Putting the S in IoT

Building Secure Connections with ESP-IDF

A Security-First Approach to ESP-IDF Networking

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Presentation Goal: Security layer by layer

WiFi Channel Security
WPA3 encrypted wireless

Secure DNS Resolution
DNS-over-HTTPS/TLS

Broker Validation
TLS + certificate verification

Mutual Authentication
Client certificate auth

Hardware Identity
eFuse + Digital Signature

Cryptography Fundamentals

Cryptographic Security Objectives

Confidentiality

Protect data from unauthorized access

Integrity

Ensure data hasn’t been modified

Authentication

Verify identity of communicating parties

Non-repudiation

Prevent denial of actions performed

Hybrid Cryptography

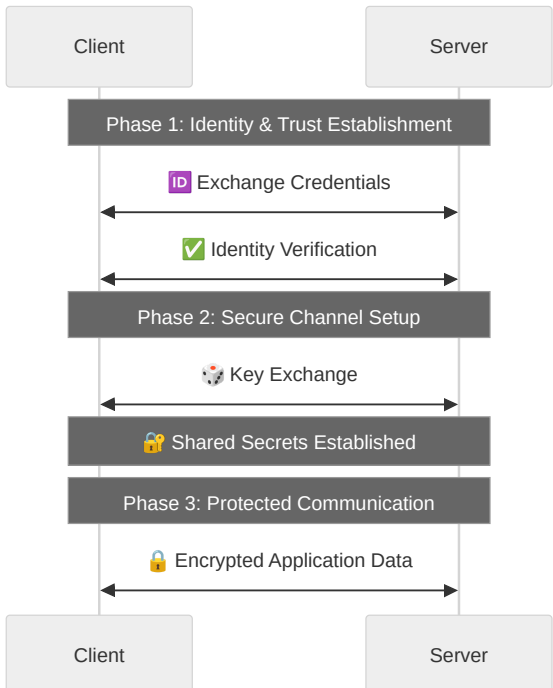
Asymmetric Cryptography

- **Key Pairs**: Public + Private keys
- **Usage**: Authentication, key exchange
- **Examples**: RSA, ECDSA, DH

Symmetric Cryptography

- **Shared Secret**: Same key encrypt/decrypt
- **Usage**: Bulk data encryption
- **Examples**: AES, ChaCha20

Generic Secure Protocol Handshake



Channel Security Foundation

Common WiFi Security Threats

🚨 Attack Vectors

WEP Vulnerabilities

- Weak 40/104-bit encryption
- IV collision attacks
- Crackable in minutes

WPA2 Dictionary Attacks

- Offline password cracking
- 4-way handshake capture
- No forward secrecy

🛡️ Management Frame Attacks

Deauth/Disassoc Spoofing

- Force client disconnection
- Man-in-the-middle setup
- Network disruption (DoS)

Evil Twin APs

- Rogue access points
- Credential harvesting
- Traffic interception

ESP-IDF WiFi Security Support

🔐 WPA3-Personal

- SAE Authentication
- Dictionary Attack Resistant
- Forward Secrecy
- H2E & Hunt-and-Peck

🏢 WiFi Enterprise

- WPA2/WPA3-Enterprise
- EAP-TLS, PEAP, TTLS
- EAP-FAST Support
- RADIUS Integration

🛡️ Security Features

- Protected Management Frames
- Enhanced Open (OWE)
- Certificate Validation
- Secure Provisioning

🔧 ESP-IDF Configuration Support

Menuconfig Options • Runtime API • Certificate Management • Event Handling

Maximum Security Configuration

```
wifi_config_t secure_config = {
    .sta = {
        .ssid = "SecureNetwork",
        .password = "StrongPassword123",
        .threshold.authmode = WIFI_AUTH_WPA3_PSK,        // Force WPA3
        .pmf_cfg = {
            .required = true                              // Override default (Optional)
        },
        .sae_pwe_h2e = WPA3_SAE_PWE_HASH_TO_ELEMENT,    // Override default (Both)
        .transition_disable = true,                       // Override default (false)
    }
};
```

⚡ ESP-IDF Defaults vs Override

```
# WPA3 enabled by default in ESP-IDF
CONFIG_ESP_WIFI_ENABLE_WPA3_SAE=y      # ✅ Default: enabled
# PMF Optional by default - we override to Required
# Transition allowed by default - we override to disabled
```

