Wireless Sensing

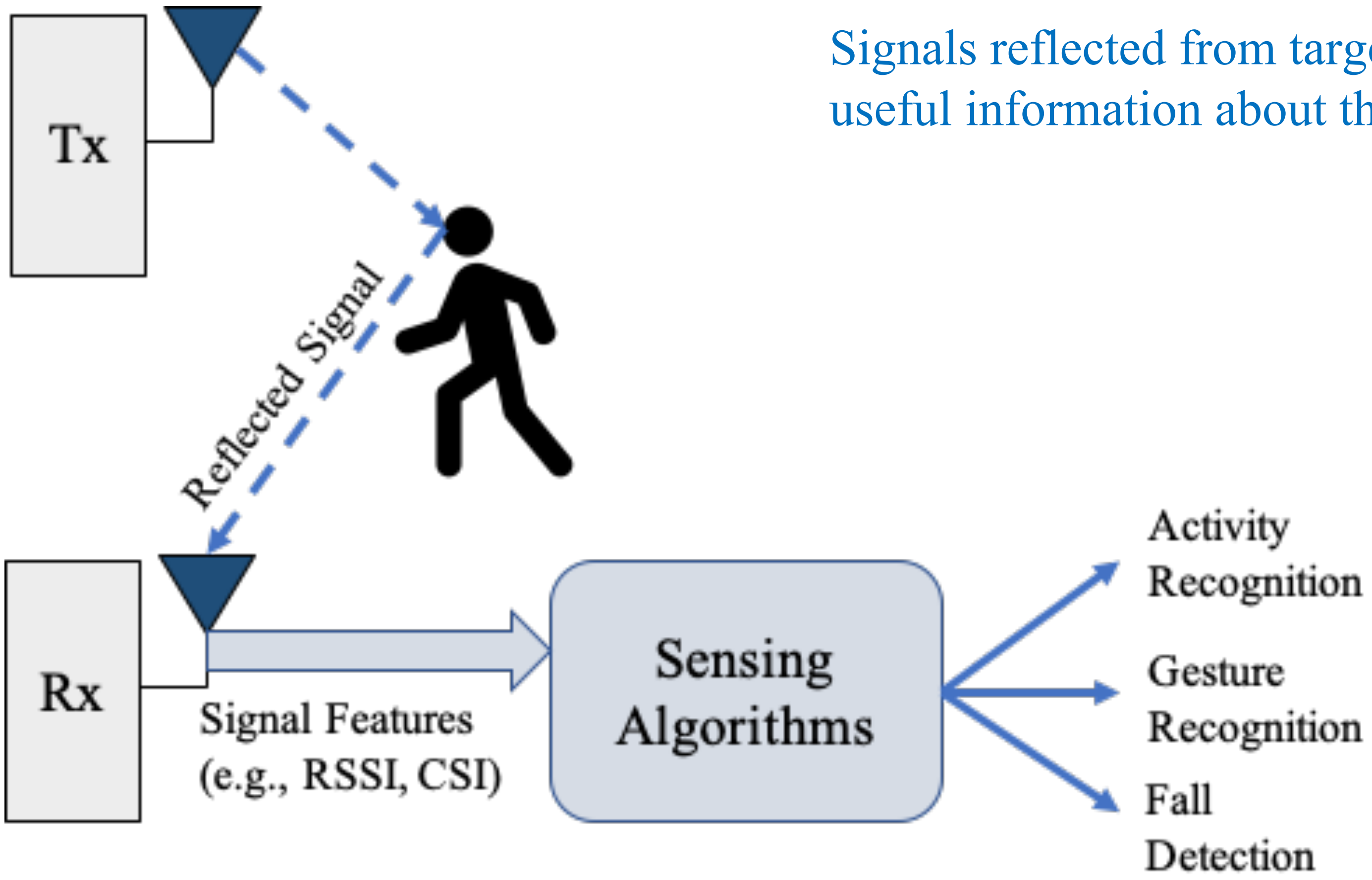
Overview

1. Motivation of Wireless Sensing
2. Principle of Wireless Sensing
3. WiFi Sensing
4. Radar Sensing

Motivation of Wireless Sensing

- Wireless signals good for both communication and remote sensing
- Sensing becoming indispensable in modern living
  - Wearable sensors monitoring heartrate, activity, …
  - Camera: monitor human behaviour, surveillance, …
- Wearable is obtrusive; camera does not work in the dark/fog and has privacy concerns
