Wireless Power Transfer

Wireless Sensing

Overview

1. Simultaneous Wireless Information and Power Transfer (SWIPT)
2. Radio Frequency (RF) Sensing

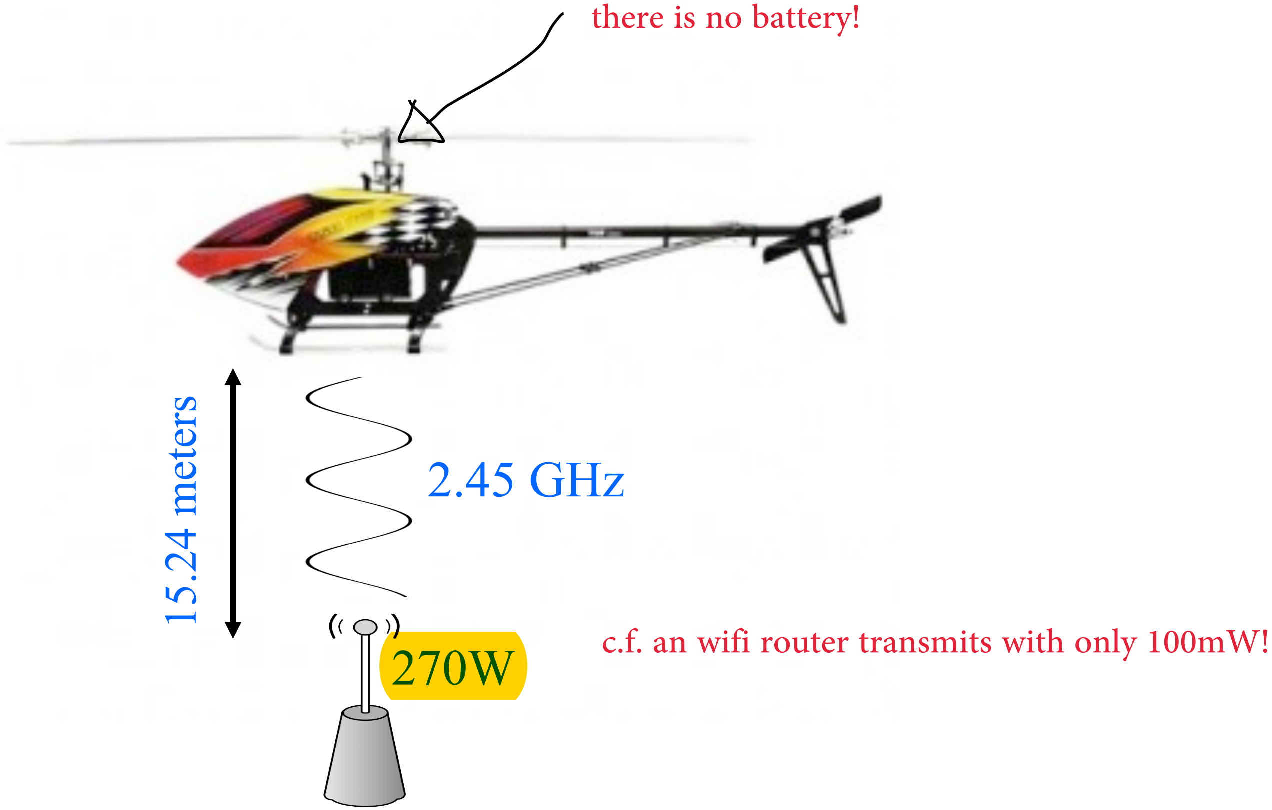
The 3 Capabilities of Radio Frequency

- Wireless communication: data/information transfer from a Tx to a Rx
- Wireless power transfer: transfer of power/energy from a Tx to a Rx
- Wireless sensing: remote sensing of humans and other phenomena

Simultaneous Wireless Information and Power Transfer (SWIPT)

Flying a Helicopter without a Battery!

A 1960 Experiment!