Practical Configuration

```
wifi_config_t practical_config = {
    .sta = {
        .ssid = "MyNetwork",
        .password = "MyPassword123",
        .threshold.authmode = WIFI_AUTH_WPA2_PSK,        // WPA2 minimum
        .pmf_cfg = {
            .required = false                             // ✅ Use default (Optional)
        },
        .sae_pwe_h2e = WPA3_SAE_PWE_BOTH,                // ✅ Use default (Both)
        .transition_disable = false,                      // ✅ Use default (allowed)
    }
};
```

🔧 ESP-IDF Secure Defaults

```
CONFIG_ESP_WIFI_ENABLE_WPA3_SAE=y      # ✅ Default: WPA3 enabled
      # ✅ Default: PMF Optional (connects when supported)
    # ✅ Default: Transition allowed (backward compatibility)
        # ✅ Default: SAE PWE Both (H2E + Hunt-and-Peck)
```

Configuration Comparison

🛡️ Practical Approach

- WPA2 minimum, WPA3 preferred
- **PMF Optional** for wider compatibility
- **Transition allowed** for legacy networks
- **Works with most networks**

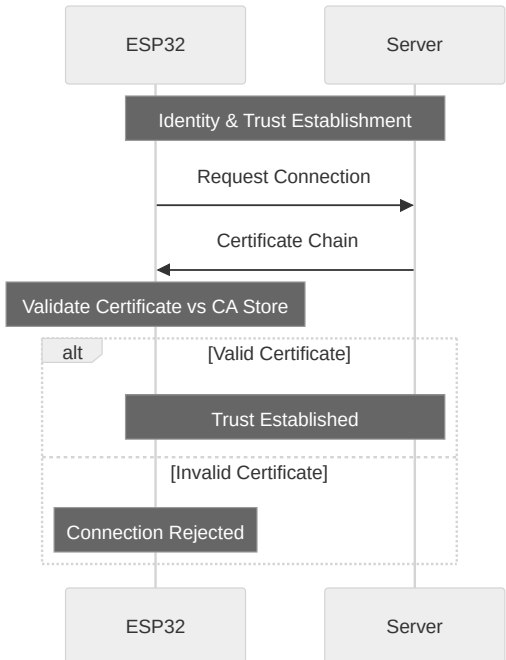
✅ ESP-IDF Smart Defaults

- **Auto WPA3 upgrade**: Connects WPA3 when available, falls back to WPA2
- **PMF when supported**: Enables PMF automatically if AP supports it
- **Side-channel protection**: H2E method available by default
- **Maximum compatibility**: Works with 99% of existing networks

Best Practice: Start with practical config, upgrade to maximum security in controlled environments

Certificate Validation

Certificate-Based Trust



Credential Exchange

- Server presents X.509 certificate
- Contains public key + identity claims
- Signed by trusted Certificate Authority

Certificate Bundle

📦 What is Certificate Bundle?

130+ root CA certificates (Mozilla Root Store)

- Same CAs used by web browsers
- Auto-updated with ESP-IDF releases
- ~60KB flash

Perfect for:

- ☁️ **Cloud services** (AWS IoT, Azure IoT)
- 🌐 **Public APIs** (GitHub, REST endpoints)
- 🔒 **Let's Encrypt** certificates

⚙️ Enable in menuconfig:

```
Component config → mbedTLS → Certificate Bundle
  → [*] Enable trusted root certificate bundle
```

Configuration:

```c
#include "esp_crt_bundle.h"

esp_tls_cfg_t cfg = {
    .crt_bundle_attach = esp_crt_bundle_attach,
    .skip_common_name = false,  // Verify hostname
};
```

Works with all protocols:

- HTTPS, MQTT, WebSockets, custom TLS

Global CA Store

Benefits:

- Runtime certificate loading
- Memory efficient for multiple connections
- Centralized management

Configuration:

```
esp_tls_set_global_ca_store(
    server_root_cert_pem_start,
    server_root_cert_pem_end - server_root_cert_pem_start
);

esp_tls_cfg_t cfg = {
    .use_global_ca_store = true,
};

esp_tls_free_global_ca_store();
```