- Wireless sensing works remotely (unobtrusively) without privacy concerns and works in the dark/fog too
- Wireless sensing becoming commercial success: 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/

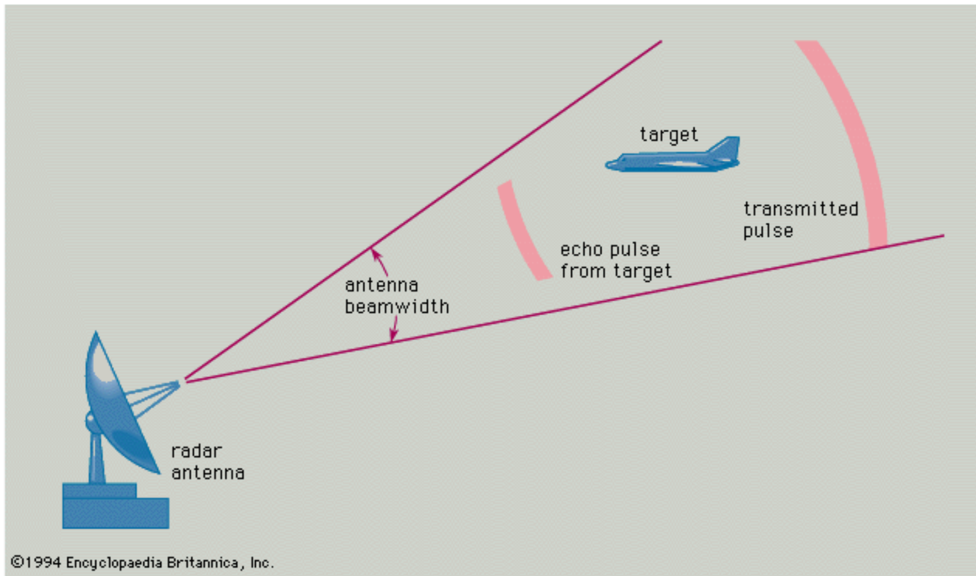
Principle of Wireless Sensing



Signals reflected from target reveals useful information about the target

Types of Sensing Sensing

- **WiFi Sensing**: existing wireless signals and equipment used for sensing
- **Radar Sensing**: Specialised wireless signals and equipment



