Lab: WiFi

Introduction

The purpose of this lab is to get you some hands-on experience with WiFi on a microcontroller:

- Scan and join networks
- Host a network
- Host and access web services

For this lab we will be writing code using PlatformIO. We'll be working on the Heltec WiFi LoRa 32 v3 boards this time though, which are also supported by the Arduino libraries.

Goals

- Interact with WiFi networks
- Explore some basic IoT web services

Equipment

- Computer
- Heltec WiFi LoRa 32 v3 + USB cable (3 total for the group)

Github Classroom

- https://classroom.github.com/a/7FRzH5E5

Partners

- This lab should be done with **your group of three**

Submission

- Write your answers up for each task and submit a PDF to Gradescope.

  Remember: I'm not looking for a formal lab report. Just your answers in any format that makes sense. The goal is to prove that you did the lab and spent some time thinking about it.

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Lab Setup

1. Setting up PlatformIO

To program our boards, we're going to use PlatformIO. It's a relatively new embedded toolchain management system. One of the really hard parts about embedded systems development is making sure you have the right tools installed on your computer: compiler, programmer, debugger, etc. And every hardware board and software framework you work with has slightly different tools that are required. PlatformIO automatically determines what stuff you need to program a board, and so far in my experience it does a decent job. It has worked on Windows, Linux, and MacOS (both Intel and ARM). It doesn't have a lot of development progress though, so I'm a little worried about its long-term prospects.

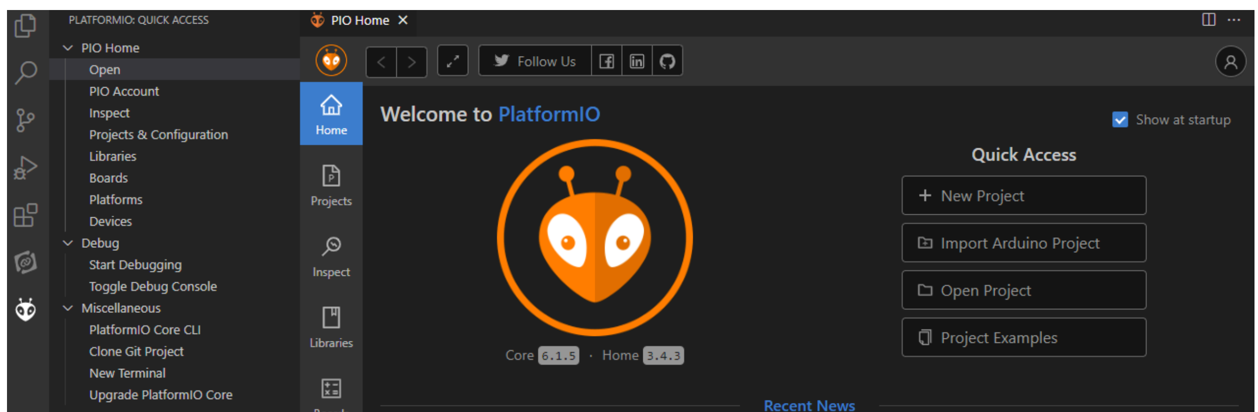
For better and for worse, PlatformIO is almost entirely used as an extension for VSCode, so that means we'll be using VSCode to write our software and PlatformIO to manage our toolchains, compile code, upload it to boards, and display output from boards.

- Install Platform IO

  Follow the steps here: https://platformio.org/install/ide?install=vscode

  It'll take a minute or two to actually install PlatformIO. When it's done, you'll have to reload VSCode and the little Ant icon will appear on the left side of it.

- Get yourself to the PlatformIO homepage



TASK: None. Continue to the next section.

2. Create Your Lab Git Repo

I'll want to look at the code you wrote, so I need to give you somewhere to put it. Github classroom makes private repos for each student team so you can get the starter code and upload your own modifications. I can access all student repos, but you can only access your own.

- There is a github classroom link on the first page of this document. Click it!

- Pick a team name
    - Unless someone else already started it, in which case, join their team name

- Generally, do what github classroom says

- At the end, it should create a new private repo that you have access to for your code
    - Be sure to commit your code to this repo often during class!

