IOT_project1

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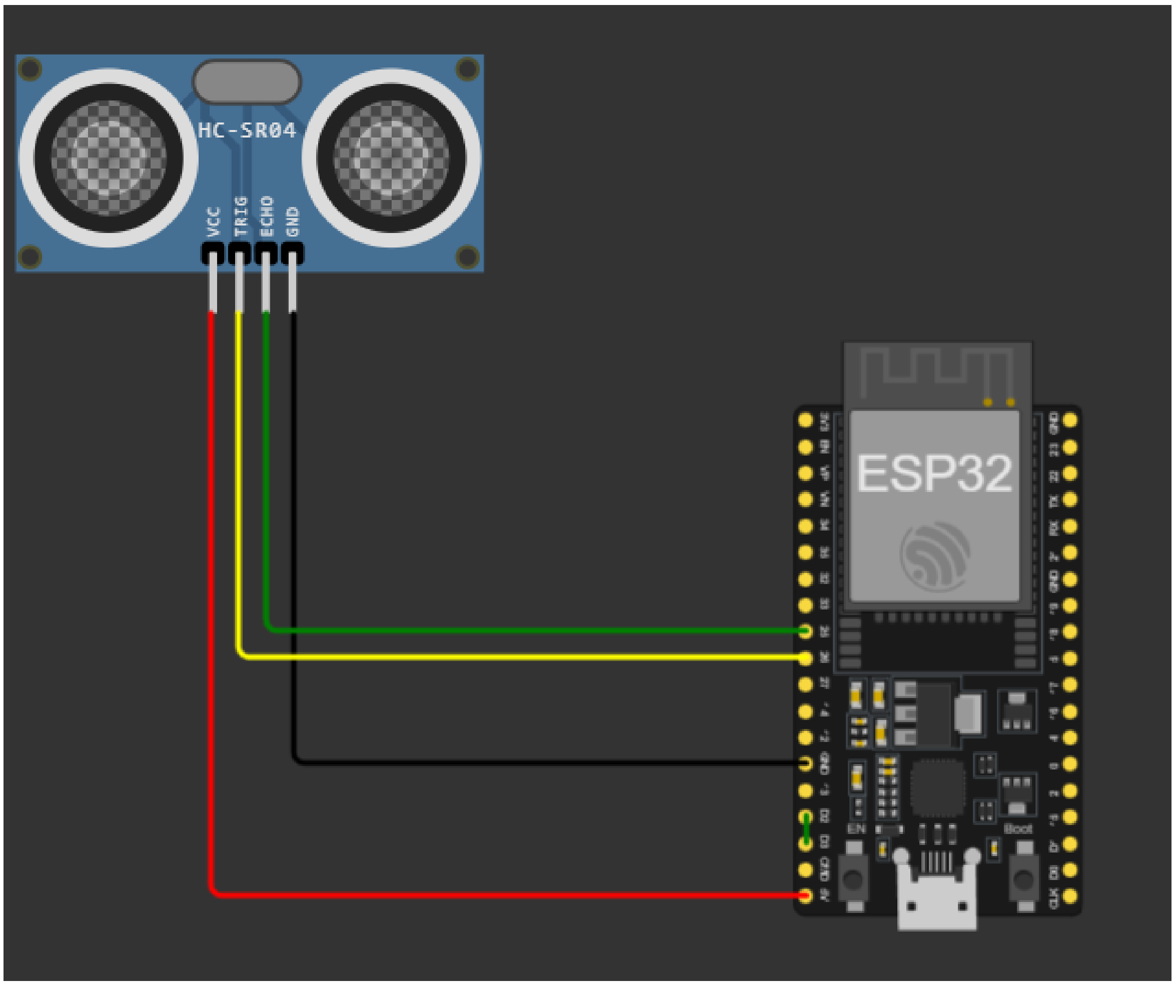
Requirements summary



The project goal is to implement parking occupancy node, on an ESP32 connected with the HC-SR04 ultrasonic distance sensor (as represented in the schematic above).
Using esp_now for wifi communication purposes and a battery as an alimentation supply.

