Lecture 6: Device-Free Localization

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1 Overview

This lecture is on:

- Device-Free Localization: Using radio signals to track human location, gestures and motion without any sensors on their bodies.
- Wireless communication review.
  - Packet detection
  - Carrier Frequency Offset (CFO)

2 Device-Free Localization

The following are some applications of device-free localization:

- Smart Homes
- Energy Saving
- Gaming and VR
- Elderly fall detection
- Security

2.1 WiTrack

WiTrack performs device-free localization by measuring the distance of the subject from a transceiver. By putting together the measurements of two or more transceivers, it is possible to triangulate the location of the subject.

Distance from the transceiver can be measured as:

$$distance = reflection\_time \times speed\_of\_light$$

2.1.1 pulse-echo resolution

The most simple approach to measure distance is by sending a short pulse, and listening for its echo. Unfortunately, this approach is not very viable, since it requires sub-nanosecond sampling in order to achieve good resolution; Multi-GHz samplers are expensive, have high noise, and create large I/O problem.

pulse-echo resolution:

$$d_r = \frac{c \times T_{sample}}{2} \tag{1}$$

$$T_{sample} = \frac{1}{R_{sample}} \tag{2}$$

where T_{sample} is the sample time R_{sample} is the sample rate.

Hence, in order to achieve a resolution of 15 cm, a rate of 1 giga-samples per second is required. In comparison, traditional WiFi/LTE transceivers perform about 10 - 80 mega-samples per second.

2.1.2 FMCW resolution

In order to measure distance, WiTrack employs a different technique called Frequency Modulated Carrier Wave (FMCW). The concept behind FMCW is that it is possible to measure reflection time by modulating the frequency of the emitted wave, and measuring the frequency from the received wave. If the transceiver gradually increases the signal frequency over time, one can estimate travel time by comparing the signal received agaist the signal currently being sent (As shown in Figure 1).

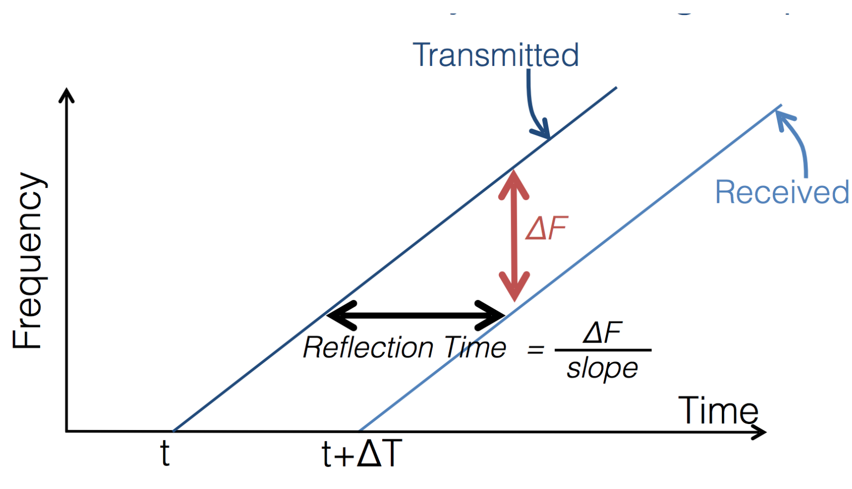

Figure 1: Transmitted and received FMCW signal.

$$T_{reflection} = \frac{\Delta F}{slope} \tag{3}$$

Where the slope is chosen by the transceiver. In particular, we want to make the slope as gradual as possible in order to maximize the achieved resolution.

$$slope = \frac{BW_{total}}{T_{sweep}} \tag{4}$$

Subtracting the frequencies form the two signals can be easily done using a mixer; a cheap, low power hardware device. Feeding both signals to a mixer, and performing an FFT of the output will yield a peak at ΔF.