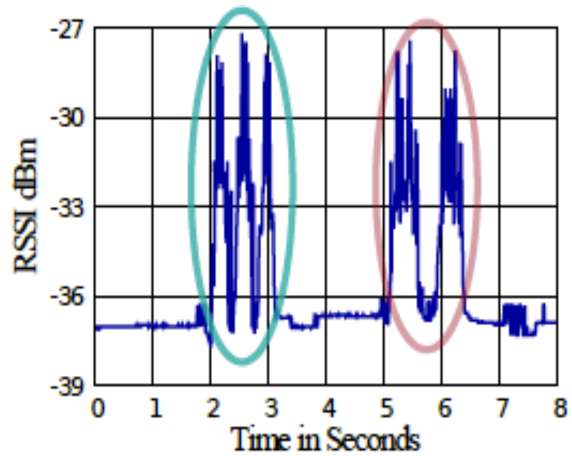
WiFi Sensing

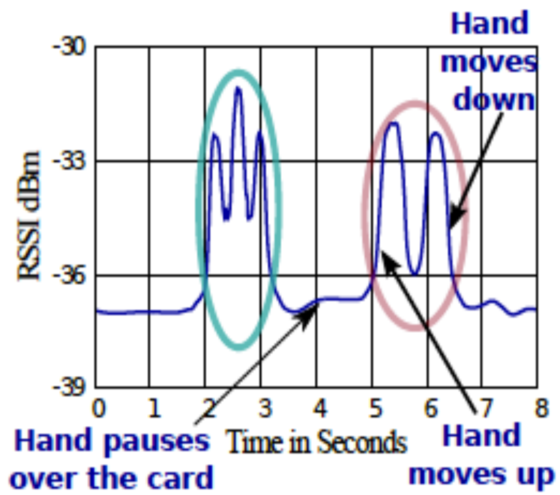
WiFi Signal Information used for Sensing

- Two typical WiFi signal data used for sensing:
  - **RSS:** easy to access, but limited sensing capability
  - **CSI** (channel state information): difficult to obtain, but enables fine-grained and more accurate sensing

Sensing with RSS

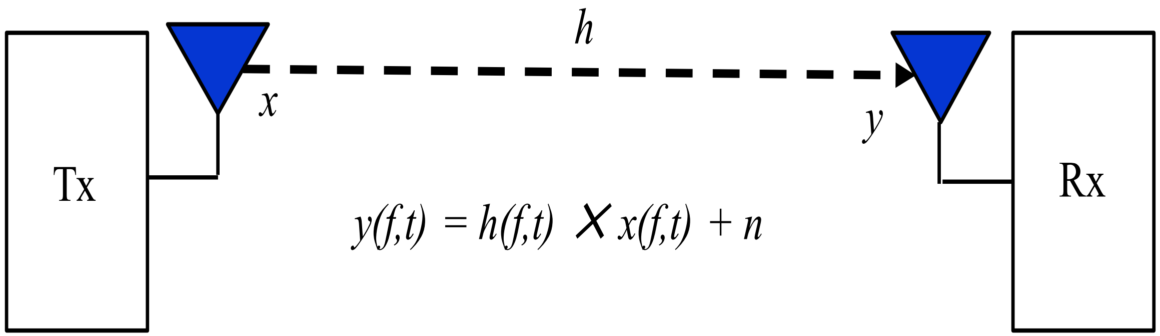
- Single scaler value (in dBm) reported for the whole WiFi channel
- Pros: Widely available: most device hardware/OS report the RSS for each packet received
- Cons: Coarse and unstable; difficult to achieve fine-grained sensing





WiFi Sensing with CSI

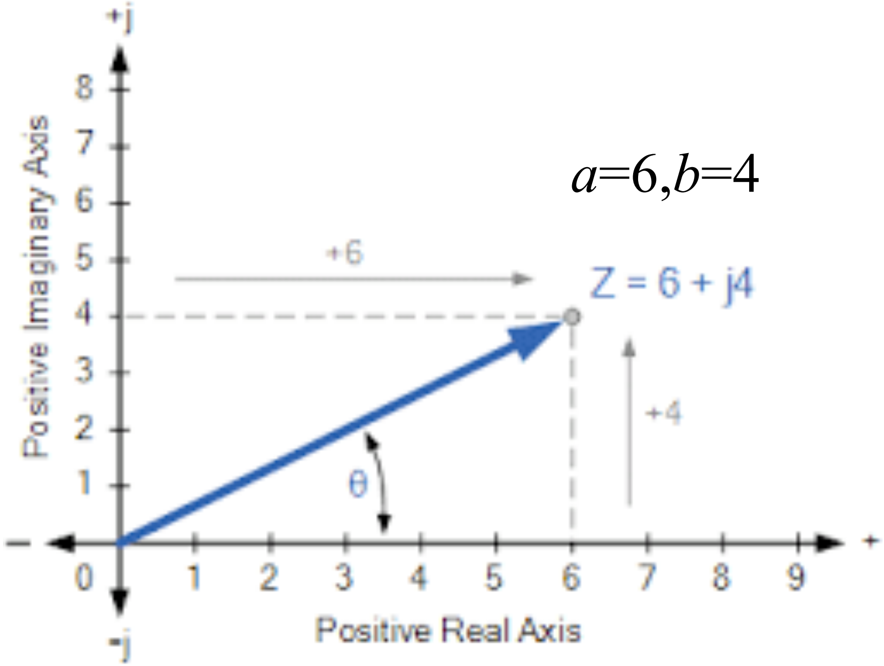
- RSS averages signal amplitude over the entire channel bandwidth; cannot reveal the channel response, i.e., how the amplitude and phase changes for different frequencies within the channel; RSS therefore is good only for **coarse** sensing and unsuitable for **detailed** sensing tasks
- Signal **phase** 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