- The repo link might 404. If so, you first have to go to https://github.com/nu-ce346-student and join the organization
    - I'm reusing the CE346 org for student repos for this class. Don't worry about it

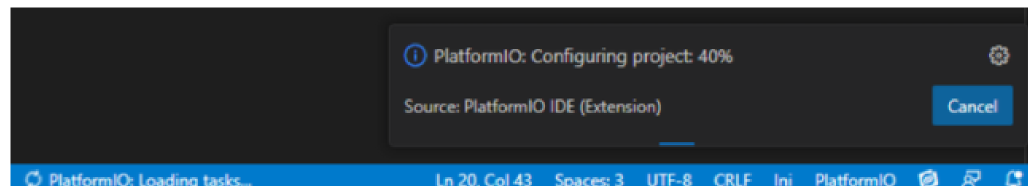
- Clone the repo locally on your computer
    - If you're on Windows: git BASH does a good job https://gitforwindows.org/
        - Make sure there are no space characters in the entire path to the repo. Probably put it somewhere like "C:/iot_apps/REPONAME" if you have a space in your username.
    - If you're on MacOS or Linux, you can clone the repo from command line
    - We'll be using VSCode for everything, and it has a mechanism for working with git too, so you could use that: https://code.visualstudio.com/docs/sourcecontrol/overview#_cloning-a-repository

TASK: None. Continue to the next section.
However, make sure to commit your code as you go, as I'll want to see the final results.

3. Load the Example Apps

Let's get an initial app working on the hardware now.

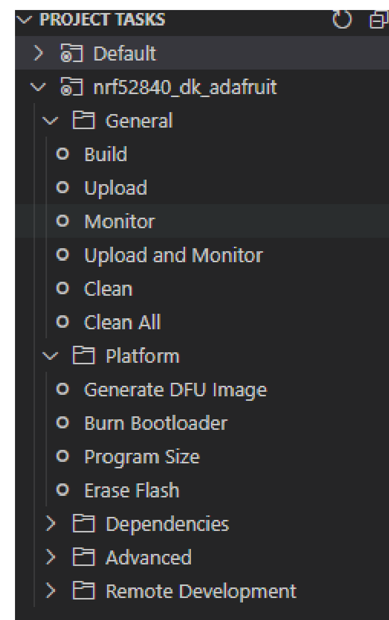
- Use the "Open Project" button on the PlatformIO homepage to open one of the folders within your group's Github starter repo. The best one to start with is "blink-and-print".
    - The first time you open a folder in that repo with PlatformIO, expect a lot of loading to occur. It needs to install an entirely new toolchain to compile and upload code for ESP-32 microcontrollers. On my desktop, this took about five minutes to complete. You'll see something like this:



- You should now have two useful toolbars to interact with code.

The first is the VSCode explorer tab on the left, which will show you the file structure of the application and allow you to open the code in src/main.cpp.

The second is the PlatformIO tab on the left, which will show you "Project Tasks" like Build (compile code), Upload (load code onto the board), and Monitor (open a serial console to see print output from the board). I mostly use "Upload and Monitor" which recompiles, uploads, and opens a serial terminal all at once. If you later end up opening multiple projects at once, the blue bar at the bottom has both shortcuts to these actions and tells you which project the actions are applying to.



- Plug your board into your computer using your USB micro cable and the USB-C to Micro USB adapter in the box with the board.

- When you plug in the board for the first time, check that orange LED by the "RST" button lights up. That means the board has power.

  A weird quirk of this hardware is that it MUST have a USB adapter somewhere inline when you plug it in. Plugging in directly via a USB-C to USB-C cable fails to power the board (the implemented something about that incorrectly…). Each box should have a USB-C to Micro USB adapter, which you can use in conjunction with the USB micro cable you already have from previous labs.

- In PlatformIO, click "Upload and Monitor" to compile and flash the application and then automatically open a serial port to it.

  - Windows: If you get an error there's a very real chance you need to install a USB driver for the board. It worked fine for me on one of my Windows computers, but not the other two. I needed to install the "CSP210x Windows Drivers" (not the Universal one), and then it worked. https://www.silabs.com/developers/usb-to-uart-bridge-vcp-drivers?tab=downloads

  - Even after that, you might get a very cryptic error on Windows, about not having access to the COM port. A reboot resolves this issue. Linux and MacOS should hopefully be fine, but let me know if you have issues.

  - I've also sometimes found that commands fail the first time, but succeed the second time. It didn't happen too often, but be willing to try it if things are going wrong.

- The LED should now be blinking (you'll know it's hella bright) and you should see a count of which iteration of the main loop we're on.

- Take a look at the code in `main.cpp` and try modifying some things to make sure you understand it.