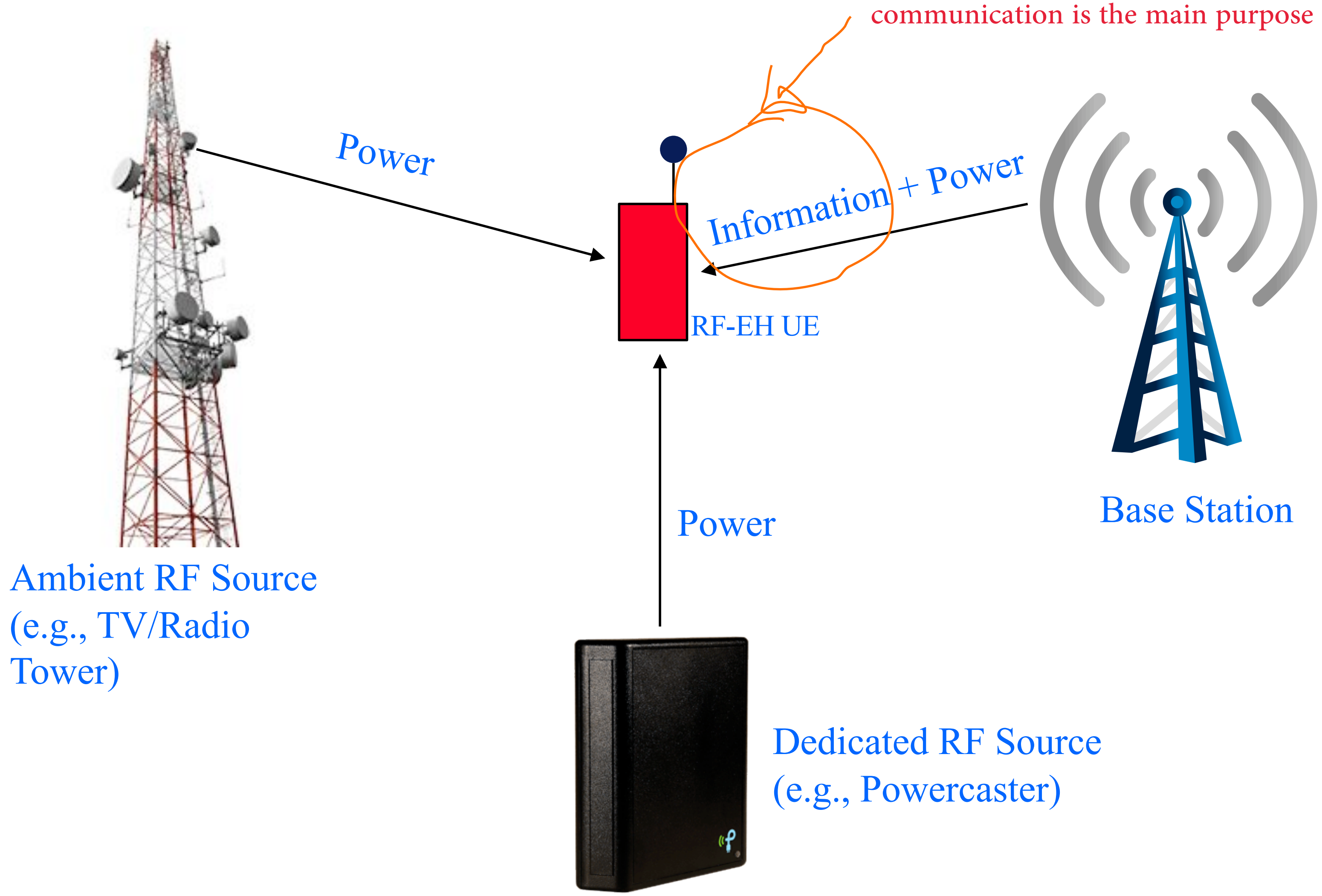


Applications of Wireless Power Transfer and RF Energy Harvesting

- Sensor and IoT networks: recharge/power difficult to reach sensors through RF energy harvesting
- Medical implants: recharge/power electronic circuits in modern implanted medical devices
- Wearable and body area networks: recharge/power body-worn sensors
- Cellular relays: power relays through RF energy harvesting
- UAV/drone: extend flying time of UAVs/drones through remote charging (UAVs can be used as flying relays in cellular networks)

RF Energy Sources

RF-EH UE: RF energy harvesting user equipment



RF energy sources

- Ambient sources
  - e.g. TV/radio/cellular towers
- Dedicated sources
  - Deploy static RF sources (high cost)
  - Mobile RF sources (can move around and provide power where needed; e.g., mobile robot to charge IoT sensors in a factory, flying drone to charge sensors in a large agriculture field, etc.)
  - Hybrid (some static and some mobile)

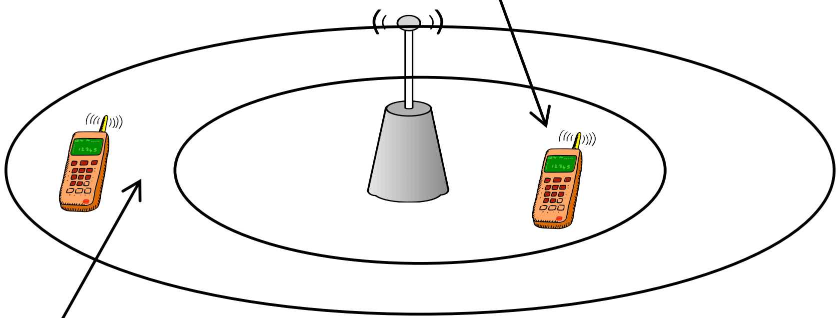
Dedicated sources

- Deploy dedicated infrastructure
- Density and coverage must be planned for the deployment
- Example of commercial products (indoor): *powercaster* (can be wall-mounted)

17.1cm H x 15.9cm W x 4.1cm

915 MHz TX91501 powercaster transmitter (3W/1W)
www.powercastco.com

Base station as an RF energy source



EH possible in this zone

EH circuits usually have higher sensitivity (e.g., -10 dBm) than conventional information decoders (e.g., -60 dBm)

Information decoding possible in this zone, but not EH

In-band vs. Out-of-band RF Energy Harvesting

e.g., 900MHz for power transfer and 2.4GHz for communication

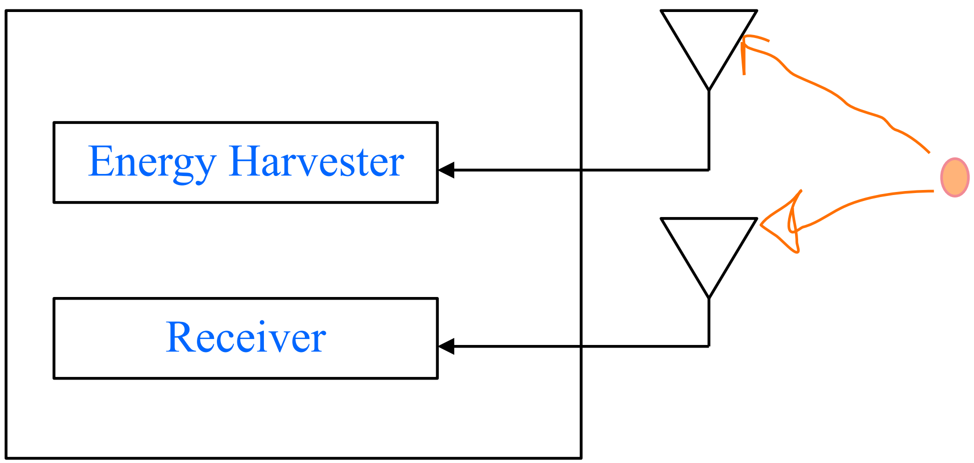
- Out-of-band: energy harvesting uses different frequencies than those used for communication; must use separate antennas for energy harvesting and communications (the antenna is tuned to the frequencies used for either energy harvesting or communication)

