mmWave Beam Steering via Visible Light Sensing

Muhammad Kumail Haider
Rice University, Houston TX
kumail.haider@rice.edu

ABSTRACT

Wireless communication in mmWave bands with wide bandwidths and directional links is crucial for high data rate demands of future networks. A key challenge in mmWave networking is maintaining beam alignment under device mobility such as rotation or translation. We present LiSteer, a novel system which acquires and steers mmWave beams at mobile devices by repurposing indicator LEDs on wireless Access Points (APs) to passively acquire direction estimates using off-the-shelf light sensors, and demonstrate that LiSteer maintains beam alignment at the narrowest beamwidth level even in case of device mobility, without incurring any training overhead at mobile devices. Our extensive evaluation on custom hardware and simulation platforms shows LiSteer achieves direction estimates within 2.5 degrees of ground truth on average, and achieves beam steering accuracy of more than 97% while in tracking mode.

ACM Reference Format:
Muhammad Kumail Haider Rice University, Houston TX kumail.haider@rice.edu. 2018. mmWave Beam Steering via Visible Light Sensing. In *10th Wireless of the Students, by the Students, and for the Students Workshop (S3 '18), November 2, 2018, New Delhi, India.* , 3 pages. https://doi.org/10.1145/3264877.3264884

1 INTRODUCTION

The ever-increasing demand for high speed wireless connectivity to support applications like virtual and augmented reality and uncompressed video streaming is straining the capacity of current WiFi and cellular networks. The wide GHz-scale bandwidth coupled with phased array antennas to realize high directionality in the mmWave spectrum can solve this problem by realizing data rates of up to 100 Gb/sec. However, a key challenge is that end nodes need to align their beams via beam training mechanisms [5] to establish and maintain highly directional links, incurring 10's of *ms* of overhead. This overhead represents missed opportunity to transmit 100's of Mb, severely degrading throughput and disrupting high-rate, low-latency applications. Mobile nodes present an even greater challenge, where beam alignment may be repeatedly lost due to mobility, requiring more training epochs and incurring overhead each time.

We present LiSteer, a system which steers mmWave beams at mobile devices by tracking indicator LEDs on wireless Access Points (APs) to passively acquire direction estimates, eliminating the need for beam search at the clients. Our design is motivated by the observation that most off-the-shelf wireless APs are equipped with light sources like notification LEDs, which are in close proximity to their phased array antennas. Therefore, by tracking this indicator LED at client devices using off-the-shelf light sensors (e.g., photodiodes), we can "point" the client's antenna beams towards the AP, without requiring any in-band training or beam search.

For this, we exploit the pseudo-optical properties of mmWave channels; specifically the dominant Line of Sight (LOS) propagation, limited scattering and reduced multipath due to very short wavelength [2]. Since visible light band exhibits similar dominant LOS propagation, our key idea is to estimate the Angle of Arrival (AoA) corresponding to the LOS path from the AP's indicator LED, and approximate it as the AoA in the mmWave band due to close proximity of AP's LED and its phased array antenna. Therefore, we select the client-side beam as the one with the highest gain along the AoA for the LOS path. We show that by passively tracking AP's indicator LED, a LiSteer client continuously adapts its antenna beams without requiring any beam training.

We implement LiSteer on custom dual-band testbeds and perform extensive over-the-air experiments in various environments and under different mobility scenarios to evaluate key components of LiSteer design. Our hardware platforms encompass off-the-shelf light sensors for light sensing and 60 GHz wideband transceivers with electronically steerable phased arrays. Our results show that LiSteer achieves direction estimates within 2.5 degrees of ground truth on average, and achieves beam steering accuracy of more than 97% while in tracking mode.

S3 '18, November 2, 2018, New Delhi, India

ACM ISBN 978-1-4503-5932-0/18/11…$15.00
https://doi.org/10.1145/3264877.3264884

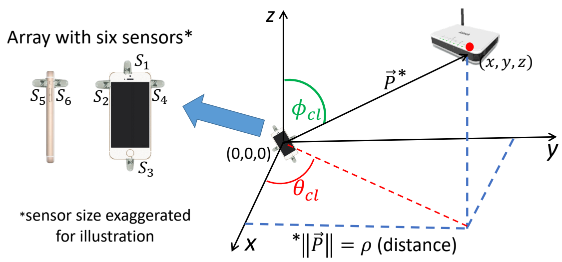


Figure 1: LED tracking via light sensor array.

2 LISTEER DESIGN

2.1 AoA Estimation via Light

The key challenge in exploiting the light source at the AP for direction tracking in LiSteer is that, unlike lasers, light intensity from LEDs (or common light bulbs) is *incoherent*, and off-the-shelf light sensors can only measure the *intensity* of the incident light. Therefore, AoA estimation techniques in radio bands via antenna array phase difference (e.g., [7]) cannot be used. For this, we devise a novel method for incoherent-light Angle of Arrival (il-AoA) estimation by using an array of light sensors.

