec": 28947  
 },  
 "arp\_analysis": {  
 "target\_analysis": {  
 "ip": "192.168.10.1",   
 "mac": "aa:bb:cc:dd:ee:01",  
 "role": "gateway",  
 "reachability": "intermittent"  
 },  
 "recent\_requests": [  
 {  
 "timestamp": 1723526598000,  
 "target\_ip": "192.168.10.1",  
 "tx\_attempts": 3,  
 "response\_received": true,  
 "response\_time\_ms": 12  
 },  
 {  
 "timestamp": 1723526595000,  
 "target\_ip": "192.168.10.1",  
 "tx\_attempts": 3,  
 "response\_received": false,  
 "timeout\_ms": 3000  
 },  
 {  
 "timestamp": 1723526592000,  
 "target\_ip": "192.168.10.1",  
 "tx\_attempts": 3,  
 "response\_received": false,  
 "timeout\_ms": 3000  
 }  
 ],  
 "statistics": {  
 "total\_requests": 15,  
 "successful\_responses": 10,  
 "failed\_requests": 5,  
 "success\_rate": 0.67,  
 "average\_response\_time\_ms": 18.5  
 }  
 },  
 "ap\_connection\_info": {  
 "bssid": "bb:cc:dd:ee:ff:00",  
 "ssid": "Factory-IoT-5G",  
 "channel": 149,  
 "bandwidth": "80MHz",  
 "band": "5G",  
 "rssi": -67,  
 "link\_speed\_mbps": 200,  
 "connection\_duration\_sec": 28947  
 },  
 "rf\_diagnostics": {  
 "signal\_quality": {  
 "rssi": -67,  
 "snr": 18,  
 "noise\_floor": -95,  
 "signal\_strength": "fair",  
 "trend": "declining"  
 },  
 "channel\_analysis": {  
 "primary\_channel": 149,  
 "center\_frequency": 5745,  
 "channel\_utilization": 65,  
 "interference\_sources": [  
 {  
 "type": "bluetooth",  
 "strength": "weak",  
 "frequency\_overlap": false  
 },  
 {  
 "type": "industrial\_equipment",   
 "strength": "moderate",  
 "frequency\_overlap": true,  
 "estimated\_impact": "medium"  
 }  
 ]  
 },  
 "rf\_calibration": {  
 "last\_calibration": 1723495200000,  
 "calibration\_status": "normal",  
 "errors\_detected": false,  
 "next\_calibration\_due": 1723581600000  
 }  
 },  
 "traffic\_analysis": {  
 "recent\_5min": {  
 "rx\_bytes": 2457600,  
 "tx\_bytes": 1843200,  
 "rx\_packets": 1890,  
 "tx\_packets": 1432,  
 "rx\_errors": 23,  
 "tx\_errors": 8,  
 "rx\_dropped": 12,  
 "tx\_dropped": 3  
 },  
 "beacon\_monitoring": {  
 "beacons\_expected": 300,  
 "beacons\_received": 287,  
 "beacon\_loss\_rate": 0.043,  
 "consecutive\_missed\_max": 3,  
 "avg\_beacon\_interval\_ms": 102.1  
 },  
 "packet\_loss\_analysis": {  
 "overall\_loss\_rate": 0.021,  
 "upstream\_loss\_rate": 0.018,  
 "downstream\_loss\_rate": 0.024,  
 "loss\_pattern": "sporadic",  
 "correlation\_with\_interference": true  
 }  
 },  
 "baseband\_statistics": {  
 "rx\_sensitivity": -85,  
 "false\_alarm\_rate": 2.1,  
 "cca\_busy\_time\_percent": 35,  
 "txop\_utilization": 0.23,  
 "retry\_statistics": {  
 "short\_retries": 145,  
 "long\_retries": 28,  
 "retry\_rate": 0.12  
 }  
 },  
 "environmental\_factors": {  
 "nearby\_networks": [  
 {  
 "ssid": "Factory-Guest",  
 "bssid": "bb:cc:dd:ee:ff:01",  
 "channel": 153,  
 "rssi": -72,  
 "interference\_potential": "low"  
 },  
 {  
 "ssid": "Industrial-Control",   
 "bssid": "cc:dd:ee:ff:00:11",  
 "channel": 149,  
 "rssi": -58,  
 "interference\_potential": "high"  
 }  
 ],  
 "channel\_congestion": {  
 "primary\_channel\_busy": 0.65,  
 "secondary\_channel\_busy": 0.42,  
 "recommendation": "consider\_channel\_switch"  
 }  
 }  
 },  
 "root\_cause\_analysis": {  
 "primary\_causes": [  
 "channel\_interference",  
 "ap\_load\_fluctuation"  
 ],  
 "contributing\_factors": [  
 "industrial\_equipment\_interference",  
 "co\_channel\_ap\_competition",  
 "declining\_signal\_strength"  
 ],  
 "probability\_scores": {  
 "rf\_interference": 0.8,  
 "ap\_overload": 0.6,  
 "hardware\_issue": 0.2,  
 "network\_congestion": 0.7  
 }  
 },  
 "recommendations": {  
 "immediate\_actions": [  
 "monitor\_signal\_strength\_trend",  
 "consider\_ap\_roaming",  
 "increase\_arp\_timeout"  
 ],  
 "short\_term\_fixes": [  
 "request\_channel\_change",  
 "optimize\_ap\_placement",  
 "reduce\_non\_critical\_traffic"  
 ],  
 "long\_term\_solutions": [  
 "deploy\_additional\_ap",  
 "implement\_load\_balancing",  
 "upgrade\_to\_wifi6e"  
 ]  
 }  
 },  
 "err": null  
}