e.g., use 2.4GHz for both power transfer and comms

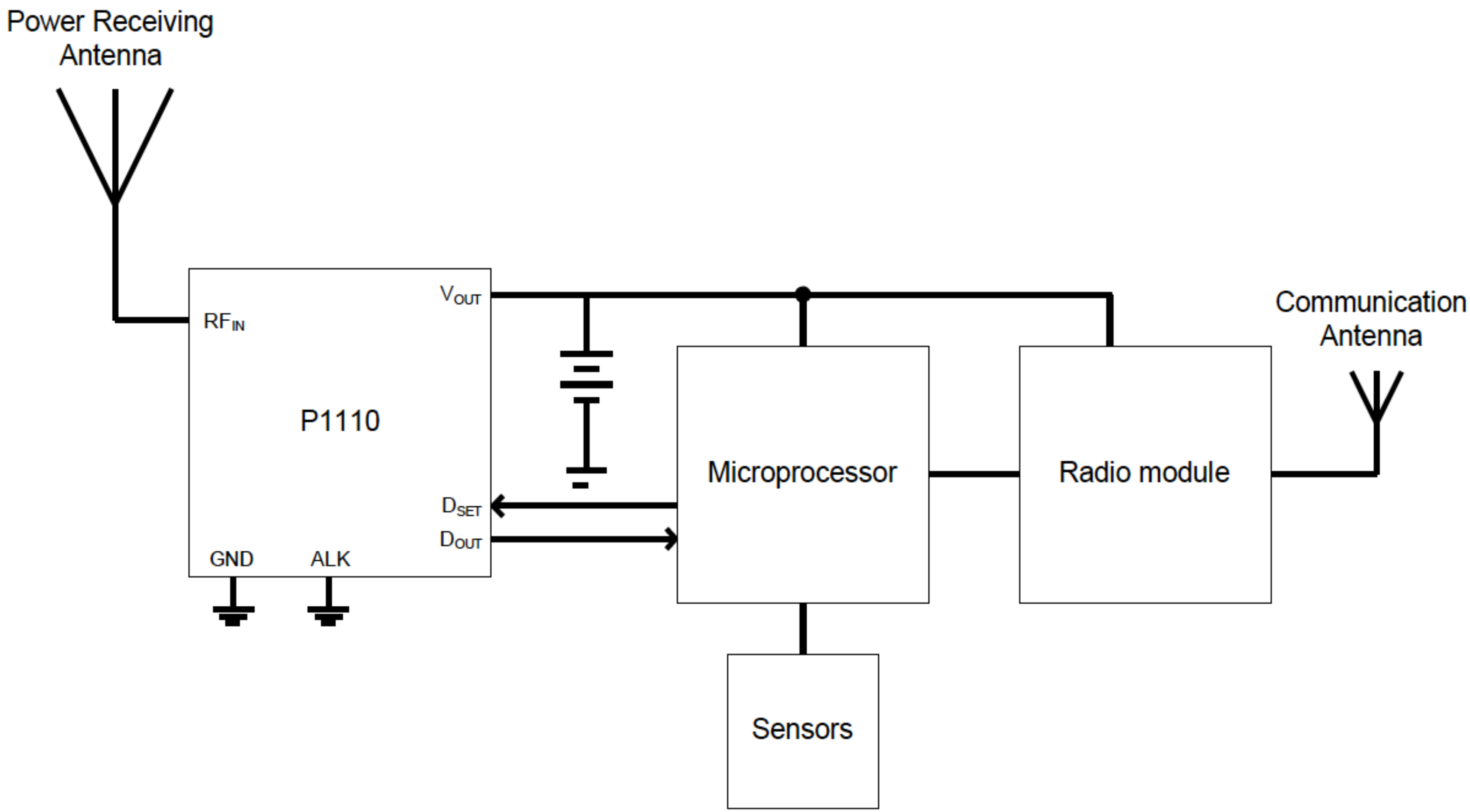
- In-band: the same RF signals used for both communication and energy harvesting; unfortunately, if signal is processed for communication (decoding), it *cannot* be used for energy harvesting
- Three choices for in-band energy harvesting
  - Separate antennas (similar to out-of-band; independent antennas for communication and energy harvesting)
  - Single antenna with time switching (use the signal for either communication or EH, one at a time)
  - Single antenna with power splitting (use the same signal for both communication and energy harvesting in parallel, but by splitting the signal power)

Energy harvesting with separate antennas

- Larger form factor and higher cost, but
- Cleaner separation of signals
  - Entire signal power available for energy harvesting ($P_H = P_R \times \eta$; η is RF-DC conversion efficiency)
  - No additional noise for information processing ($C=W\log(1+P_R/P_N)$; P_N is thermal/antenna noise)