FMCW resolution:

$$d_r = \frac{c \times T_{min}}{2} \tag{5}$$

$$T_{min} = \frac{\Delta F_{min}}{slope} \tag{6}$$

$$\Delta F_{min} = \frac{1}{T_{sweep}} \tag{7}$$

where T_{min} is the smallest reflection time observed, and ΔF_{min} is the smallest measurable ΔF

Then:

$$d_r = \frac{c}{2} \times \frac{\Delta F_{min}}{slope} = \frac{c}{2} \times \frac{\frac{1}{T_{sweep}}}{\frac{BW_{total}}{T_{sweep}}} \tag{8}$$

$$d_r = \frac{c}{2BW} \tag{9}$$

Note: At any point in time, the instantaneous bandwidth employed is low, but over time a large bandwidth is required to allow for the changing signal frequency, and increased resolution.

2.1.3 Challenge: Multipath

We can eliminate *static multipath* by subtracting consecutive received signals. The key observation here is that the emitted signal will always bounce back from static objects in the same way. Because of this, any received signal that is constant over time belongs to a static object (either a direct reflection, or a reflection produced by multipath), and can be disregarded for human localization.

We still have to deal with *dynamic multipath*, in which the signal bounces back in a path that includes both a human and a static object. In this case, we observe that the direct path from the transceiver to the subject will be the smallest path observed. The signal that is measured to be closest to the transceiver must then be the one belonging to the subject, and signals measured as farther away can be disregarded as multipath.

2.2 Retrieving Full Human Silhouette

By combining FMCW's distance estimation with antenna arrays to measure AoA, it is possible to determine the 3D location of a subject, and visualize its silhouette using only a single transceiver. We can use a vertical and a horizontal array to track vertical and horizontal AoA respectively, and FMCW to measure the distance from the transceiver. Since the antenna arrays are able to track multiple AoA, the silhouette of a human can be reconstructed.

Figure 2: Signal received from dynamic multipath.

2.2.1 Challenge: We only obtain blobs in space

At frequencies that are able to traverse walls, the human body is specular, and the different body parts perfectly reflect the received signal (so the signal is not received by the transceiver). Because of this, it is not possible to obtain the complete human silhouette with the signal received at a single point in time.

Solution Idea: it is possible to exploit human motion to gather different silhouette views over time, and aggregate them to generate a full silhouette. As a subject walks toward the transceiver, different body parts will reflect the emitted signal back to the transceiver, so the different snapshots will show different body parts. In particular, the chest is a large convex reflector, which can be used as a pivot for motion and segmentation comparison when reconstructing the whole silhouette.

It is even possible to classify subjects based on their reconstructed silhouette by training an ml model.

3 Wireless Communication Review

In this section, we review packet detection and carrier frequency offset.

3.1 Packet Detection

We begin with the classical setup, where Alice is trying to transmit to Bob. Our main question is, how will Bob be able able to detect Alice's packets? We start with the simplest method, using a threshold in the power of the received signal.

3.1.1 Approach 1: Using a signal threshold

One approach for Bob to sense the packet header is to listen until his received power exceeds some threshold. Figure 3 below shows the typical receiver response of Bob. Initially, there will be noise at some low power level. Once Alice transmits, the received power will spike and Bob would start decoding. The algorithm would then be:

packet detection:

if($P_{received} > thresh$)
start decoding

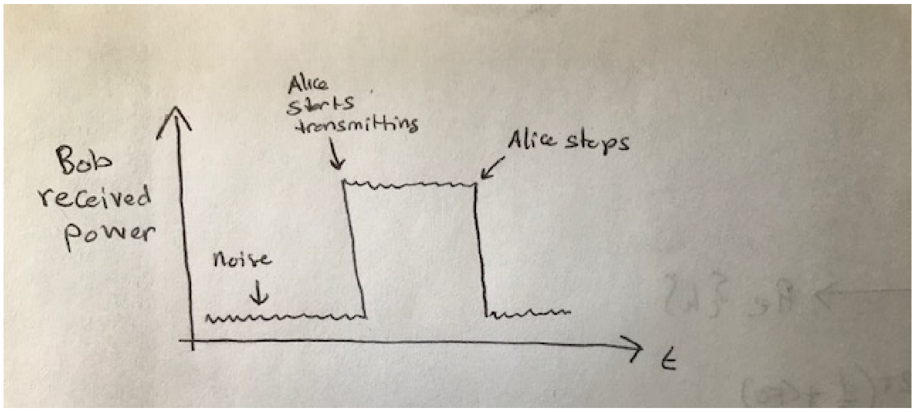

Figure 3: Example of the variation in Bob's received power.