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 = $\sqrt{a^2+b^2}$, $Phase = \tan^{-1}\frac{b}{b}$)

a=6,b=4



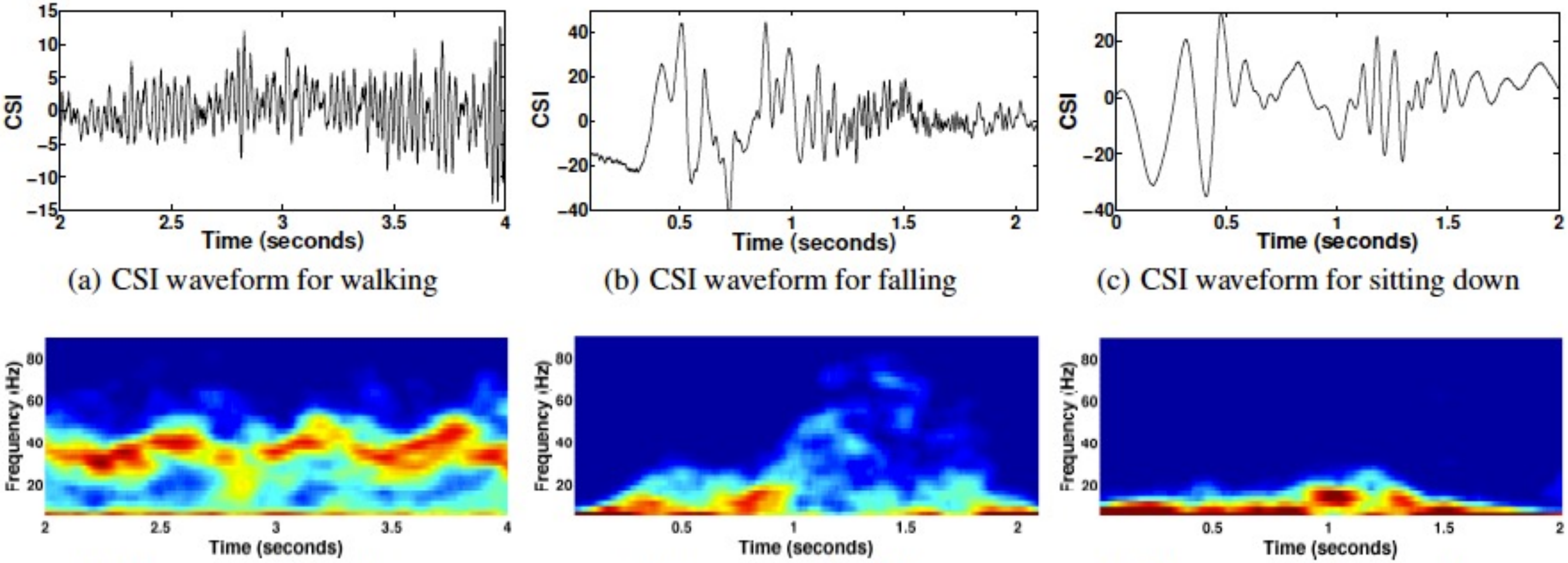
Use of CSI in Wireless Communication

- 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

- 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
- The phase values in CSI are often very noisy in WiFi due to low-cost hardware; hence only the amplitude value of the CSI is typically used for sensing (future WiFi devices may provide more accurate phase values as they need to implement high QAM modulations that require accurate detection of large number of different phase values)