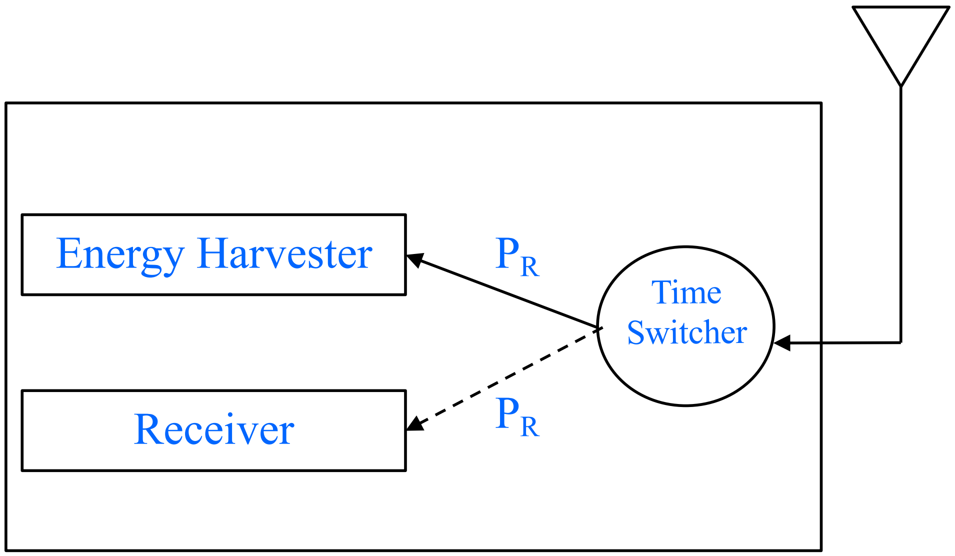


Commercial example of in-band RF energy harvesting with separate antennas [from powercastco.com]



Energy harvesting with a single antenna: *time switching*

- Loss of opportunity (time slots) for both energy harvesting and communication, but
- Cleaner separation (in time) of signals
  - Entire signal power available for energy harvesting [$P_H = P_R \times \eta$]
  - No additional noise for information processing [$C=W\log(1+P_R/P_N)$]

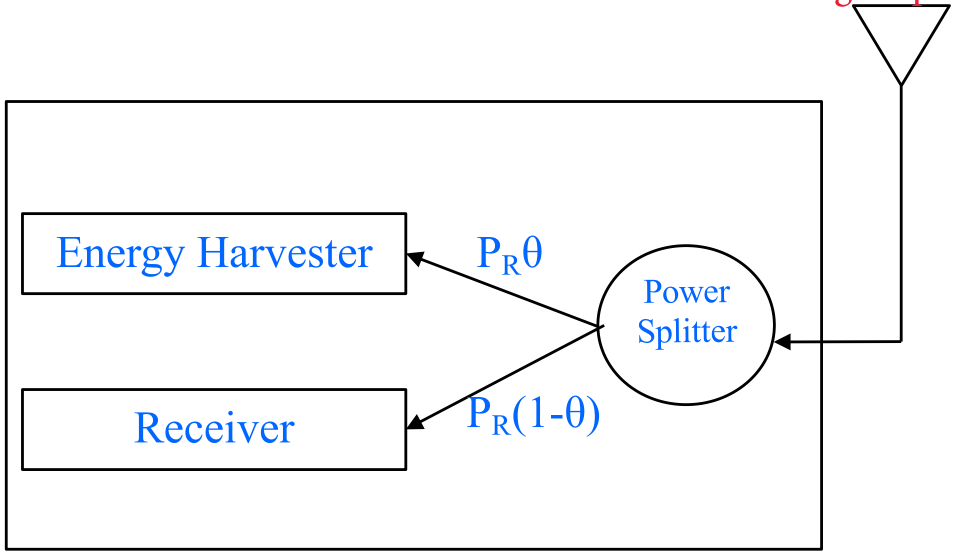


Energy harvesting with a single antenna: *power splitting*

- No opportunity (time slot) loss, but
- Power is split, which reduces harvested energy [$P_H = P_R \times \theta \times \eta$; θ is fraction of received signal used for energy harvesting]
- Signal sharing introduces signal processing noise, which further reduces communication capacity [$C=W\log(1+P_R(1-\theta)/(P_N+P_{SP}))$; P_{SP} is the power of signal processing noise]

increased noise

decreased signal power



From power to energy

- Harvested RF energy (E_H) is a product of two variables
  - Harvested RF power at the receiver (P_H)
  - Time duration, T, for which the P_H is being harvested
  - $E_H = P_H \times T$
- P_H may vary over time (e.g., the mobile device is at different distances from the power transmitter at different times)
  - $E_H = P_{H1} \times T_1 + P_{H2} \times T_2 + \ldots$

RF harvested power at the receiver

- Harvestable power at receiver (P_H) = received power (P_R) x RF-DC conversion efficiency (η)
- $P_H = P_R \times \eta = RSS \times \eta$ (RSS is reported by most devices)
- Example: we can harvest only 500pW for a RSS of -60dBm for a 50% RF-DC conversion efficiency
- Received power (P_R) depends on RF propagation model

1 nW

Can WiFi AP become an ambient source?

- AP transmit power = 1 mW
- AP transmission frequency = 2.4 GHz
- AP to receiver distance = 2 m
- Conversion efficiency $\eta = 0.5$
- Assume free-space unit antenna gain
- Q: How much power harvested during packet reception?
- A:
  - $P_R = 244$ nW (-36 dBm)
  - $P_H = 244$ nW x 0.5 = 122 nW (122nJ/s)
- Q: How long will it take to harvest 122mJ?
- A: 1 million seconds = 277 hours!!