Example: `examples/protocols/https_request/`

DNS Security

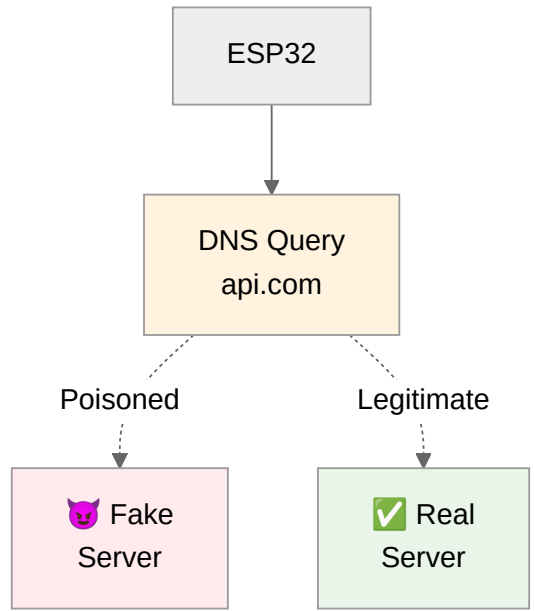
DNS Security Problem

DNS Vulnerabilities

- 🔓 **Unencrypted**: Queries in plaintext
- 🎯 **Cache poisoning**: Fake responses
- 👀 **Traffic analysis**: Monitoring behavior
- 🚫 **DNS hijacking**: Malicious redirects

Risk: ESP32 connects to wrong server

- ❌ No response verification
- ❌ Complete security bypass
- ❌ Firmware updates compromised



ESP-DNS Component

Protocol Support

- **UDP/TCP DNS (53)**: ❌ Plaintext, ⚡ Fast
- **DoT (853)**: ✅ TLS encrypted, memory overhead
- **DoH (443)**: ✅ HTTPS encrypted, memory overhead

🛡️ Security Features

- Certificate validation with ESP-IDF bundle
- Protection against DNS spoofing
- Encrypted query/response (DoT/DoH)

⚙️ Implementation

- Drop-in replacement for system DNS
- Standard `getaddrinfo()` interface
- Automatic fallback mechanisms
- Component: `esp-protocols/esp_dns`
- Add: `idf.py add-dependency "espressif/esp_dns^0.1.0"`

Example: `esp-protocols/components/esp_dns/examples/esp_dns_b`

MQTT Secure Connection Solution

MQTT Security Challenge

The Problem

Plain MQTT offers:

- Unencrypted transmission
- No broker authentication
- No client authentication
- No message integrity validation

Attack Scenarios

- Traffic interception and analysis
- Broker impersonation attacks
- Unauthorized message injection
- Device impersonation

Our Security Solution

1. **Transport Security**: TLS encryption
2. **Broker Verification**: Certificate validation
3. **Client Authentication**: Multiple options
4. **Hardware Integration**: ESP32 security features

ESP-IDF MQTT Examples

- `examples/protocols/mqtt/tcp/`
- `examples/protocols/mqtt/ssl/`
- `examples/protocols/mqtt/ssl_mutual_auth/`
- `examples/protocols/mqtt/ssl_ds/`

Plain TCP MQTT

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Basic MQTT Configuration

```
esp_mqtt_client_config_t mqtt_cfg = {
    .broker = {
        .address = {
            .uri = "mqtt://broker.hivemq.com:1883",
        }
    }
};
```

What This Provides

- Direct TCP connection to broker
- Unencrypted MQTT messaging
- Anonymous client connections
- Development and testing baseline

Security Limitations

- All messages transmitted in cleartext
- No server identity verification
- No client authentication required
- Vulnerable to MITM attacks

Use Cases:

- Development and testing
- Local network prototyping
- Non-sensitive IoT data

Example: `examples/protocols/mqtt/tcp/`

Secure MQTT Transport

TLS-Enabled MQTT

```
esp_mqtt_client_config_t mqtt_cfg = {
    .broker = {
        .address = {
            .uri = "mqtts://mqtt.eclipseprojects.io:8883",
        },
        .verification = {
            .crt_bundle_attach = esp_crt_bundle_attach,
        }
    }
};
```

