Passive Wi-Fi: Bringing Low Power to Wi-Fi Transmissions

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Outline

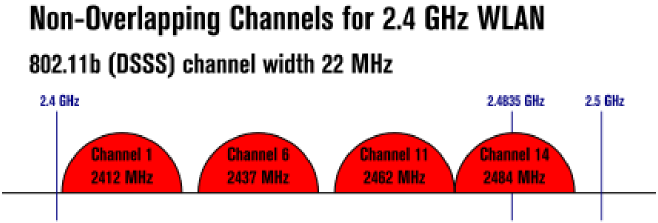
1. Introduction: How does WiFi work?
   - Electromagnetic Waves
   - Wave modulation
2. Passive WiFi
   - The design
   - Resolved issues
   - Implementation and tests

Wave basics

We can describe the electromagnetic wave with 3 properties

- frequency $\rightarrow sin(f * t)$
- amplitude $\rightarrow a * sin(t)$
- phase $\rightarrow sin(t + p)$

WiFi frequency



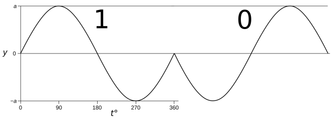
Carrier wave

- A WiFi device generates the carrier wave setting an appropriate frequency and amplitude.
- This wave is modulated in order to encode information in it.

Wave modulation

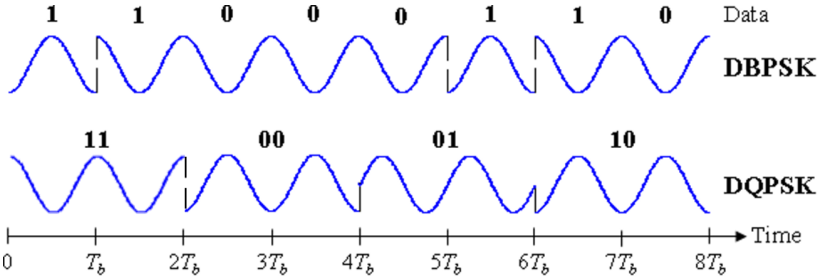
- modulation = modification
- You can modulate any of the 3 properties of the wave.
- In WiFi the phase is modulated

Phase-shift keying



- Binary PSK
  - 0 - 0°
  - 1 - 180°
- Quadrature PSK
  - 00 (0) - 225°
  - 01 (1) - 135°
  - 11 (2) - 45°
  - 10 (3) - 315°
  - using Grey's code

Differential PSK

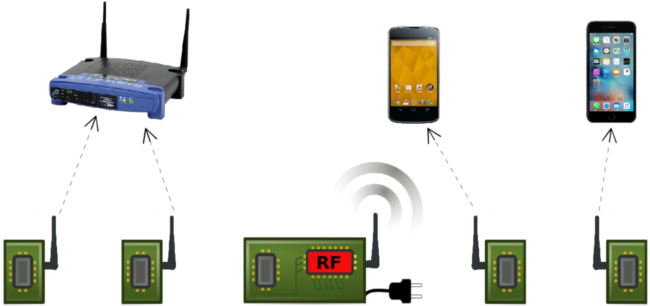


Error avoidance

Due to high possibility of interference data is further encoded with DSSS/CCK rather than sent bit per wave word.

Goal of passive WiFi

- The design targets IEEE 802.11b
- The main goal is to lower power usage for IoT devices



Design

The passive WiFi design consists of two parts:

- RF device
- passive device

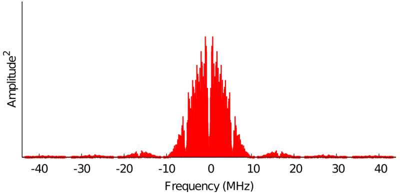
The RF device is plugged in to a standard power socket.
The passive device is a part of some other device running on battery.

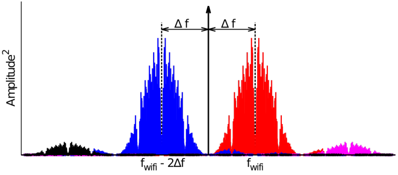
Design

- Plugged-in device generates the carrier wave, offsetting it between two channels.
- Passive device uses backscatter modulation to offset the wave back in the middle of the channel and generate data in the signal.
  - This is achieved by generating a square wave at frequency Δf and offsetting its phase to create DBPSK/DQPSK modulation.

Frequency shift result

This also produces a duplicate wave on the other side.

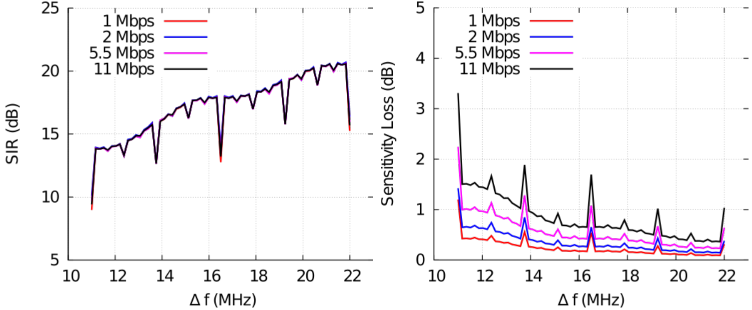




But thanks to Δf being small we save a lot of energy.