Lesson learned: WiFi frequency is too high and the transmit power is too low to be an effective RF energy source

Experimental RF energy harvesting rates

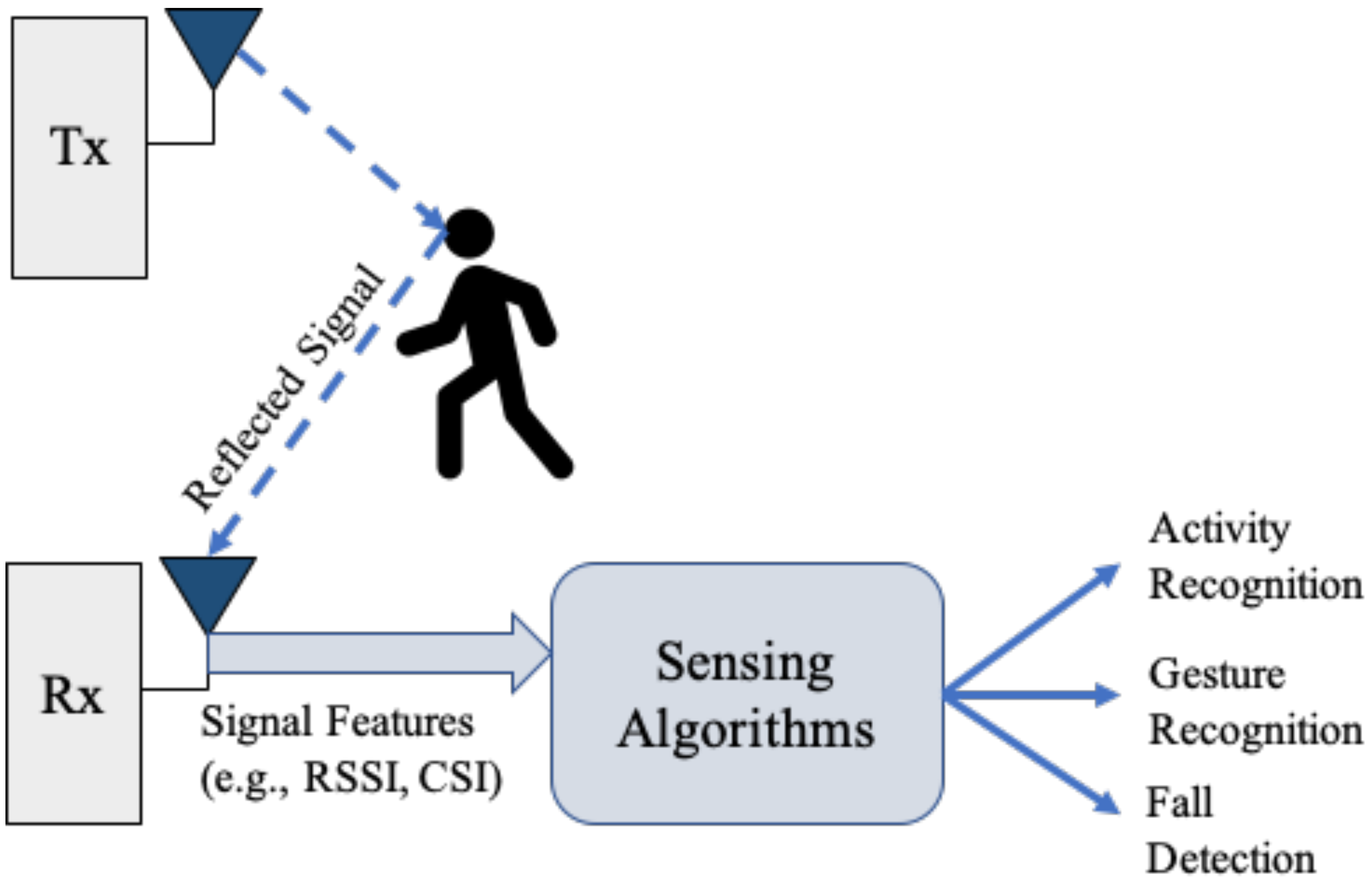
Source	Source Power	Frequency	Distance	EH rate
Isotropic RF Transmitter	4 W	902-928 MHz	15 m	5.5 μW
Isotropic RF Transmitter	1.78 W	868 MHz	25 m	2.3 μW
Powercaster	3 W	915 MHz	5 m	189 μW
TV Tower	960 kW	674-680 MHz	4.1 km	60 μW

can power many small sensors

Source: Wireless Networks With RF Energy Harvesting: A Contemporary Survey, by Xiao Lu, Ping Wang, Dusit Niyato, Dong In Kim, and Zhu Han, IEEE Communications Surveys and Tutorials, VOL. 17, NO. 2, SECOND QUARTER 2015

RF Sensing

Human Sensing



Commercial Success of RF Sensing

- Several start-ups now offer commercial RF Sensing solutions: sleep monitoring, vital sign monitoring, fall detection, localization and tracking, activity monitoring, people counting, and so on.
  - https://www.celeno.com/wifi-doppler-imaging
  - https://www.emeraldinno.com/
  - https://walabot.com/walabot-home
  - https://www.originwirelessai.com/wirelessai
  - https://xkcorp.com/

Signal Features

- Received Signal Strength (RSS): *average* signal amplitude
- Channel State Information (CSI): *detailed* amplitude/phase
- Time of Flight (ToF): estimates range
- Doppler shift: estimates velocity