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

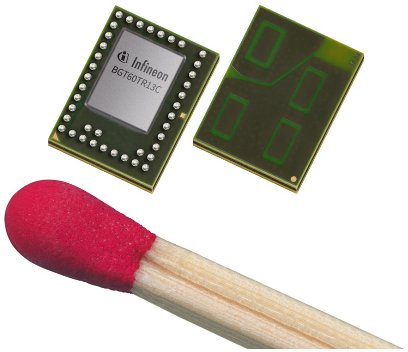
- CSI is generated and consumed at the **PHY layer**, but human sensing algorithms execute at the **application layer**
- How to access CSI from application layer?
- Firmware of most WiFi chipsets can be modified to extract CSI
- Example of a freely available CSI extraction tool: **nexmon** (https://github.com/seemoo-lab/nexmon_csi)

Radar Sensing

Radar

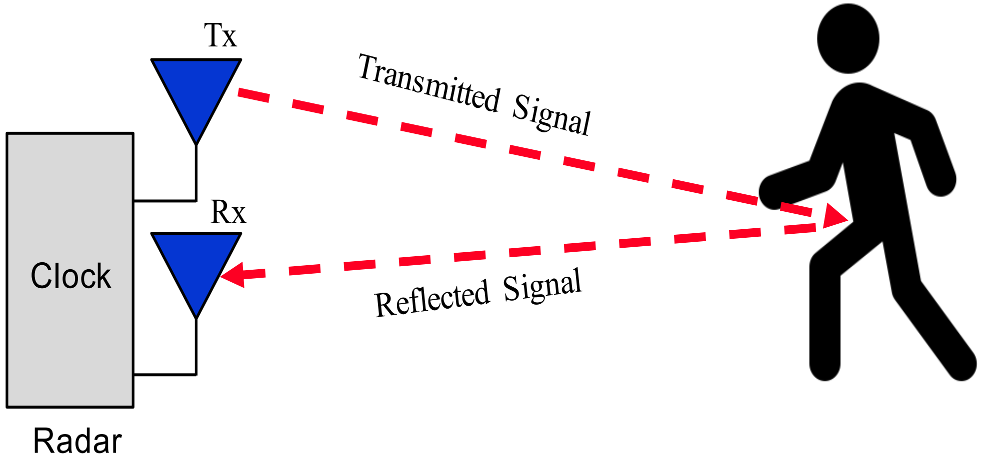
- **RA**dio **D**etecting **A**nd **R**anging
- Detects objects and estimates the range/distance
- Traditional radars are large equipment/antenna; designed to detect objects at far, such as ships, aircrafts, cars, …
- New trends in radar sensing: **IoT radar sensors**