Interference

Mirror wave's side lobes cause interference. Below are measurements of Δf to reduce them.



Standard WiFi uses additional filters to get rid of those side lobes.

Interference

In the end $\Delta f = 12.375$MHz has been chosen.

- Sensitivity loss is below 2dB for all bitrates
- The wave and mirror wave only occupy two channels

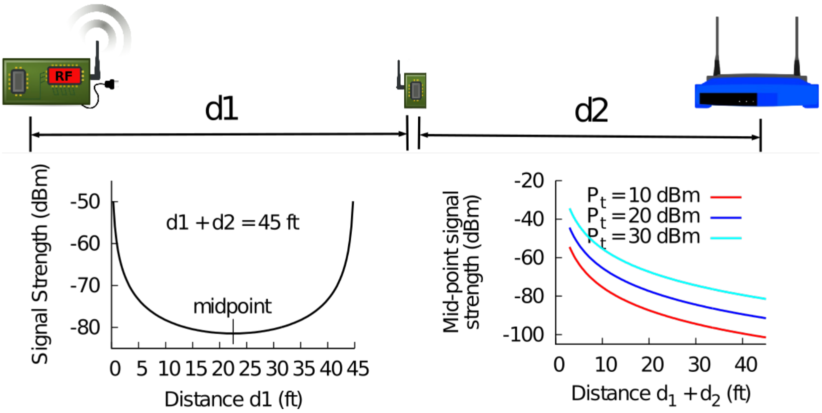
Range analysis

Power at the receiver:

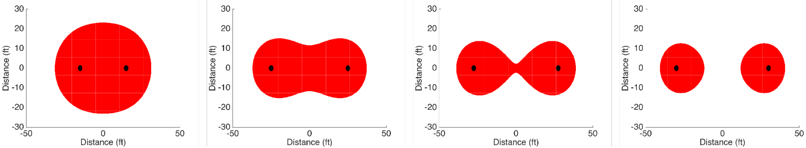
$$P_r = (\frac{P_t G_t}{4\pi d_1^2})(\frac{\lambda^2 G_{passive}^2}{4\pi}\frac{|\Delta\Gamma|^2}{4}\alpha_{wifi})(\frac{1}{4\pi d_2^2}\frac{\lambda^2 G_r^2}{4\pi})$$

P_t and G_t is the power and gain of plugged-in device.
$G_{passive}|\Delta\Gamma|^2$ is the backscatter coefficient (here 1.1dB)
α_{wifi} is the energy loss from backscatter (4.4dB incl. losing half the energy for mirror wave)

Range analysis



Range analysis



30/50/55/60 feet separation of plugged-in device and receiver

Carrier sense

WiFi uses CSMA to send signal only when no other device is sending theirs.
This couldn't be done in the passive device so the plugged-in devices performs it.
When passive device can start its job the plugged-in device sends a packet using ON/OFF words.

0 : 9	10	11 : 12	13 : 15
Device ID	Ack	Rate	Check Bits

This kind of communication takes 18μW at 160kbps.

ACKs

WiFi uses ACKs to report correct decoding of messages. This couldn't be done in the passive device so the plugged-in devices performs it.

0 : 9	10	11 : 12	13 : 15
Device ID	Ack	Rate	Check Bits

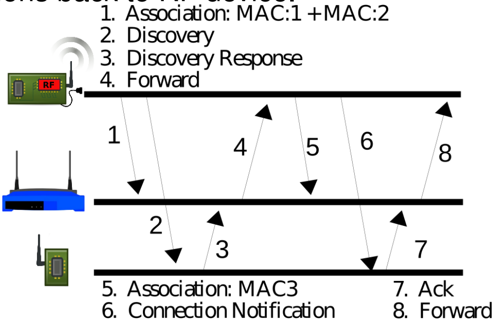
Rate adaption

The WiFi standard determines which bitrate and thus protocol should be used when there's a lot of interference.
The plugged-in device counts retransmissions and if there are many it switches to a lower more stable bitrate.

0 : 9	10	11 : 12	13 : 15
Device ID	Ack	Rate	Check Bits

Communicating with the RF device

The passive device and RF device work simultaneously to produce a WiFi signal.
If RF device is listening then it cannot send anything.
So we can introduce a proxy router that will forward communications back to RF device.