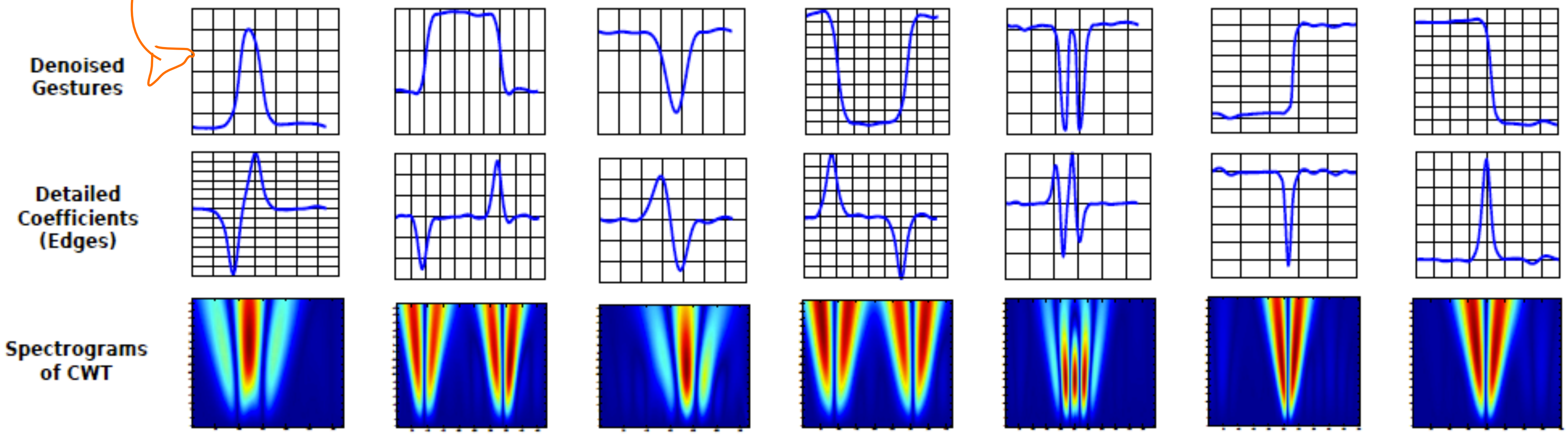
Human Sensing with RSS

- Single scaler power value (dBm) reported for the whole channel
- Built-in support: all mobile devices measure and report RSS; no special hardware/software needed
- As RSS is affected by human presence in the wireless environment, human activities can be detected from the RSS patterns

Controlling a smartphone through hand gesture; hand gestures affect the WiFi RSS at the phone

Example of RSS-based hand Gesture Detection

the first row is simply filtered RSS time series



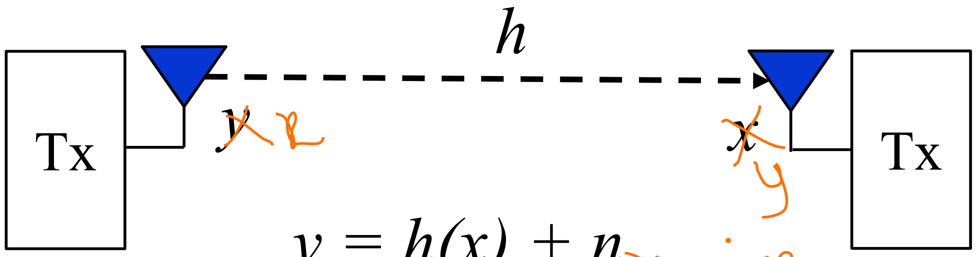
(a) Up-Down (b) Up-||-Down (c) Down-Up (d) Down-||-Up (e) Right-Left (f) Up (g) Down

available in Moodle for you to read

Source: Abdelnasser, Youssef, and Harras: WIGEST, INFOCOM 2015

CSI

- RSS averages signal amplitude over the entire channel bandwidth; cannot reveal the channel response, i.e., how the amplitude and phase changes for different frequencies within the channel; RSS therefore is good only for **coarse** sensing and unsuitable for **detailed** sensing tasks
- Signal **phase** changes when the reflector moves or changes location; changes in path length will cause phase change (why?)
- CSI refers to known channel properties, i.e., how the channel affect the amplitude and phase of the transmitted signal, between a Tx and Rx

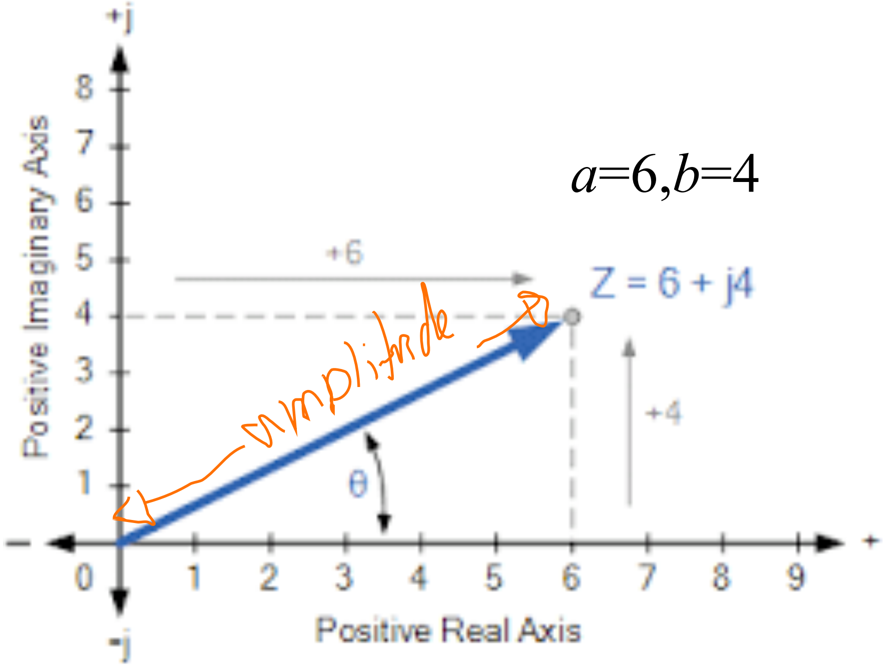


$$y = h(x) + n$$ noise

CSI estimation involves estimating *h*

Mathematical Representation of CSI

- CSI tells us how much the channel will **attenuate the amplitude** and how much it will **shift the phase** of the transmitted signal
- CSI is a **complex number**, which can be represented as either
  - $Ae^{j\theta}$ (A=amplitude, θ=phase, j=$\sqrt{-1}$), or
  - $a+jb$ (Amplitude = $\sqrt{a^2+b^2}$, $Phase = \tan^{-1}\frac{b}{\cancel{b}\,a}$)