### 5. 遙測資料持續監控 (Device → Controller)

**Topic**: rtk/v1/factory/workshop/smart-camera-003/telemetry/wifi.connectivity

**Retained**: false

{  
 "schema": "telemetry.wifi.connectivity/1.0",   
 "ts": 1723526610000,  
 "metrics": {  
 "arp\_success\_rate": 0.72,  
 "avg\_response\_time\_ms": 15.3,  
 "packet\_loss\_rate": 0.019,  
 "rssi": -66,  
 "link\_quality": 68,  
 "throughput\_mbps": {  
 "rx": 12.5,  
 "tx": 8.3  
 }  
 },  
 "trend\_indicators": {  
 "signal\_improving": true,  
 "connectivity\_stabilizing": true,  
 "interference\_decreasing": false  
 }  
}

### 6. 狀態更新顯示網路品質改善 (Device → Controller)

**Topic**: rtk/v1/factory/workshop/smart-camera-003/state

**Retained**: true

{  
 "schema": "state/1.0",  
 "ts": 1723526611000,  
 "health": "warn",  
 "fw": "2.1.4",  
 "uptime\_s": 28954,  
 "cpu\_usage": 42.1,  
 "memory\_usage": 58.7,  
 "temperature\_c": 52.3,  
 "wifi\_stats": {  
 "connection\_status": "connected",  
 "ssid": "Factory-IoT-5G",  
 "rssi": -66,  
 "link\_quality": "fair",  
 "packet\_loss\_rate": 0.019,  
 "arp\_success\_rate": 0.72,  
 "last\_connectivity\_issue": 1723526601000,  
 "interference\_level": "moderate"  
 },  
 "net": {  
 "interface": "wlan0",  
 "ip": "192.168.10.203",  
 "gateway": "192.168.10.1",  
 "dns": ["192.168.10.10", "8.8.8.8"],  
 "bytes\_rx": 48576000,  
 "bytes\_tx": 23456000,  
 "connection\_uptime\_sec": 28947  
 },  
 "diagnosis": {  
 "last\_event": "wifi.arp\_loss",  
 "last\_event\_time": 1723526601000,  
 "error\_count": 0,  
 "warning\_count": 1,  
 "network\_stability": "improving"  
 },  
 "device\_specific": {  
 "camera\_streaming": {  
 "status": "active",  
 "resolution": "1080p",  
 "bitrate\_kbps": 2500,  
 "frames\_dropped": 12,  
 "stream\_health": "good"  
 }  
 }  
}

## 診斷分析結果

### 根本原因

1. **頻道干擾**: 工業設備在相同頻道產生干擾，導致封包遺失
2. **AP 負載波動**: 同頻道其他 AP 競爭造成的週期性干擾
3. **訊號強度下降**: RSSI 從 -60dBm 降至 -67dBm

### 即時處理動作

**調整 ARP 參數**:

{  
 "id": "arp-tune-001",  
 "op": "network.arp.config",   
 "schema": "cmd.network.arp.config/1.0",  
 "args": {  
 "timeout\_ms": 5000,  
 "retry\_count": 5,  
 "probe\_interval\_sec": 30,  
 "adaptive\_timeout": true  
 }  
}