In particular, the intensity of light is modeled by Lambertian radiation pattern for LOS propagation [1] as follows:

$$I(\rho, \gamma, \psi) = T \cdot C \cdot \left(\frac{m+1}{2\pi}\right) \cdot cos(\psi) \cdot \frac{cos^m(\gamma)}{\rho^2} \quad (1)$$

where T is LED's transmit power, C is a calibration constant, γ is the irradiance angle between light source and sensor separated by distance ρ, and ψ is the Angle of Arrival (AoA) at the sensor. m is the Lambertian order, which is unity for common LEDs.

Since the size of mobile devices is usually much smaller than the AP-client distance, we approximate the irradiance angle and distance from the AP to be the same at all sensors ($\forall j, \gamma_j = \gamma, \rho_j = \rho$). With this, the ratio of intensities at any two adjacent sensors is a function of their AoA only, independent of ρ and γ. That is, $\frac{I_{j1}}{I_{j2}} \approx \frac{cos(\psi_{j1})}{cos(\psi_{j2})}$. As such, if the sensors are placed at right angles on the array, we can estimate the AoA in the plane carrying the sensors as:

$$\hat{\psi}_{j1} = tan^{-1}\left(\frac{I_{j2}}{I_{j1}}\right) \quad (2)$$

Since sensor arrangement is fixed and known at the client, we consider the ratio of intensities at adjacent sensors in three perpendicular planes to estimate the 3-D AoA of the LOS path. Therefore, we propose an array with at least six sensors arranged mutually orthogonally, as depicted in Fig. 1.

2.2 Beam Adaptation Protocol

The LiSteer architecture, depicted in Fig. 2, is divided into two distinct bands; a *Communication Band* comprising mmWave radios and a *Sensing Band* with AP's LED and device's light-sensor array.

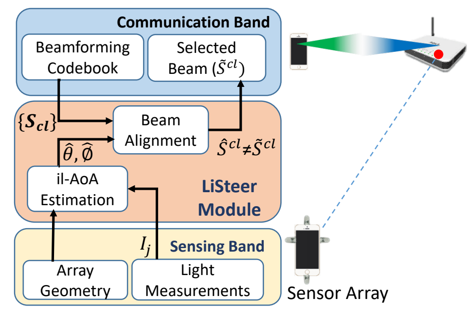


Figure 2: LiSteer node architecture.

LiSteer beam steering comprises two phases; an initial *Beam Acquisition* phase where the AP does a single beam-sweep at its end as a part of association, whereas client beam is selected via il-AoA estimation by computing the beam with the highest directivity gain along the LOS path AoA. After this, LiSteer enters *Beam Steering* mode, where the client keeps tracking AP's LED and hence its maximal strength beam. If this maximal beam estimate becomes different from the beam currently being used for communication, an interrupt is passed to the MAC layer to adapt the current beam. As such, LiSteer steers client-side beams without incurring any training or feedback overhead. For AP beam adaptation during the Beam Steering phase, we repurpose the mandatory and periodic beacon sweeps in WLANs. Moreover, since client-side beam training is replaced by il-AoA estimation driven beam selection, multiple clients can simultaneously train for AP side beams during the beacon sweeps.

If beam alignment is lost due to tracking error or blockage of LOS path, LiSteer enters Beam Acquisition again.

3 PERFORMANCE EVALUATION

3.1 Implementation

We have implemented key components of LiSteer on a custom dual-band hardware platform, as well as on a trace- and model-driven indoor-WLAN simulator. For hardware implementation, we use off-the-shelf LEDs and light sensors for Sensing Band. For mmWave band, we use two distinct systems to capture different aspects of mmWave channels and system design. First we integrate a configurable Software Defined Radio (SDR) based X60 wideband mmWave platform [6] into our tested. It equips a *user-configurable* 24-element phased array antenna from SiBeam. X60 allows us to evaluate LiSteer under practical phased arrays with wide beams, beam-overlap and side lobes. For achieving highly directional beams with minimum side-lobes, we also integrate a horn antenna based platform into our testbed, with 7° beamwidth antennas.

To explore a broader set of operational conditions beyond the capabilities of our hardware platform, including multiple clients, different mobility patterns and client speeds, we also develop a custom MATLAB WLAN simulator. To drive

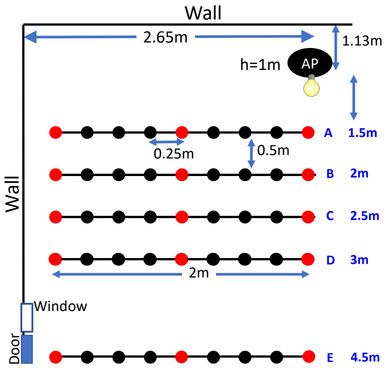


Figure 3: Testbed setup for dual-band experiments.