However, this method has a few drawbacks. Firstly, it is not trivial to determine the threshold. Since the received power decreases with distance squared, too large of a threshold would prevent receiving signals if Alice is far away. Secondly, it requires a relatively high SNR. A stronger approach is the sliding window method.

3.1.2 Approach 2: Sliding Window

We start with two windows, A and B, that are consecutive in time. We compute the power in the two windows,

$$P(A) = \sum_{n=1}^{T_A} |y[n]|^2 \tag{10}$$

$$P(B) = \sum_{n=T_A+1}^{T_B} |y[n]|^2 \tag{11}$$

where T_A is the total time of window A, and T_B is the total sliding window time. In order to differentiate noise from the start of a transmission, we compute the ratio $\frac{P(B)}{P(A)}$, as we slide the window in time. During periods without a signal and only noise, the ratio will be approximately 1. During the start of Alice's transmission, the spike in Bob's received power will result in window B having a larger power than window A, resulting in a spike in the power ratio, allowing Bob to start decoding. Figure 4 illustrates this concept.

The advantages of this method is that it is robust to varying SNR. Additionally, taking the ratio of the powers instead of subtracting them is less sensitive to signal variations.

3.2 Carrier Frequency Offset

In networking systems, signals are transmitted centered at a specific frequency, $f_{carrier}$, or f_c (Fig. 5). A carrier frequency is selected because different transmission protocols occupy different

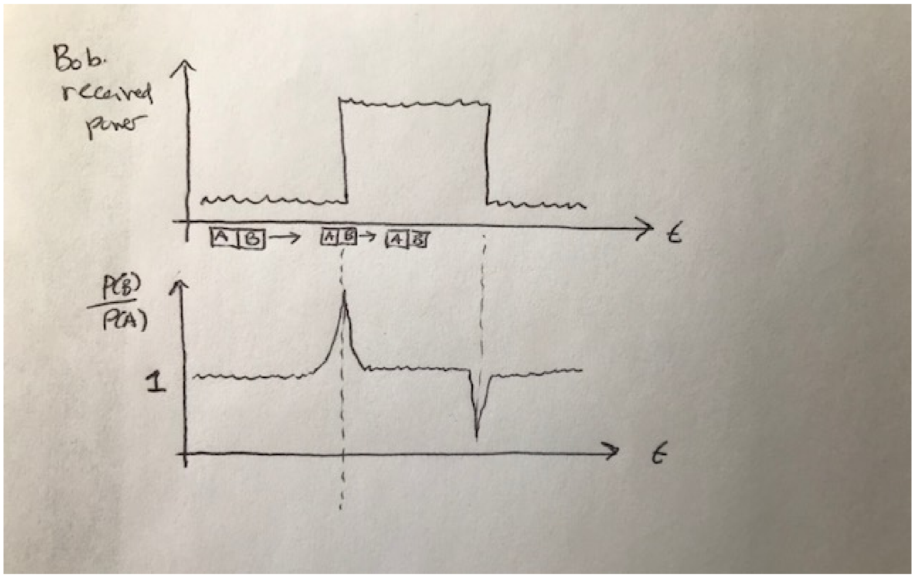

Figure 4: Sliding window approach on Bob's received power. During instances of receiving Alice's signal, the ratio P(B)/P(A) changes rapidly, allowing Bob to start decoding.

bandwidths in space, for example, WiFi uses a 2.4GHz transmission frequency. The signal we want to transmit, $x(t)$ is shifted in the frequency domain by f_c by multiplication with a cosine, giving our transmitted signal

$$x_p(t) = x(t)cos(2\pi f_c t) \tag{12}$$

The receiver obtains a signal $y(t)$ and removes f_c by multiplying the received $y(t)$ by the same cosine,

$$y_p(t) = y(t)cos(2\pi f_c^{'} t) \tag{13}$$

where $f_c^{'}$ is the receiver's estimate of the carrier frequency. In an ideal system, $f_c = f_c^{'}$. However, in practical systems, there is an offset, known as the carrier frequency offset (CFO), which causes the received carrier frequency estimate to differ, $f_c^{'} = f_c + CFO$. The CFO greatly complicates the channel process.