Security Components

- **esp-tls**: TLS implementation layer
- **tcp_transport**: Secure socket transport
- **Certificate Bundle**: Pre-loaded root CAs

Security Improvements

- All MQTT traffic encrypted (TLS 1.2/1.3)
- Server identity verified via certificates
- Protection against eavesdropping
- Man-in-the-middle attack prevention

Example: `examples/protocols/mqtt/ssl/`

Broker Verification Options

Certificate-Based Verification

- Certificate Bundle - `.crt_bundle_attach`
- Custom Root CA - `.certificate`
- Global CA Store - `.use_global_ca_store`

Alternative Methods

- Pre-Shared Key - `.psk_hint_key`
- Custom Common Name - `.common_name`

Custom Root CA Example

```
extern const uint8_t ca_cert_pem_start[]
  asm("_binary_ca_cert_pem_start");

.verification = {
    .certificate = (const char *)ca_cert_pem_start,
}
```

Username/Password Authentication

Basic Configuration

```
.credentials = {
    .username = "device_12345",
    .client_id = "esp32_sensor_01",
    .authentication = {
        .password = "secure_device_password",
    }
}
```

All Credential Fields

- `.username` - MQTT username
- `.client_id` - MQTT client identifier
- `.authentication.password` - MQTT password

Advantages:

- Simple implementation
- Easy credential rotation
- Broker-managed users
- Standard MQTT feature

Best Practices:

- Store credentials in encrypted NVS
- Use strong, unique passwords
- Implement credential rotation
- Monitor authentication failures

Certificate-Based Authentication

Mutual TLS Configuration

```
extern const uint8_t client_cert_pem_start[]
  asm("_binary_client_crt_start");
extern const uint8_t client_key_pem_start[]
  asm("_binary_client_key_start");

.credentials = {
    .authentication = {
        .certificate = (const char *)client_cert_pem_start
        .certificate_len = 0, // PEM null-terminated
        .key = (const char *)client_key_pem_start,
        .key_len = 0, // PEM null-terminated
        .key_password = "optional_key_password",
        .key_password_len = 21,
    }
}
```

Security Benefits:

- Cryptographically strong authentication
- No password transmission
- Unique device identity
- Non-repudiation

Digital Signature Authentication

DS Peripheral Configuration

```
.credentials = {
    .authentication = {
        .ds_data = esp_secure_cert_get_ds_ctx(),
    }
}
```

Supported Devices

- ESP32-S2, ESP32-S3
- ESP32-C3, ESP32-C5, ESP32-C6, ESP32-C61
- ESP32-H2, ESP32-P4

Authentication Field

- `.ds_data` - DS context handle

Security Benefits:

- RSA private key never exposed in software
- Hardware-accelerated RSA signing
- Tamper-resistant authentication
- Uncompromisable device identity

ESP-IDF Reference:

`examples/protocols/mqtt/ssl_ds/`

Complete Secure MQTT Solution

Encrypted Transport

- TLS 1.2/1.3 with certificate bundle

Mutual Authentication

- Server verification via certificates
- Client authentication with DS peripheral

Production Ready

- Hardware-backed device identity
- Complete protection against MITM attacks

MQTT Security Stack:

- Transport encryption (TLS)
- Broker verification (certificates)
- Client authentication (hardware)

Hardware Security

Device Identity Challenge

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What We've Built So Far

✅ **Secure WiFi** (WPA3 encryption)

✅ **Secure DNS** (DoH/DoT resolution)

✅ **Certificate Validation** (CA bundle/custom)

✅ **MQTT Authentication** (certificates/passwords)

🤔 **But private keys still in software...**

Next Hardening Layer: Hardware Security

🔒 **Hardware-bound private keys**

- Never exposed to software

⚡ **Hardware-accelerated crypto**

- DS/HMAC peripherals

🏭 **Immutable device identity**

- eFuse root of trust

🛡️ **Tamper-resistant authentication**

- Uncompromisable credentials

eFuse Root of Trust

eFuse Architecture

🔒 One-Time Programmable Memory

- Hardware-protected storage

🔑 256-bit Key Blocks

- Up to 6 blocks on newer devices
- Purpose-bound usage
- Hardware protection

Root of Trust Capabilities

```c
// Burn key to eFuse (one-time)
uint8_t key[32];
esp_fill_random(key, sizeof(key));
esp_efuse_write_key(EFUSE_BLK_KEY0,
    ESP_EFUSE_KEY_PURPOSE_HMAC_DOWN_DIGISIGN,
    key, sizeof(key));

// Protect from software access
esp_efuse_set_read_protect(EFUSE_BLK_KEY0);
```