**請求頻道切換評估**:

{  
 "id": "channel-eval-001",  
 "op": "wifi.channel.evaluate",  
 "schema": "cmd.wifi.channel.evaluate/1.0",   
 "args": {  
 "current\_channel": 149,  
 "candidate\_channels": [36, 40, 44, 48, 157, 161],  
 "evaluation\_duration\_sec": 30,  
 "include\_interference\_scan": true  
 }  
}

### 持續監控策略

**加強遙測頻率**:

{  
 "id": "monitor-enhance-001",  
 "op": "telemetry.schedule",  
 "schema": "cmd.telemetry.schedule/1.0",  
 "args": {  
 "metrics": ["wifi.connectivity", "wifi.interference"],  
 "interval\_sec": 10,  
 "duration\_sec": 1800,  
 "alert\_thresholds": {  
 "arp\_success\_rate": 0.8,  
 "packet\_loss\_rate": 0.05,  
 "rssi\_threshold": -70  
 }  
 }  
}

## E. WiFi 漫遊診斷範例

*複雜的漫遊機制診斷，包含 AP 選擇與切換過程分析*

# 漫遊問題診斷完整 MQTT 範例

## 情境描述

設備 office-ap-001 在辦公室環境中，RSSI 降到 -75dBm 並持續 10 秒，但系統未觸發漫遊機制。

## MQTT 訊息流程

### 1. 事件觸發 (Device → Controller)

**Topic**: rtk/v1/office/floor1/office-ap-001/evt/wifi.roam\_miss

**Retained**: false

{  
 "schema": "evt.wifi.roam\_miss/1.0",  
 "ts": 1723526401000,  
 "severity": "warning",  
 "trigger\_info": {  
 "rssi\_threshold": -70,  
 "duration\_ms": 10000,  
 "cooldown\_ms": 300000  
 },  
 "diagnosis": {  
 "internal\_scan\_skip\_count": 3,  
 "environment\_ap\_count": 8,  
 "candidate\_ap\_count": 2,  
 "current\_bssid": "aa:bb:cc:dd:ee:ff",  
 "current\_rssi": -75,  
 "candidates": {  
 "2g": {  
 "bssid": "00:00:00:00:00:00",  
 "rssi": 0,  
 "channel": 0  
 },  
 "5g": {  
 "bssid": "11:22:33:44:55:66",  
 "rssi": -42,  
 "channel": 36  
 },  
 "6g": {  
 "bssid": "77:88:99:aa:bb:cc",  
 "rssi": -48,  
 "channel": 37  
 }  
 },  
 "scan\_timing": {  
 "last\_scan\_time": 1723526395000,  
 "last\_full\_scan\_complete\_time": 1723526380000  
 }  
 }  
}

### 2. Controller 請求詳細診斷 (Controller → Device)

**Topic**: rtk/v1/office/floor1/office-ap-001/cmd/req

{  
 "id": "roam-diag-001",  
 "op": "diagnosis.get",  
 "schema": "cmd.diagnosis.get/1.0",   
 "args": {  
 "type": "wifi.roaming",  
 "detail\_level": "full",  
 "include\_history": true,  
 "include\_rf\_stats": true  
 },  
 "timeout\_ms": 15000,  
 "expect": "result",  
 "ts": 1723526402000  
}

### 3. Device 命令確認 (Device → Controller)

**Topic**: rtk/v1/office/floor1/office-ap-001/cmd/ack

{  
 "id": "roam-diag-001",  
 "ts": 1723526402200,  
 "accepted": true,  
 "err": null  
}