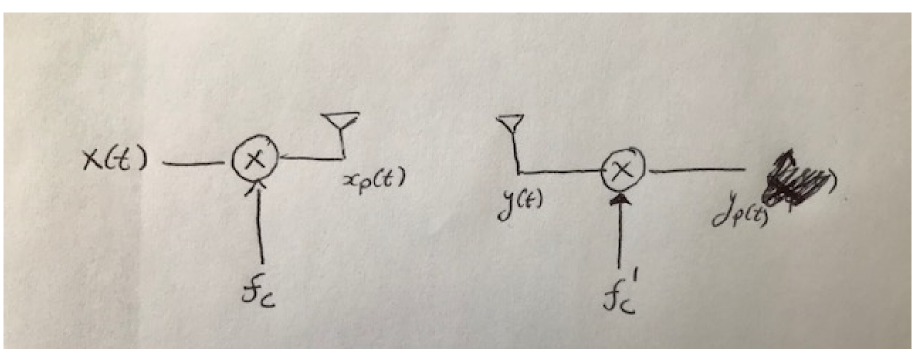

Figure 5: Diagram of frequency modulation process.

Recall, a line of sight channel is estimated as

$$h = \frac{1}{d} e^{-j2\pi \frac{d}{\lambda}} \tag{14}$$

where d is the distance between receiver and transmitter, and λ is the signal wavelength. With CFO, our channel estimate becomes

$$h = \frac{1}{d} e^{-j2\pi(\frac{d}{\lambda} + CFO \times t)} \tag{15}$$

Indicating that the CFO adds a phase shift that varies in time. This can be visualized in the complex diagram for h as shown in Figure 6.

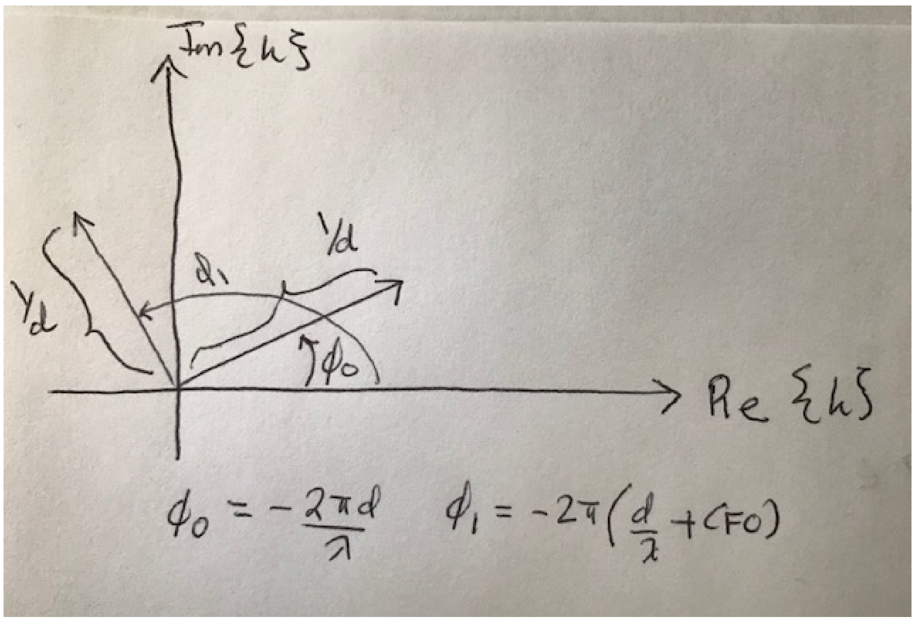

Figure 6: Example of the effect CFO on the phase of the channel h. The CFO adds a phase that varies linearly in time.

Recall that the received signal, $y(t)$ is

$$y(t) = hx(t) + n(t) \tag{16}$$

And our estimate our objective is to estimate $x(t)$ at the receiver. Our estimate is

$$x\hat{(t)} = \frac{y(t)}{\hat{h}(t)} \tag{17}$$

indicating that an unknown phase offset that varies in time can strongly affect our estimate of $x(t)$.

References

[1] F. Adib, Z. Kabelac, D. Katabi, and R. C. Miller. 2014, 3D tracking via body radio reflections. *Usenix NSDI*