Sub-Nanosecond Time of Flight on Commercial Wi-Fi Cards

Deepak Vasisht, Swarun Kumar, and Dina Katabi
Massachusetts Institute of Technology
{deepakv,swarun,dk}@mit.edu

1. SYSTEM OVERVIEW

The time-of-flight of a signal captures the time it takes to propagate from a transmitter to a receiver. Time-of-flight is perhaps the most intuitive method for localization using wireless signals. If one can accurately measure the time-of-flight from a transmitter, one can compute the transmitter's distance simply by multiplying the time-of-flight by the speed of light. Today, GPS, the most widely used outdoor localization system, localizes a device using the time-of-flight of radio signals from satellites. However, applying the same concept to indoor localization has proven difficult. Systems for localization in indoor spaces are expected to deliver high accuracy (e.g., a meter or less) using consumer-oriented technologies (e.g., Wi-Fi on one's cellphone). Unfortunately, past work could not measure time-of-flight at such an accuracy on Wi-Fi devices [10, 2]. As a result, over the years, research on accurate indoor positioning has moved towards more complex alternatives such as employing large multi-antenna arrays to compute the angle-of-arrival of the signal [11, 4]. These new techniques have delivered highly accurate indoor localization systems.

Despite these advances, time-of-flight based localization has some of the basic desirable features that state-of-the-art indoor localization systems lack. In particular, measuring time-of-flight does not require more than a single antenna on the receiver. In fact, by measuring time-of-flight of a signal to just two antennas, a receiver can intersect the corresponding distances to locate its source. Thus, a receiver can locate a wireless transmitter with no support from the surrounding infrastructure. This is quite unlike current indoor localization systems, which require multiple access points at known locations, to find the distance between a pair of mobile devices. Furthermore, each of these access points need to have many antennas – far beyond what is supported in commercial Wi-Fi devices.

In this demo, we will present Chronos, a system that combines a set of novel algorithms to measure the time-of-flight to sub-nanosecond accuracy on commercial Wi-Fi cards. In particular, we will measure distance/time-of-flight between two devices equipped with commercial Wi-Fi cards, without any support from the infrastructure or environment fingerprinting.

CCS CONCEPTS

•**Networks** → **Network protocols;** •**Hardware** → *Signal processing systems;*

SIGCOMM '15 August 17-21, 2015, London, United Kingdom

ACM ISBN 978-1-4503-3542-3/15/08.
DOI: http://dx.doi.org/10.1145/2785956.2790043

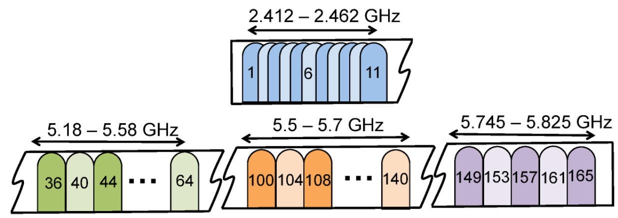


Figure 1: **Wi-Fi Bands:** Wi-Fi bands at 2.4 GHz and 5 GHz.

KEYWORDS

Wireless, RF Localization, Time-of-flight

2. CHALLENGES

Why is it that one cannot accurately measure time-of-flight on commercial Wi-Fi devices? In particular, to achieve state-of-the-art positioning accuracy, one must measure time-of-flight at sub-nanosecond granularity. However, doing so on commercial Wi-Fi cards is fundamentally challenging for the following three reasons.

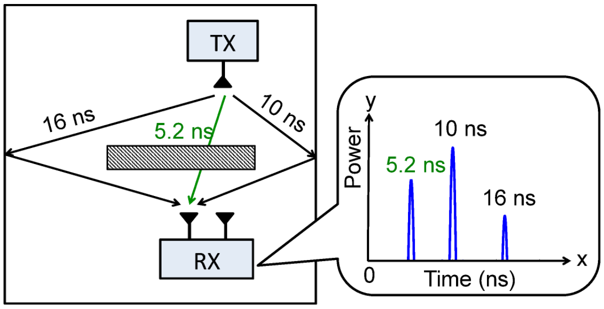
Limited Time Granularity: First, the straightforward approach to measure time-of-flight is to read off the clock of the Wi-Fi radio when the signal arrives [10]. Unfortunately, the clocks on today's Wi-Fi cards operate at tens of MHz, limiting their resolution in measuring time to tens of nanoseconds [2, 8, 6]. To put this in perspective, a clock running at 20 MHz (the bandwidth of typical Wi-Fi systems), can only tell apart distances separated by 15 m, making it impractical for accurate indoor positioning. Even recent state-of-the-art systems that measure time-of-flight using high-resolution 88 MHz Wi-Fi clocks [5] and super-resolution channel processing techniques [12] suffer a mean localization error of about 2.3 m.