60GHz radar chip from Infineon 5mmx5.5mm



principle of Radar Sensing

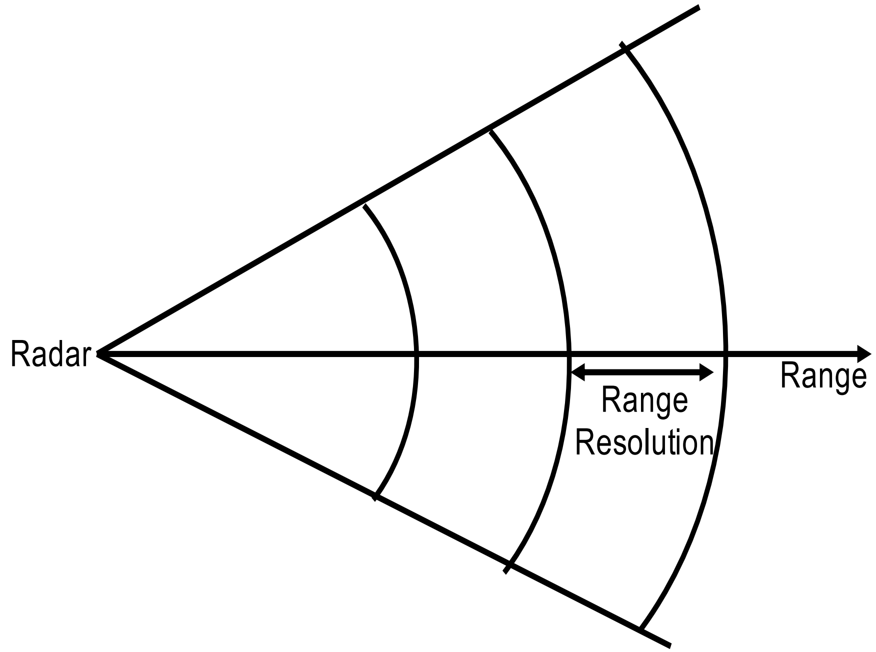
- Range, i.e., distance can be obtained if we can measure time of flight (ToF)
  - Range = ToF x speed of light
- **Radar:** a fundamental concept to estimate ToF and range by generating a wireless signal and then measuring the reflected signal



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

Range vs. Resolution

- Range: the maximum distance from which a radar can reliably detect and estimate the range of an object (how **far** the radar can see)
- Resolution: ability to separate two or more targets at different ranges within the same bearing (how **clearly** the radar can see)
- longer range radars have lower resolution and vice-versa.
- Both range and resolution measured in units of distance, e.g., in meters
- Resolution = c/2B meter; c = speed of light



Example

Question: What is the resolution of a 24GHz radar operating within the ISM band from 24 GHz to 24.25 GHz

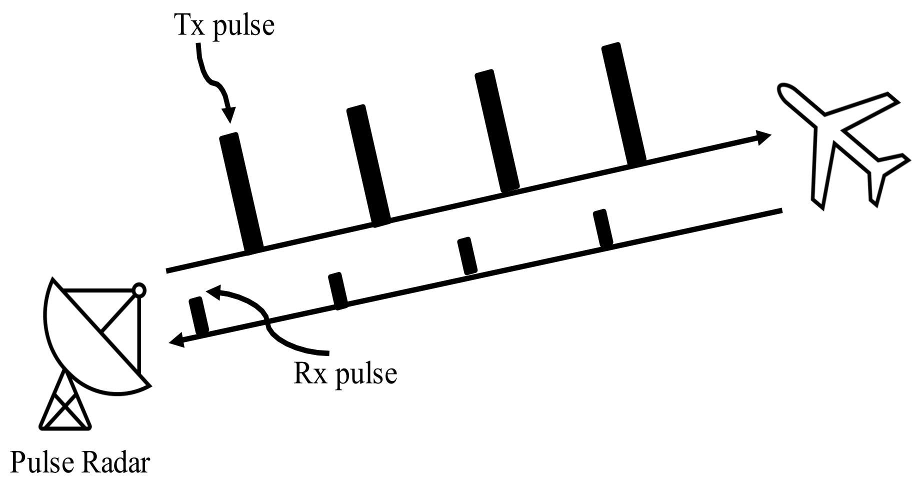
Solution:

Bandwidth (B) = 24.25 – 24 = 0.25GHz
Speed of light (c) = $3\text{x}10^8$ m/s
Resolution = c/2B = $(3\text{x}10^8)/(2\text{x}0.25\text{x}10^{9)}$ = 60cm