### 4. Device 回傳詳細診斷結果 (Device → Controller)

**Topic**: rtk/v1/office/floor1/office-ap-001/cmd/res

{  
 "id": "roam-diag-001",   
 "ts": 1723526403500,  
 "ok": true,  
 "result": {  
 "diagnosis\_type": "wifi.roaming",  
 "device\_type": "wifi\_access\_point",  
 "collection\_time": 1723526403000,  
 "data": {  
 "roaming\_analysis": {  
 "trigger\_reasons": [  
 "poor\_signal\_quality",  
 "scan\_skip\_detected"  
 ],  
 "skip\_analysis": {  
 "total\_skips\_10sec": 3,  
 "skip\_reasons": ["scan\_in\_progress", "channel\_switch\_delay"],  
 "last\_successful\_scan": 1723526395000,  
 "scan\_interval\_ms": 5000,  
 "expected\_scan\_count": 2,  
 "actual\_scan\_count": 0  
 },  
 "environmental\_scan": {  
 "total\_ap\_detected": 8,  
 "same\_ssid\_ap\_count": 3,  
 "better\_rssi\_ap\_count": 2,  
 "roam\_candidate\_count": 2  
 }  
 },  
 "current\_connection": {  
 "bssid": "aa:bb:cc:dd:ee:ff",  
 "ssid": "OfficeWiFi-5G",  
 "rssi": -75,  
 "channel": 149,  
 "bandwidth": "80MHz",  
 "band": "5G",  
 "connection\_duration\_ms": 1847500,  
 "last\_roam\_time": 1723524553500  
 },  
 "roam\_candidates": [  
 {  
 "band": "5G",  
 "bssid": "11:22:33:44:55:66",  
 "ssid": "OfficeWiFi-5G",   
 "rssi": -42,  
 "channel": 36,  
 "bandwidth": "80MHz",  
 "estimated\_throughput\_mbps": 450,  
 "load\_percentage": 25,  
 "roam\_score": 85  
 },  
 {  
 "band": "6G",  
 "bssid": "77:88:99:aa:bb:cc",  
 "ssid": "OfficeWiFi-6G",  
 "rssi": -48,  
 "channel": 37,  
 "bandwidth": "160MHz",   
 "estimated\_throughput\_mbps": 980,  
 "load\_percentage": 15,  
 "roam\_score": 92  
 }  
 ],  
 "rf\_statistics": {  
 "interference\_level": "moderate",  
 "noise\_floor\_dbm": -95,  
 "channel\_utilization\_percent": 45,  
 "retry\_rate\_percent": 12.5,  
 "packet\_loss\_rate\_percent": 2.1  
 },  
 "scan\_history": [  
 {  
 "timestamp": 1723526395000,  
 "duration\_ms": 850,  
 "channels\_scanned": [36, 40, 44, 48, 149, 153, 157, 161],  
 "ap\_found": 8,  
 "trigger\_reason": "periodic\_background"  
 },  
 {  
 "timestamp": 1723526380000,  
 "duration\_ms": 1200,  
 "channels\_scanned": [36, 40, 44, 48, 149, 153, 157, 161],  
 "ap\_found": 7,  
 "trigger\_reason": "roam\_evaluation"  
 }  
 ]  
 }  
 },  
 "err": null  
}

### 5. 狀態更新 (Device → Controller) - 定期發送

**Topic**: rtk/v1/office/floor1/office-ap-001/state

**Retained**: true

{  
 "schema": "state/1.0",  
 "ts": 1723526404000,  
 "health": "warn",  
 "fw": "1.2.3",  
 "uptime\_s": 4567,  
 "cpu\_usage": 35.2,  
 "memory\_usage": 42.8,  
 "temperature\_c": 38.5,  
 "wifi\_stats": {  
 "current\_rssi": -75,  
 "connection\_quality": "poor",  
 "roaming\_enabled": true,  
 "last\_roam\_attempt": 0,  
 "roam\_candidate\_count": 2  
 },  
 "net": {  
 "interface": "wlan0",  
 "ip": "10.0.1.23",  
 "bytes\_rx": 1048576,  
 "bytes\_tx": 524288,  
 "packets\_dropped": 127  
 },  
 "diagnosis": {  
 "last\_event": "wifi.roam\_miss",  
 "last\_event\_time": 1723526401000,  
 "error\_count": 1,  
 "warning\_count": 3  
 }  
}

## 診斷分析結果

基於這次診斷資料，可以得出以下結論：

### 根本原因分析

1. **掃描跳過問題**: 10秒內有3次掃描被跳過，導致無法及時發現更好的AP
2. **掃描觸發延遲**: 上次完整掃描距離事件發生已經21秒
3. **候選AP可用**: 環境中有2個更好的AP可供漫遊

### 建議動作

1. **立即動作**: 觸發一次完整的環境掃描
2. **配置調整**: 降低掃描間隔或調整掃描跳過條件
3. **持續監控**: 關注後續5分鐘內的漫遊行為

### Controller 後續動作建議

**觸發環境掃描命令**:

{  
 "id": "emergency-scan-001",  
 "op": "wifi.scan",  
 "schema": "cmd.wifi.scan/1.0",  
 "args": {  
 "scan\_type": "full\_active",  
 "channels": [36, 40, 44, 48, 149, 153, 157, 161],  
 "dwell\_time\_ms": 100,  
 "priority": "high"  
 },  
 "timeout\_ms": 10000,  
 "expect": "result",  
 "ts": 1723526405000  
}