> **note:** the parking is considered OCCUPIED if the measured distance is less than 50 cm

Implementation

The node is battery powered, so minimizing battery usage is critical; in order to reduce power consumption the sensor stays in deep sleep for the largest part of its duty cycle. The wake-up timer is set to 30 seconds; after the wake up, the sensor will perform the following operations (in the specified order):

1. performing a sensor data measurement
2. turn on wifi antenna
3. send sensor reading (& wait for eventual response)
4. turn of wifi antenna
5. set the EPS32 in deep sleep mode

> **note:** the whole implementation is provided here

Performing a sensor data measurement

The HC-SR04 ultrasonic distance sensor has 4 pins:

- **VCC** voltage supply 5v
- **GND** ground
- **TRIG** require a puls of 10uS to start the measure
- **ECHO** to get the distance

> **note:** the distance is retrieved in terms of pulse durations (microseconds), the following formula is used to compute the distance in centimeters.
>
> $$D_{cm} = T_{pulseduration} \cdot 0.034/2$$

As specified in the documentation, this sensor can read distances between 2 cm - 450 cm.
Following it is provided the function that performs the sensor measurements and the data structure used to save the results.

```
String sensorDataRead(int sensorInput, int sensorData){
 digitalWrite(sensorInput, LOW);   //for safety reasons
 delayMicroseconds(2);

 //start sensors reading
 digitalWrite(sensorInput, HIGH);
 delayMicroseconds(10);
 digitalWrite(sensorInput, LOW);

 //read
 int read = (pulseIn(sensorData, HIGH)*0.034/ 2)<limitDistance;
 state = (ParkingSpotState)read;

 return ParkingSpotStat_STRING[state];
}
```

```
#define GENERATE_STRING(STRING) #STRING,
#define FOREACH_PARKING(PARK) \
        PARK(FREE)   \
        PARK(OCCUPIED)  \

enum ParkingSpotState{
  FREE = 0,
  OCCUPIED = 1
};
static const char *ParkingSpotStat_STRING[] = {
    FOREACH_PARKING(GENERATE_STRING)
};
```

Sending info on the parking state

In this phase, the node turns on the wifi, sends the message (FREE or OCCUPIED) to the specified MAC address (throw esp_now protocol), waits for 2000 microseconds (to avoid communication error and to get an eventual response), and turns off the wifi again.

> **note:** in reality, the two last operations are implemented inside the *goToDeepSleep* function, but they are reported here for clearness.

Following are provided all the functions concern this phase:

```
void wifiSetup(){
 //wifi setup
 WiFi.mode(WIFI_STA);
 esp_now_init();
 esp_now_register_send_cb(onDataSent);
 esp_now_register_recv_cb(onDataRecv);
 memcpy(peerInfo.peer_addr, broadcastAddress, 6);
 peerInfo.channel = 0;
 peerInfo.encrypt = false;
 esp_now_add_peer(&peerInfo);
}
```

```
void sendBroadcastMessasge(String message){
 wifiSetup();

 WiFi.setTxPower(transmissionPower);
 esp_now_send(broadcastAddress, (uint8_t*)message.c_str(), message.length()+1);
}
```

```
void onDataSent(const uint8_t *mac_addr, esp_now_send_status_t status){
  if(status!=0)Serial.println("network error");
}
```

> **note:** it's possible to customize the *TxPower* value, following you would find evaluations for 2 dBm and 19.5 dBm.

Going to deep sleep

As we said above, to save battery, the device goes into deep sleep mode for 30 seconds each cycle.
Following is provided the function that performs this operation:

```
void goToDeepSleep(){
 delayMicroseconds(2000);  //for safety reasons
 WiFi.mode(WIFI_OFF);
 esp_sleep_enable_timer_wakeup(dutyCyclePeriod * uS_TO_S_FACTOR);
 esp_deep_sleep_start();
}
```