Types of Radar

- Pulse: long range detection, bulky, power-hungry, used in large infrastructure, e.e.g, weather station, control tower, etc.
- FMCW (Frequency Modulated Continuous Wave): light-weight, energy efficiency, low cost, suitable for mobile devices (e.g., smartphones) and IoTs

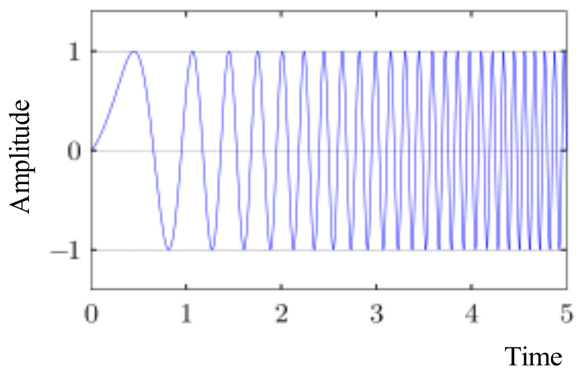
Pulse Radar

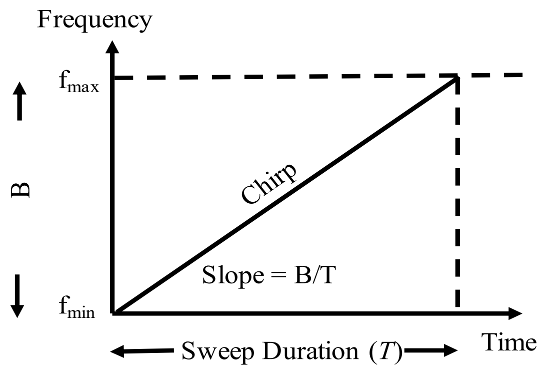


- Very short pulses: **μs** or **ns**
- Very high peak power: kW or MW
- Suitable for long range applications: e.g., aircraft detection
- Highly directional; rorates continuously to cover 360°
- 10-100 pulses per sec., silent in between; low average power
- Received pulses are very weak (due to long distance)
- Bandwidth (B) = 1/*w* (*w* = pulse width); Resolution = c/2B =(c x *w*)/2.
- Better resolution with narrower pulses: wider pulses contain more energy; hence they provide longer detection range, but echoes from multiple objects can overlap yielding lower resolution

FMCW Radars

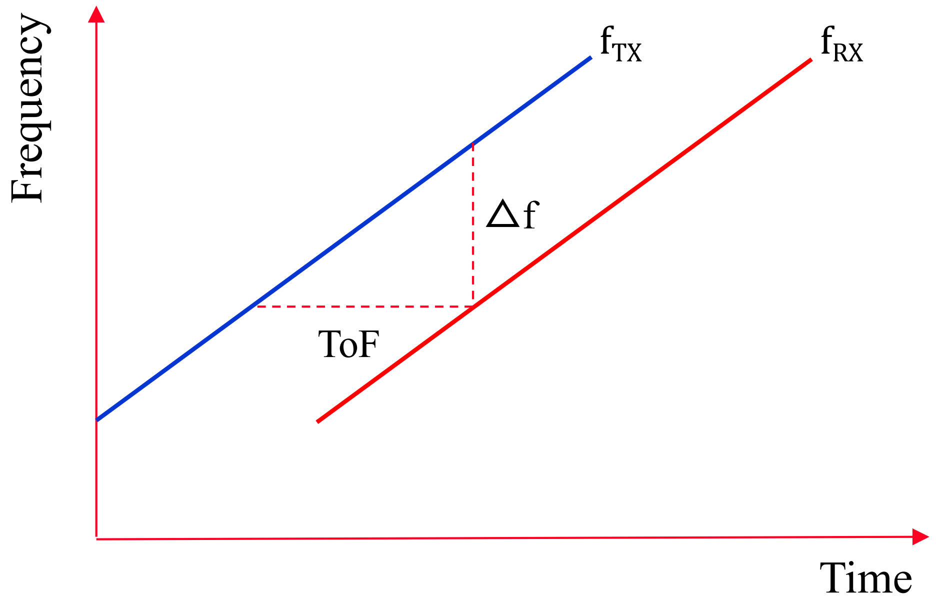
- Unlike pulses, FMCW transmits continuous wave (CW)
- Frequency of the CW is modulated using linear upchirp