- Also try out the `screen-example` application, which demonstrates how to use the screen on the board, which is slow but totally functional.
  - I put an secret in there for you.

TASK: None. Continue to the next section.

Reference Documentation

4. ESP32 Arduino WiFi Library

Our Heltec board has an ESP32 microcontroller. It is a general-purpose microcontroller, but it has a WiFi radio peripheral (much like the nRF52 series is a microcontroller + BLE/15.4 radio). We'll be programming that chip and writing our own code in PlatformIO.

Documentation:

- Arduino WiFi Library API:
  https://github.com/arduino-libraries/WiFi/blob/master/docs/api.md
  - WARNING: This isn't actually the library we're using. Our library just emulates this one, and it doesn't match precisely. These docs are way better though for Client-side stuff (they don't have Access Point stuff at all).

- ESP32 WiFi Library Docs:
  https://docs.espressif.com/projects/arduino-esp32/en/latest/api/wifi.html#
  - This **is** the library we're using. But the docs aren't exactly great. You'll still have to use it for Access Point stuff.

- ESP32 WiFi Examples:
  https://github.com/espressif/arduino-esp32/tree/master/libraries/WiFi/examples
  - You'll find that these cover all the basic things you want to do. My strong recommendation is that you don't do too much copy-paste from them and instead use them as inspiration to write your own code. You'll learn more that way.

  - You'll find that a lot of code does get reused across sections. Definitely feel free to copy-paste your own code from prior sections.

Note: for this particular class, **you are allowed to use code you find online** as long as you cite it. There isn't as much of a plagiarism concern here since our goal is really to learn about networks, not write software. Citing where the code came from is a good practice for others who might have to understand your own code.

TASK: None. Continue to the next section.

Interact with WiFi

5. Scan for WiFi networks

The first step of doing anything with WiFi is scanning for available WiFi networks.

- Create an app that can scan for WiFi networks and display them in terminal. We've provided some starter code in `wifi-scanner`

- I highly recommend you go look at some example code.

- For each network you find, print out at least the following information:
    - SSID
    - Channel
    - Encryption
    - RSSI

1. **TASK:** Demonstrate ability to scan networks
    - Show me the terminal output from a scan
    - Commit your `wifi-scanner` code to your shared repo

6. Connect to the Internet

Now let's connect to the Internet and get some data from it! We'll contact an NTP server and request the current time. It'll be in UTC, but it should make it obvious that everything is working.

- Open the `wifi-client` starter code

- You'll need to specify an SSID and Password for a WiFi network. There are several options here:
  - Use your home WiFi network. Should work fine, but you have to be at home.

  - Use Device-Northwestern network. I got this working fine too! And it works on-campus. But you need to do a setup step.

    You first need to register the device with Northwestern. There's a web portal to do so, and it seems to work automatically and pretty quickly (definitely within a minute). https://device.wireless.northwestern.edu/ (You do NOT need to enable "Sharing".)

    To get your MAC address, you'll have to program an app on your device that will spit out the MAC address as the first thing it does. The `wifi-client` app already does this for you! Make sure you have the endianness right. The device's MAC address should start with Espressif's OUI: F4-12-FA

  - Use your smartphone as a Wireless Hotspot. I've done this in the past and it was fine. Definitely less desirable, but we aren't going to be transferring any meaningful amount of data.

- Make sure you can successfully connect to the WiFi network and get an IP address. Sometimes this just doesn't work for me after I reprogram or reset a device. Resetting again once or twice has always fixed it.

- Use the Network Time Protocol to get the current time and date. Here's a library to use: https://github.com/taranais/NTPClient

  It's already been enabled for you in the application's `platformio.ini` file.

  The example in the README is probably enough to work with. You'll want to print time *and* the date though.

1. **TASK:** Demonstrate ability to get time through the Internet
   - Show me the terminal output printing the current date AND time
   - Commit your `wifi-client` code to your shared repo

7. Scan Promiscuously

This is a little more off the beaten path, but you can use an ESP32 not just to send packets, but also to receive packets. Most radios, the ESP32 included, have an option called "promiscuous mode" where they collect not just packets intended for them, but **all** packets it can sense. We'll use the ESP32 to do a promiscuous scan of WiFi packets and find packets being sent by the client app we created previously.

- Start from the `wifi-promiscuous` example code.