Packet Detection Delay: Second, any measurement of time-of-flight of a packet necessarily includes the delay in detecting its presence. To make matters worse, this packet detection delay is typically orders-of-magnitude higher than time-of-flight for indoor Wi-Fi environments [7]. In fact, in our experiments described later, we observed the median packet detection delay to be $\sim$ 177 ns, with a standard deviation of $\sim$ 25 ns; while the median propagation delay was $\sim$ 22 ns. Today, there is no way to tease apart the time-of-flight from this detection delay.

Multipath: Finally, in indoor environments, signals do not experience a single time-of-flight, but a time-of-flight spread. To see why, observe that wireless signals in indoor environments travel along multiple paths, and bounce off walls and furniture. As a result, the receiver obtains several copies of the signal, each having experienced a different time-of-flight. To perform accurate localization, one must therefore be able to disentangle the time-of-flight of the most direct path from all the remaining paths.

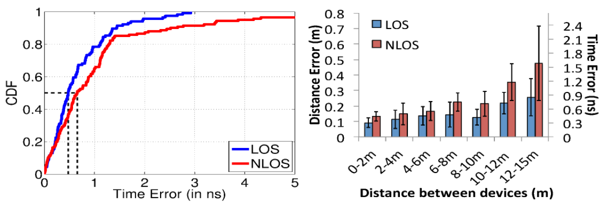
3. OUR SOLUTION

We design algorithms that overcome the above limitations and



(a) Testbed (b) Multipath Profile

Figure 2: **Combating Multipath:** Consider a signal propagating from a transmitter to a receiver along three paths as shown in (a): an attenuated direct path and two reflected paths of lengths 5.2 ns, 10 ns and 16 ns respectively. The combined signal is processed by Chronos to produce (b). The plot has three peaks corresponding to the propagation delays of the three paths, with peak magnitudes scaled by their relative attenuations.



(a) Time of Flight (b) Accuracy with Distance

Figure 3: **Time-of-Flight Accuracy**: (a) measures the CDF of error in time-of-flight between two devices in Line of Sight (LOS) and Non-Line of Sight (NLOS). (b) plots accuracy in time-of-flight between two devices as the distance between them is varied.

measure the time-of-flight at sub-nanosecond accuracy using off-the-shelf Wi-Fi cards. On a high level, our approach is based on the following observation: If one had a very wideband radio (e.g., a few GHz), one could measure time of flight at sub-nanosecond accuracy. While each Wi-Fi frequency band is only tens of Megahertz wide, there are many such bands that together span a very wide bandwidth, as shown in Fig. 1. Our solution therefore collects measurements on multiple Wi-Fi frequency bands and stitches them together to give the illusion of a wide-band radio. Our key contribution is an algorithm that achieves this, despite the fact that Wi-Fi frequency bands are non-contiguous, and in some cases, a few Gigahertz apart. By doing this, we can negate the need for a high bandwidth clock and get accurate time-of-flight measurements.

As discussed before, indoor environments are rich in multipath, causing wireless signals to bounce off objects in the environment like walls and furniture. The received signal is therefore the sum of these multiple signal copies, each having experienced a different propagation delay and attenuation, as shown in Fig. 2. Dealing with multipath effect requires two steps: a) Identifying different signal reflections and, b) Choosing the signal component corresponding to the direct path. To identify different signal reflections, we design an algorithm to leverage the sparsity in signal reflection to tease apart different signal reflections and plot signal profiles (e.g., Fig. 2(b)). Once the different signal reflections have been disentangled, we choose the path with the shortest time-of-flight as the direct path, as any reflected path has travelled a longer distance than the direct path. For lack of space, we refer the reader to [9] for a detailed discussion of these algorithms.