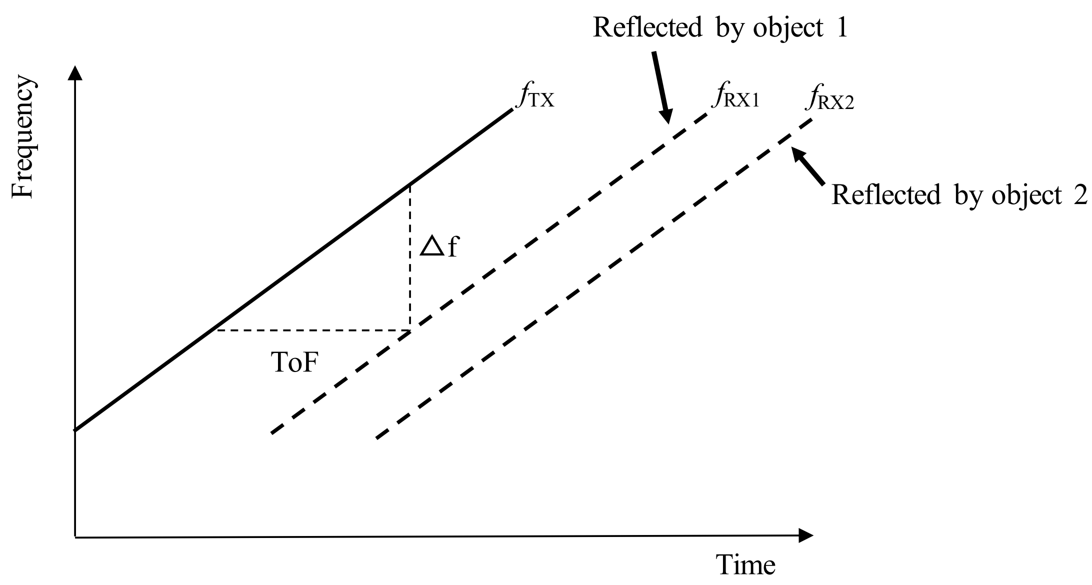
Rang Estimation with FMCW

- Instantaneous frequency difference, Δf
- $ToF = \Delta f / S$
- $Range = ToF \times c = (\Delta f \times c)/S$



Detecting Multiple Objects with FMCW

- Two objects located at the same bearing would produce two reflected chirps with slight delays between them



Resolution of FMCW

- Assume 2 objects located at the same bearing but Δd from each other
- Δf = instantaneous frequency difference between the 2 received chirps
- $(\Delta f)/(2\Delta d/c) = S = B/T$; *$2\Delta d/c$ is the difference between RTT of 2 objects*
- Two frequencies within a signal can be distinguished if $\Delta f > 1/T$ (law of FFT)
- For $\Delta f = 1/T$, *we have* $\Delta d = c/2B$

Summary

1. Wireless signals are good for both communication and sensing
2. Two major types of wireless sensing: WiFi Sensing and Radar Sensing
3. Using RSS and CSI, WiFi can be used for many human sensing and monitoring applications
4. RSS is readily available, but cannot provide fine-grain sensing
5. CSI can provide fine-grain sensing, but modifications required to access CSI in commodity WiFi devices
6. Radar can provide accurate range and motion information; more sophisticated sensing applications are possible with radars, but they require dedicated infrastructure for sensing
7. Millimeter wave FMCW radars have emerged as a popular IoT sensing device with applications in many IoT domains: health, smart home, smart industry, smart transport, …