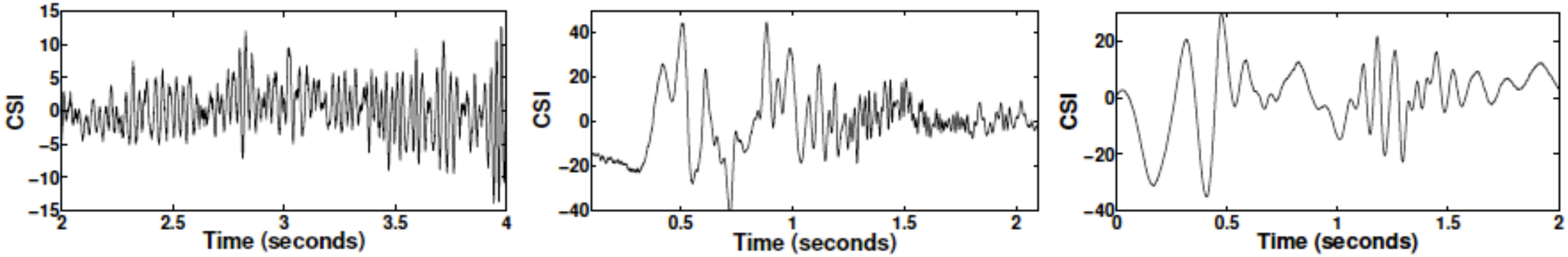
Use of CSI in Wireless Communication

- CSI is used at the PHY layer
- CSI is used in the PHY layer of WiFi and cellular networks to estimate the channel (quality) and improve communication reliability and data rates
- In WiFi, the packet preamble contains known signals, which is compared with the received signals to estimate CSI at the receiver; the receiver then uses the CSI to decode the data symbols in the packet payload; the Rx may also provide CSI feedback to the Tx, e.g., in 802.11n, so the Tx can adjust the data rates (modulation and coding) or configure MIMO transmission parameters

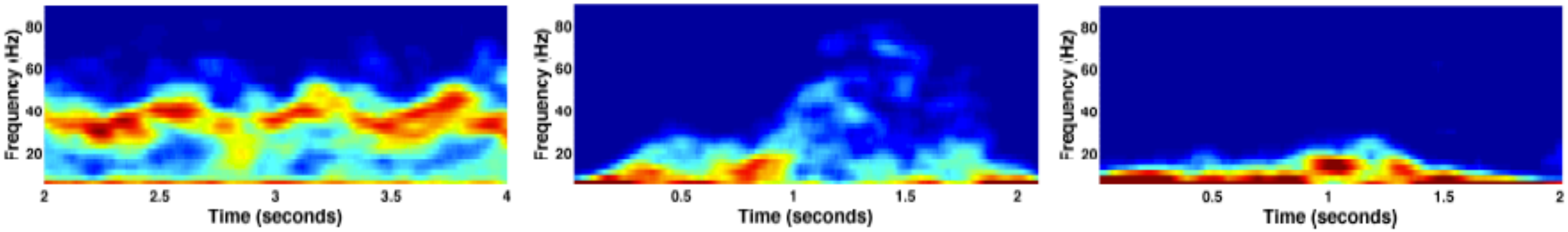
Human Sensing with CSI

- RSS averages signal amplitude over the entire channel bandwidth; cannot reveal the channel response, i.e., how the amplitude and signal changes for different frequencies within the channel; RSS therefore is good only for **coarse** sensing; unsuitable for **detailed** sensing tasks
- Signal phase changes when the reflector moves or changes location; changes in path length will cause phase change (why?)
- CSI returns both amplitude and phase for each subcarrier of WiFi OFDM; e.g., up to 52 amplitude-phase values for 20MHz channel for each packet received
- **CSI time series:** by configuring a Tx to transmit packets at a fixed rate, a receiver can obtain a time series of CSI at a target rate, e.g., 100 packets/s leads to CSI sampling at 100Hz
- Patterns for different human activities, such as a fall, can be learnt from the CSI time series

Example of CSI-based Sensing



(a) CSI waveform for walking (b) CSI waveform for falling (c) CSI waveform for sitting down



(d) Sepctrogram for walking (e) Sepctrogram for falling (f) Sepctrogram for sitting down

Source: Wang, Liu, Shahzad, Ling, and Lu: *Understanding and Modeling of WiFi Signal Based Human Activity Recognition* MOBICOM 2015

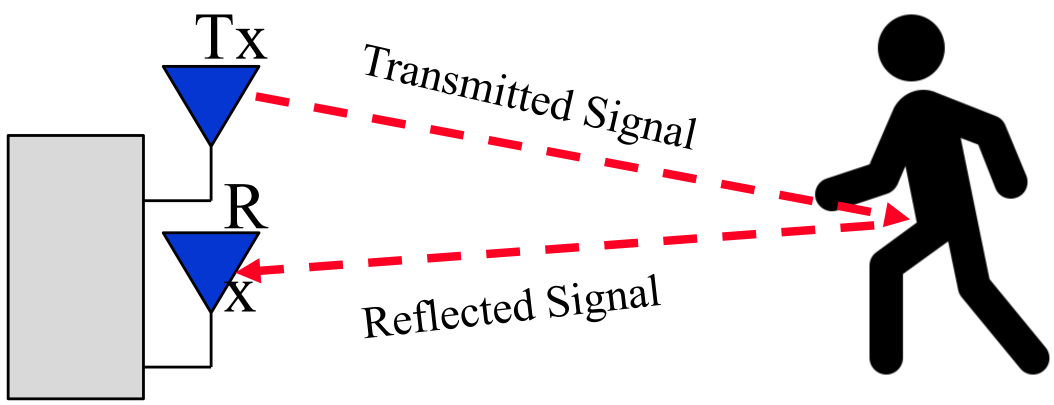
CSI Extraction Tools

in hardware

- CSI is generated and consumed at the **PHY layer**, but human sensing algorithms execute at the **application layer**
- How to access CSI from application layer?
- Firmware of most WiFi chipsets can be modified to extract CSI
- Example of a freely available CSI extraction tool: **nexmon** (https://github.com/seemoo-lab/nexmon_csi)