ESP32 Hardware Security Reference

Cryptographic Accelerators

Symmetric Cryptography

- **AES**: All devices

Flash Encryption

- **XTS-AES**: ESP32-S2, ESP32-S3, ESP32-C3, ESP32-C5, ESP32-C6, ESP32-P4
- **Custom Algorithm**: ESP32

Asymmetric Cryptography

- **RSA**: All devices
- **ECC**: ESP32-C5, ESP32-C6

Hash & Authentication

- **SHA**: All devices
- **HMAC**: ESP32-S2, ESP32-S3, ESP32-C3, ESP32-C5, ESP32-C6, ESP32-P4
- **Digital Signature (DS)**: ESP32-S2, ESP32-S3, ESP32-C3, ESP32-C5, ESP32-C6, ESP32-P4
- **ECDSA Peripheral**: ESP32-C5

Security Foundation

- **MPI (Large Number Operations)**: All devices
- **RNG**: All devices
- **eFuse Integration**: All devices

Generate Keys & Certificate

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Step 1: Generate RSA Private Key

```
# Generate 2048-bit RSA private key
openssl genrsa -out client.key 2048

# Verify key generation
openssl rsa -in client.key -text -noout
```

Step 2: Generate Certificate

```
# Generate Certificate Signing Request
openssl req -out client.csr -key client.key -new \
  -subj "/CN=ESP32-C5-Device/O=MyCompany"

# Option 1: Get certificate from CA
# (Submit CSR to Certificate Authority)

# Option 2: Self-signed certificate for development
openssl x509 -req -days 365 -in client.csr \
  -signkey client.key -out client.crt
```

Configure DS Peripheral

Step 1: Install esp_secure_cert Tool

```
# Install the official ESP-IDF tool
pip install esp-secure-cert-tool

# Verify installation
configure_esp_secure_cert.py --help
```

Step 2: Configure DS with Generated Keys

```
# Configure DS peripheral with key and certificate
configure_esp_secure_cert.py \
  -p /dev/ttyUSB0 \
  --device-cert client.crt \
  --private-key client.key \
  --target_chip esp32c5 \
  --configure_ds

# Result: esp_secure_cert.bin created automatically
# HMAC key burned to eFuse
# DS parameters encrypted and stored
```

Runtime MQTT Integration

Step 1: Load DS Context & Certificate

```
// Load DS context from esp_secure_cert partition
esp_ds_data_ctx_t *ds_data = esp_secure_cert_get_ds_ctx();
if (ds_data == NULL) {
    ESP_LOGE(TAG, "Error reading DS data");
    return;
}

// Load device certificate
char *device_cert = NULL;
uint32_t len;
esp_err_t ret = esp_secure_cert_get_device_cert(&device_ce
if (ret != ESP_OK) {
    ESP_LOGE(TAG, "Failed to get device certificate");
    return;
}
```

Step 2: Configure MQTT Client

```
// Configure MQTT with hardware-backed authentication
const esp_mqtt_client_config_t mqtt_cfg = {
    .broker = {
        .address.uri = "mqtts://test.mosquitto.org:8884",
        .verification.certificate = server_cert_pem,
    },
    .credentials = {
        .authentication = {
            .certificate = device_cert,
            .key = NULL,         // No software key needed
            .ds_data = ds_data  // Hardware handles signi
        },
    },
};
```

🛡️ Complete ESP-IDF Security Solution

🔧 Implementation Journey

Problem Statement

- Complete secure MQTT architecture
- Defense-in-depth strategy

Channel Security

- WPA3-Personal configuration
- Secure WiFi provisioning

Certificate Validation

- TLS trust establishment
- ESP-IDF certificate bundle

🔒 Advanced Security

DNS Security

MQTT Security

- Hardware-backed authentication
- TLS client certificates

Hardware Security

- Digital Signature peripheral
- Hardware identity generation

Thank You!

Questions?

END