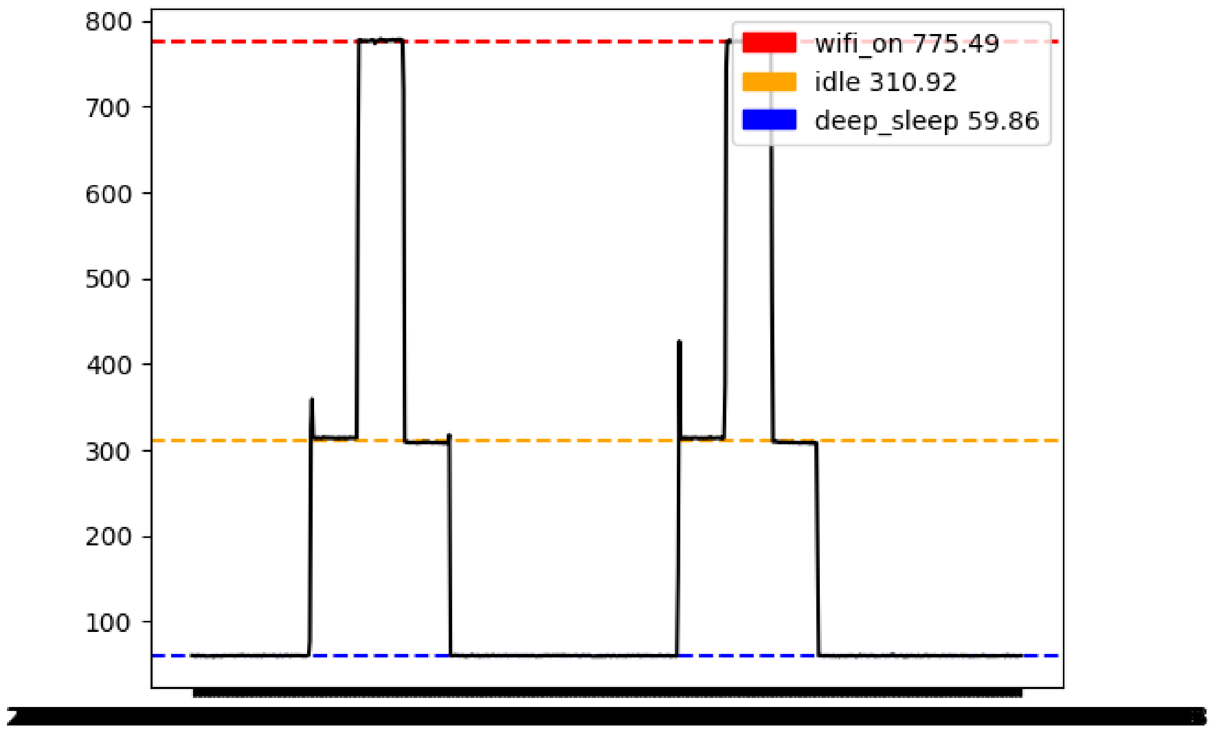
Data analysis

To estimate battery life we measured real energy consumption data in different situations. On the provided samples we had to compute the k-mean estimator to ignore measurement noise.