ToF and Range Estimation

- Range, i.e., distance can be obtained if we can measure ToF
  - Range = ToF x speed of light
- Distance can help localizing and differentiate multiple objects located at different distances
- **Radar:** a fundamental concept to estimate ToF and range by generating a wireless signal and then measuring the reflected signal

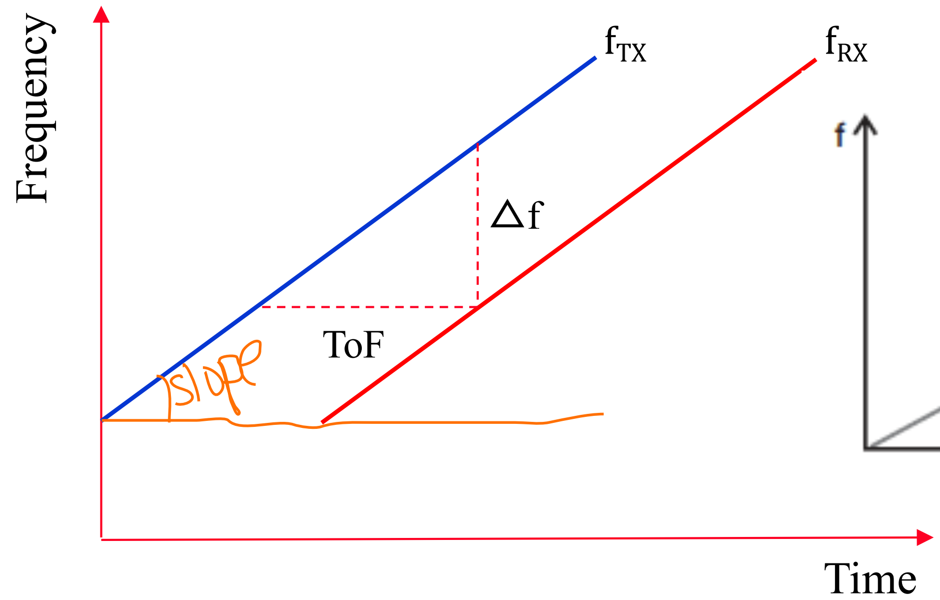


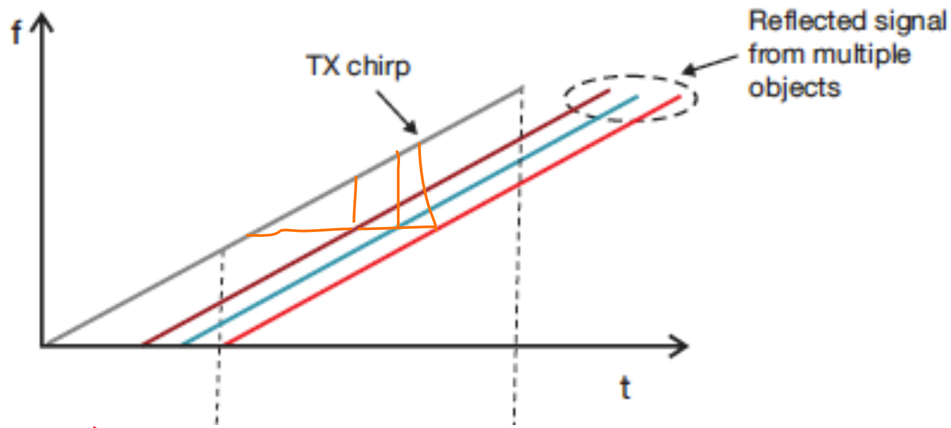
Time of Flight = time for the signal to reach the object and come back

Range Estimation with FMCW

- FMCW: Frequency Modulated Continuous Wave
- Linear chirp: frequency is increased a known constant rate → slope
- Received signal is compared to transmitted signal to work out the frequency difference (Δf)
- ToF = $\frac{\Delta f}{slope}$; Range = ToF x c (c = speed of light)

TI IWR6843 mmWave FMCW RADAR sensor





Human Sensing with Doppler Effect

- Human movement can be captured through Doppler shift at the receiver
- **Radial velocity** of different human body parts can be obtained from Doppler Shift (difference between transmitted and received frequency)
  - $v = \dfrac{\Delta f \times c}{f}$; c = speed of light

transmitted frequency

- Using FFT, it is possible to estimate Doppler and velocity from
  - FMCW range data (more accurate)
  - CSI (less accurate)

Summary

- Wireless signals are good for communication, power transfer, as well as sensing
- Time switching and power splitting are two fundamental techniques to simultaneously harvest energy from the wireless signal while using it for communications
- Using RSS and CSI, WiFi can be used for many human sensing and monitoring applications; WiFi Doppler can be used for imaging.
- FMCW, a low-cost radar technology, enables more advanced sensing with RF signals, but it cannot be achieved with existing WiFi; it requires dedicated infrastructure
- New start-ups are offering commercial RF Sensing solutions