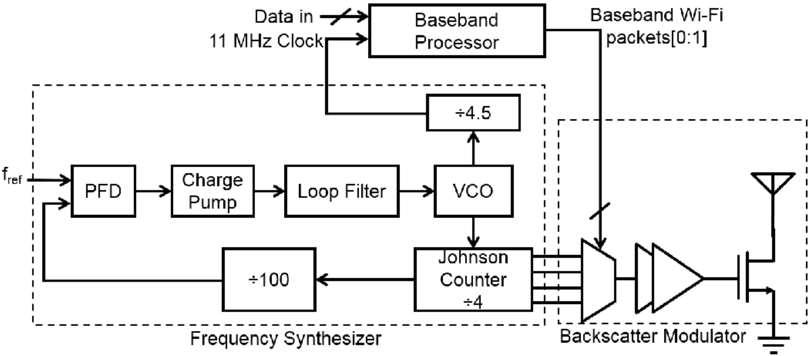


Hardware - off-shelf

- backscatter modulator (HMC190BMS8 SPDT RF switch network on a 2-layer Rodgers 4350 substrate)
- DE1 Cyclone II FPGA (encoded with Verilog)

The FPGA platform was used to implement the logic: generating headers, DSSS/CCK, CRC, DBPSK/DQPSK.

Hardware - custom circuit



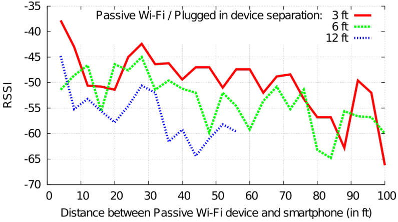
Hardware - custom circuit

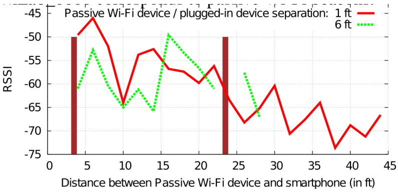
Table 1: Passive Wi-Fi's IC Power Consumption

	1 Mbps	11 Mbps
Baseband Frequency Synthesizer	5.6 µW	5.6 µW
Baseband Processor	5.0 µW	48 µW
Backscatter Modulator	3.9 µW	5.6 µW
Total Power	14.5 µW	59.2 µW

Received Signal Strength Indication
Test

Moving phone away from passive device.

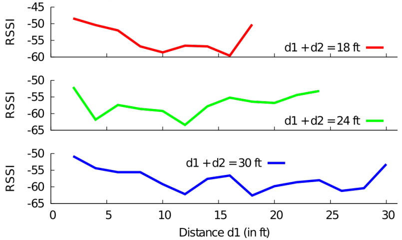


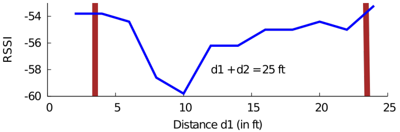


Received Signal Strength Indication

Test

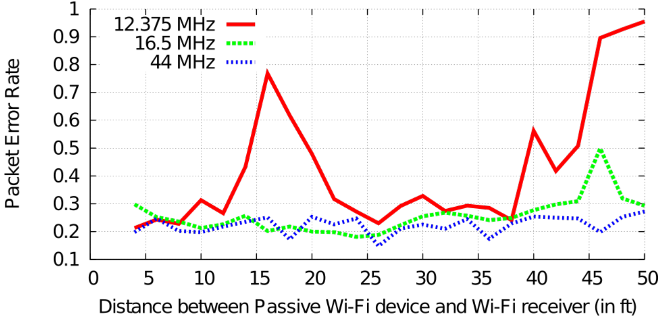
Moving passive device between RF device and phone.





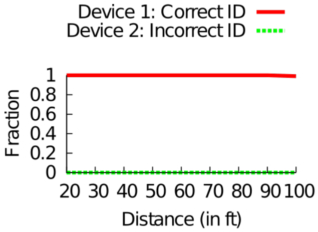
Error rate
Test

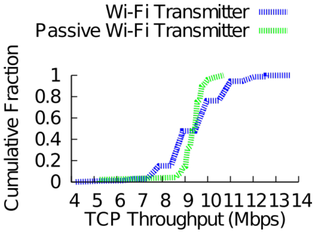
Trying out different Δf



ID mistake | Carrier sense
Test

(left) error in ON/OFF packet due to inference
(right) CSMA during TCP session comparing standard WiFi with passive WiFi





Usage

low power microphone	50μW
low power camera (2.45Mbps)	10mW
IoT WiFi	670mW
Passive WiFi (1Mbps)	65μW
Passive WiFi (11Mbps)	3mW

iBeacon

Bluetooth Low Energy	35mW
Passive WiFi (short messages)	15μW

Summary

- A plugged-in device generates carrier wave.
- Passive device modulates it - encoding data.
- The modulation occurs in backscattered signal.
- It uses less power then other solutions.
- The passive device should be close to the receiver or the plugged-in device.

References

- „Passive Wi-Fi: Bringing Low Power to Wi-Fi Transmissions" - Bryce Kellogg, Vamsi Talla, Shyamnath Gollakota and Joshua R. Smith
- WiFi channels image - CC BY Liebeskind
- DB/QPSK image - CC BY SA SaltyOrange