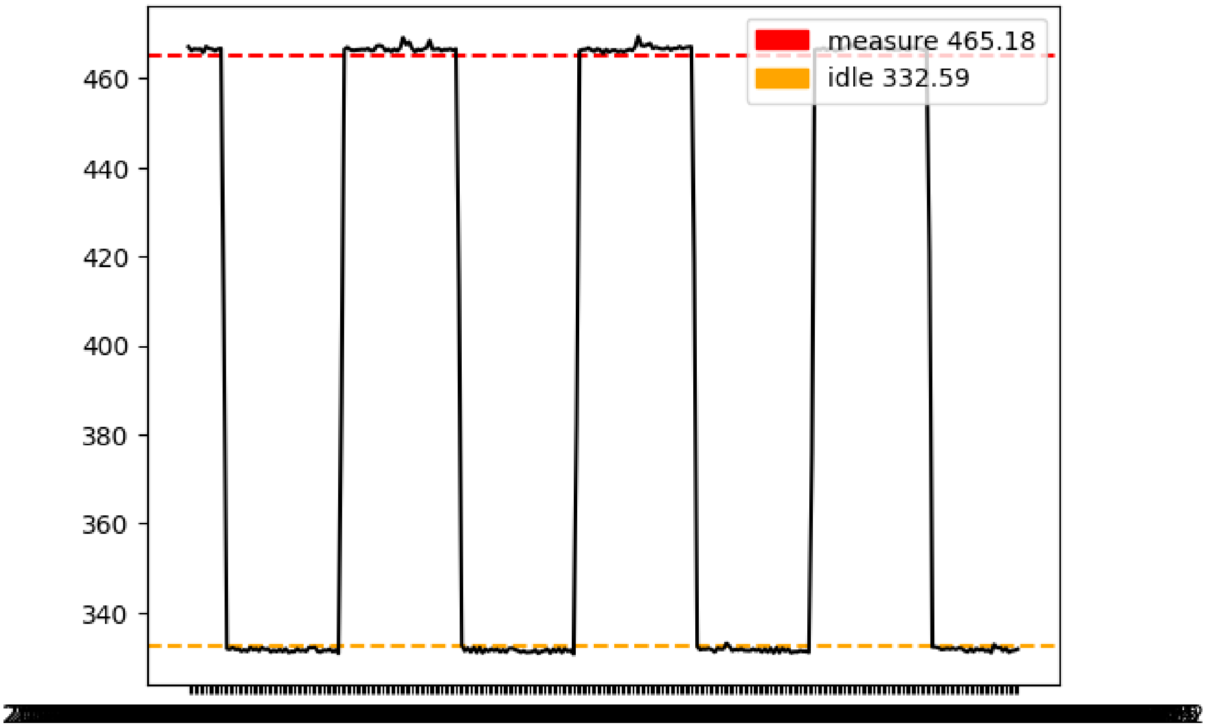
> **note:** we have noticed differents consumption data in identical device state in different situations (probabily caused by experimentl erros), we are going always to use the worst data available.

Following you can find a summary of the data analysis in terms of graphycal rappresentation and tables, but the full analysis provided here.