  The code I set up for you is based on the ESP32 sniffer application here: https://github.com/ESP-EOS/ESP32-WiFi-Sniffer/blob/master/WIFI_SNIFFER_ESP32.ino

- I recommend first getting it to scan any WiFi packets at all to make sure it's working. Print out some details about the packets so you know they seem valid.

- Next, let's find packets being sent by the `wifi-client` app we wrote. You'll need two ESP32s for this. One should use the NTP client app you wrote previously and the other will be running the promiscuous scanner.

  You'll need to figure out what channel your client device is connected on. It's available through the WiFi API once connected. Make the client app print that out.

  In your client app, you should also use `forceUpdate()` for the NTP library so it makes a network request each time instead of caching results for a minute. That way there are more packets to capture.

  To "filter" for only packets from your other ESP32 device, match against one of the address fields. Either `addr1` or `addr2` should contain the MAC address of your ESP32 client. If there's not a match, just return from the scanner function early.

- Once you can find packets from the device, grab interesting data from the packets! This is mostly in the `rx_ctrl` field of the `wifi_promiscuous_pkt_t` struct.

  The field itself is a struct of type `wifi_pkt_rx_ctrl_t`. You can find a full definition here: https://github.com/espressif/esp-idf/blob/master/components/esp_wifi/include/esp_wifi_types.h

(Tasks on next page)

1. **TASK:** Demonstrate ability to capture packets from your other device
    a. Show me the terminal output printing some packet metadata
    b. Commit your `wifi-promiscuous` code to your shared repo

2. **TASK:** Determine some information about how the ESP32 client is connected
    a. Which WiFi PHY protocol is it using to connect to the WiFi network? (e.g., 802.11b, 802.11g, 802.11n, etc.)
    b. Which channel is it connected on?
    c. How much bandwidth is it using on that channel, 20 MHz or 40 MHz?

Host WiFi

8. Host a WiFi network and connect to it

Going back to well-worn examples, let's make an ESP32 into an Access Point (AP) that runs its own WiFi network.

- Start with the `wifi-access-point` example code.
- Figure out how to make your ESP32 into a WiFi access point.

  Pick an interesting SSID for your group. You can leave the password parameter empty to make the AP open-access.
- Connect to it with some device.

  A phone works here. Although I find that on Android at least, it automatically disconnects after finding that there is no actual Internet connection.

  You can also connect with your client application! However, it'll find that Internet access isn't available and the NTP library will fail.
- The ESP WiFi libraries can provide more information about clients that are connected to it. Some starter code that fills in a `wifi_sta_list_t` is provided to you.

  You can find the definition for that struct here:
  https://github.com/espressif/esp-idf/blob/master/components/esp_wifi/include/esp_wifi_types.h
- Print out at least the following information about the clients that are connected:
  - MAC address
  - RSSI
  - Which 802.11 PHY protocols are enabled

1. **TASK:** Demonstrate creation of an Access Point
   a. Show me the terminal output printing data about a connected client
   b. Commit your `wifi-access-point` code to your shared repo

WiFi-MQTT Application

9. Use MQTT across multiple devices

This is the full demonstration application! We'll create a new network and connect two clients to it. On that network, we'll host an MQTT broker on the Access Point, publish from another device, and subscribe from a third device! If you're feeling iffy on MQTT, here's an overview: https://learn.sparkfun.com/tutorials/introduction-to-mqtt/all

- Three applications have been created for you:
  - `wifi-access-point-broker`
  - `wifi-client-publisher`
  - `wifi-client-subscriber`

- The library we'll be using for MQTT is TinyMqtt. The documentation is pretty non-existent, but the examples are good. See here: https://github.com/hsaturn/TinyMqtt/tree/main/examples

  The `simple-broker` example demonstrates running a broker. The `simple-client` example demonstrates publishing. The `client-without-wifi` example demonstrates subscribing.

  The library has already been enabled for you in the application's `platformio.ini` file.

- The TinyMQTT library requires that you run an update function in your `loop()`. To make this work, you need to avoid any use of `delay()` in your loop. You can still have periodic loop behavior though through the use of the `millis()` function and storing the past time. See `simple-client` for an example of this.

- You can publish to any topic you want (it's an arbitrary string) and with any data you want (also a string). However, make sure the data changes in some way!

1. **TASK:** Demonstrate the full working MQTT app across three devices
   a. I'll take your word for it. Write a couple of sentences on what you did and how it worked and show relevant terminal output from devices. Or you could alternatively include a link to a short video of it working
   b. Commit code for all three applications to your shared repo