4. EVALUATION

To demonstrate the performance and practicality of our design, we implemented Chronos as a software patch to the iwlwifi driver on Ubuntu Linux running the 3.5.7 kernel. To measure channel-state-information, we leverage the 802.11 CSI Tool [3] for the Intel 5300 Wi-Fi card. We measure wireless channels on both 2.4 GHz and 5 GHz Wi-Fi bands. We evaluated Chronos's performance on pairs of devices equipped with Intel 5300 Wi-Fi cards, including Thinkpad W530 laptops and Asus IEEE PC netbooks. Chronos estimated the distance between a pair of devices, placed at randomly chosen locations in a floor of our office building. The ground truth was measured using a combination of the floor maps and a Bosch GLM50 laser distance measurement tool [1]. We present two representative results here.

As shown in Fig. 3(a), Chronos achieves a median error in time-of-flight of 0.47 ns in line-of-sight and 0.69 ns in non-line-of-sight settings, corresponding to a physical distance accuracy of 14.1 cm and 20.7 cm respectively (95^{th} percentile: 1.96 ns and 4.01 ns). Our results show that Chronos achieves its promise of computing time-of-flight at sub-nanosecond accuracy. To put this in perspective, SourceSync [7], a state-of-the-art system for time synchronization, achieves 95^{th} percentile synchronization error up to 20 ns, using advanced software radios. However, we point out that unlike indoor positioning, tens of nanoseconds of error is sufficient for time-synchronization-the target application for SourceSync. Fig. 3(b) plots the median and standard deviation of error in distance computed between the transmitter and receiver against their true relative distance. We observe that this error is initially around 10 cm and increases to at most 25.6 cm at 12-15 meters. The increase is primarily due to reduced signal-to-noise ratio at further distances.

5. CONCLUSION

In this demo, we will present, Chronos, a system that measures time of flight (and hence, distance) between two devices to sub-nanosecond accuracy, using commercial WiFi cards. To our knowledge, Chronos is the first system that can measure time-of-flight on commercial Wi-Fi cards to this accuracy.

6. REFERENCES

[1] Bosch laser distance measurer glm50. http://www.boschtools.com/Products/Tools/Pages/BoschProductDetail.aspx?pid=GLM\%2050.

[2] T. Bourchas, M. Bednarek, D. Giustiniano, and V. Lenders. Practical limits of wifi time-of-flight echo techniques. In *IPSN*, pages 273–274, April 2014.

[3] D. Halperin, W. Hu, A. Sheth, and D. Wetherall. Tool release: Gathering 802.11n traces with channel state information. *ACM SIGCOMM CCR*, 2011.

[4] K. Joshi, S. Hong, and S. Katti. Pinpoint: Localizing interfering radios. NSDI, 2013.

[5] A. T. Mariakakis, S. Sen, J. Lee, and K.-H. Kim. Sail: Single access point-based indoor localization. MobiSys, 2014.

[6] K. Muthukrishnan, G. Koprinkov, N. Meratnia, and M. Lijding. Using time-of-flight for wlan localization: feasibility study, 2006.

[7] H. Rahul, H. Hassanieh, and D. Katabi. SourceSync: A Distributed Wireless Architecture for Exploiting Sender Diversity. In *ACM SIGCOMM 2010*, August 2010.

[8] L. Schauer, F. Dorfmeister, and M. Maier. Potentials and limitations of wifi-positioning using time-of-flight. In *IPIN*, 2013.

[9] D. Vasisht, S. Kumar, and D. Katabi. Sub-nanosecond time of flight on commercial wi-fi cards. *CoRR*, abs/1505.03446, 2015.

[10] S. B. Wibowo, M. Klepal, and D. Pesch. Time of flight ranging using off-the-self ieee802.11 wifi tags. POCA, 2009.

[11] J. Xiong and K. Jamieson. Arraytrack: A fine-grained indoor location system. NSDI '13, 2013.

[12] J. Xiong, K. Jamieson, and K. Sundaresan. Synchronicity: Pushing the envelope of fine-grained localization with distributed mimo. HotWireless, 2014.