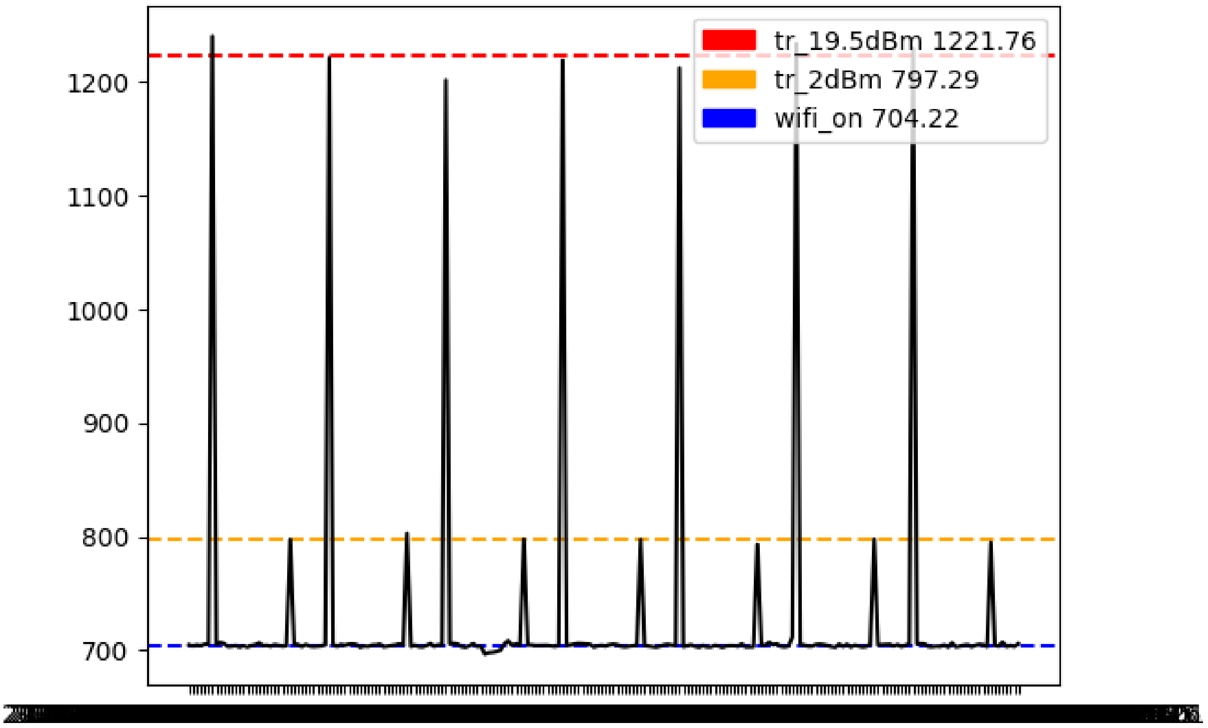
esp32 duty cycle



hc-sr04 energy absorption



esp_now energy absorption



Analysis on data summary

state	total energy absorption
during deep sleep	59.86
during idle state	332.59
during HC-SR04 distance measure	465.18
with wifi antenna on	775.49
during signal transmission (2dBm)	797.29
during signal transmission (19.5dBm default)	1221.76

Battery life estimation

The duty cycle of the node can be split in 6 phases: deep sleep, wake up, perform a distance measure, send the provided data, wait for response, go to sleep.

$$T_{sleep} \Rightarrow T_{wake-up} \Rightarrow T_{sensor-measure} \Rightarrow T_{tx} \Rightarrow T_{wifi-on} \Rightarrow T_{go-to-sleep}$$

The required time to wake up and to go to sleep is near to zero, also the required energy amount (for those two phases) is limited, so this 2 phases can be ignored.
So the total energy consumption for a single cycle becomes:

$$E_{tot} = E_{sleep} \cdot T_{sleep} + E_{sensor-measure} \cdot T_{sensor-measure} + E_{tx} \cdot T_{tx} + E_{wifi-on} \cdot T_{wifi-on}$$

We need to evaluate each term independently.

Deep sleep power absorption

As said above the device is going to stay in deep sleep mode for 30 seconds, so we can compute the absorption as follows:

$$E_{sleep} \cdot T_{sleep} == 1.795,8 \cdot 10^{-3} J$$

Distance measure power absorption

The sensor measures the pulse duration, so the required time to perform a measure change with the measured distance as expressed in the following formula:

$$T_{sensor-measure} = \frac{distance \cdot 2}{0,034} J$$

Let's consider the worst cases:

- **free parking spot:** $distance = 450cm(maxdistance) \implies T_{sensor-measure} = 26470 \cdot 10^{-9} s$
- **occupied parking spot:** $distance = 50cm \implies T_{sensor-measure} = 2941 \cdot 10^{-9} s$

As specified in the documentation, the HC-SR04 requires, as a start-measure signal, that the input *trig* stay high for $\delta t = 10 \cdot 10^{-9} s$.
The worst case possible, in terms of power absorption required to perform distance measurements, is when the parking spot is always free:

$$E_{sensor-measure} \cdot (T_{sensor-measure} + \delta t) = 1,2 \cdot 10^{-5} J$$

A more reasonable situation is when the parking spot is free for 50% of the performed measures:

$$E_{sensor-measure} \cdot T_{sensor-measure} = E_{sensor-measure} \cdot (T^{free}_{sensor-measure} \cdot 50$$

Transmission power absorption

We need to compute the transmission time, ESP_now allow to send packet with 250 bytes of data, assuming a header of 6 bytes (MAC_address size) L = 256 byte = 2048 bit.
Assuming the protocol always sends the whole packet and knowing that the transmission rate is set to 1 Mbps (as default), we can compute the transmission time as follows:

$$T_{tx} = \frac{L}{R} = 2,048 \cdot 10^{-3} s$$

We measured the instantaneous absorption for 2 different transmissions (2 dBm, 19.5 dBm default setting).

$$E^{2dBm}_{tx} \cdot T_{tx} = 1,632 \cdot 10^{-3} J$$

$$E^{19.5dBm}_{tx} \cdot T_{tx} = 2,502 \cdot 10^{-3} J$$

Waiting for response power absorption

To avoid communication errors (and eventually receive messages) the sensors will wait with wifi antenna on for 2 ms after completed the state transmission.
We can compute the energy consumption in this phase as follows:

$$E_{wifi-on} \cdot T_{wifi-on} = 1,551 \cdot 10^{-3} J$$

Total energy absorption and battery life estimation

We want to evaluate the battery life, in terms of numbers of completed cycles, for both the power transmission settings.

- power of transmission 2 dBm

$$E^{2dBm}_{tot} = E_{sleep} \cdot T_{sleep} + E_{sensor-measure} \cdot T_{sensor-measure} + E^{2dBm}_{tx} \cdot T_{tx} + E_{wifi-on} \cdot T_{wifi-on} \simeq 1,799 J$$

- power of transmission 19.5 dBm

$$E^{19.5dBm}_{tot} = E_{sleep} \cdot T_{sleep} + E_{sensor-measure} \cdot T_{sensor-measure} + E^{19.5dBm}_{tx} \cdot T_{tx} + E_{wifi-on} \cdot T_{wifi-on} \simeq 1,799 J$$

> **note:** there isn't a significant advantage in reducing the transmission power of the wifi antenna, in fact the number of cycles does not change.

$$\Longrightarrow N_{cicles} = \frac{9080}{E^{2dBm}_{tot}} \simeq 5047$$

In conclusion, the sensor has enough power for above 42 h.

Possible improvements

This chapter provides some implementation improvements designed to reduce the total energy absorption.

Send and forget

A first simple improvement is to apply a *send-and-forget* paradigm to wifi messages, avoiding keeping the wifi antenna powered for 2000 microseconds after sending the sensor state through the ESP_now message.
This improvement allows us to save $1,551 \cdot 10^{-3} J$ the equivalent of 4,35 cycles.

Longer deep-sleep time

It is reasonable to think that increasing the deep sleep time is a great improvement, but this is not the case.
Due to the limited amount of power, and time, required to perform a single parking state measure and to send the data to the sink node, increasing the distance between two measures doesn't provides a significant advantage.
For example, by modifying the deep sleep time to 3 minutes it's possible to achieve 842 cycles equivalent to 42,1 hours, instead of 42 hours.
This limited improvement can't justify the compromise in terms of the sensor responsiveness.

Non constant deep-sleep time

Similar to commercial movement sensors based on Zigbee, we can change the deep sleep time value based on the last sensor state (free or not parking spot), applying a longer time for the state that requires a larger amount of energy (the free park in this case).
As discussed in the previous paragraph, this can't improve in a significant way the battery life; unless in our specific application, we are more interested into detecting when the parking becomes free (instead of when it becomes occupied), in this case the compromise is probably acceptable.

Transmit only on changes

The idea is to save the data read from the HC-SR04 sensor in the flash memory (nonvolatile). At each new cycle the data D(t) is compared with the previous data saved in the flash D(t-1), so the sensor will communicate with the sink node and update the data in the flash memory $iff D(t) \neq D(T-1)$, otherwise the ESP32 can go directly into deep sleep, without powering on the wifi antenna and send the data to the risk node.
Assuming the parking spot changes status, in mean, every 3 hours, with this approach we avoid comunicate the node status 5035 times in 42h, saving about $12.63J$ (avoiding transmition at 19.5 dBm) the equivalent of 7,01 cycles.

To implement this improvement is required simple modifications, following you can find the two basic functions used to achieve those modifications:

```
#include <Preferences.h> //required to save boolean into nonvolatile memory
Preferences p;

void saveCurrentState(ParkingSpotState state){
  bool parkingNonVolatileState = (state==OCCUPIED);
  p.putBool("parkingState", parkingNonVolatileState);
}

ParkingSpotState getPreviousState(){
  bool parkingNonVolatileState = p.getBool("parkingState", false);
  ParkingSpotState state = (ParkingSpotState) int(parkingNonVolatileState);
  return state;
}
```

> **note:** the modified implementation for this improvement is provided here.

In conclusion, there are no ways to stretch the battery life in a significant way by simply adapting the implementation.
Due to the large amount of energy used in deep sleep mode in comparison with the other phases, there is no possibility to achieve consistent battery life without providing an external energy supply.
However a little solar panel is ideal to supply all the required power for 24 hours.