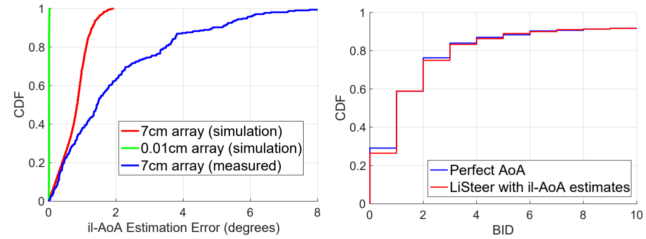
the simulator, we use the 802.11ad and visible light channel models and our own measurement traces.

Using our hardware and simulation platforms, we have evaluated LiSteer performance under a variety of environments, translational and rotational mobility scenario and client densities. The detailed description of our implementation and experimental results is reported in [3, 4]. Here we only share a subset of results highlighting the proof-of-principle and beam steering accuracy. The reported results are for the experimental scenario depicted in Fig.3, where we consider 45 client positions in front of the AP in a conference room, arranged in five client trajectories (A,B,C,D and E) at longitudinal distances 1.5m, 2m, 2.5m, 3m and 4.5m from the AP for the initial position of the client.

3.2 Key Results

We first evaluate the accuracy of il-AoA estimation using light intensities. To identify various sources of estimation error, we also perform light channel model based simulations. Fig. 4a depicts the CDF of il-AoA estimation error. First, for simulation of an array of negligible dimensions (0.01cm), we observe an almost perfect il-AoA estimation accuracy, which validates our key idea. Second, simulations for a 7cm array (same dimensions as our testbed array) show up to 2° estimation error, highlighting the impact of collocated sensors approximation on the accuracy of our method. The blue curve for over-the-air experiment results indicates that the estimation error is within 3.5° of the true AoA for more than 90% of measurement instances.

Next we consider the beam selection accuracy for experiments with phased array platform. Fig. 4b depicts the client-side beam selection accuracy plotted as a CDF of Beam Index Distance (BID). We define BID as the absolute difference between indices of LiSteer's predicted beam and the maximal strength beam in the beam-search space. First we observe that even with true AoA (i.e., perfect LOS path tracking), there is a non-zero BID for almost 70% experimental instances. This is in contrast to our horn antenna experiments, where the geometric AoA almost always leads to



(a) il-AoA estimation error. **(b) Beam acquisition error.**

Figure 4: il-AoA and beam steering accuracy.

the selection of the highest strength beams for LOS paths. The primary reason for this deviation is the imperfect beam patterns of the SiBeam phased array and presence of side-lobes, which can capture multiple paths in the channel to show slightly higher strength. Nonetheless, for almost 80% instances, the difference is within 2 beams from the beams selected via exhaustive search. The figure also shows that beam selection accuracy for over-the-air il-AoA estimates matches very closely to the beams selected using the geometric AoA and the error is negligible. The reason is that our AoA estimation error is very small compared to the relatively wide (25° to 35°) beams of the phased array platform. This shows that il-AoA estimates in LiSteer are sufficiently accurate for geometric AoA based beam selection.

4 CONCLUSION

We present LiSteer to steer mmWave beams at mobile devices by tracking indicator LEDs on wireless APs to passively acquire direction estimates, and demonstrate that LiSteer acquires and maintains beam alignment despite device mobility, without incurring any training overhead at clients.

5 ACKNOWLEDGMENTS

This research was supported by Cisco, Intel, and by NSF grants CNS-1642929 and CNS-1514285.

REFERENCES

[1] J. R. Barry. *Wireless Infrared Communications*, volume 280. Springer Science & Business Media, 2012.

[2] M. K. Haider, Y. Ghasempour, and E. W. Knightly. Searchlight: Tracking device mobility using indoor luminaries to adapt 60 ghz beams. In *Proc. of ACM MobiHoc*, 2018.

[3] M. K. Haider, Y. Ghasempour, D. Koutsonikolas, and E. W. Knightly. Listeer: mmwave beam acquisition and steering by tracking indicator leds on wireless aps. In *Proc. of ACM MobiCom*, 2018.

[4] M. K. Haider and E. W. Knightly. itrack: Tracking indicator leds on aps to bootstrap mmwave beam acquisition and steering. In *Proc. of ACM HotMobile*, 2018.

[5] T. Nitsche, C. Cordeiro, A. Flores, E. Knightly, E. Perahia, and J. Widmer. IEEE 802.11ad: Directional 60 GHz Communication for Multi-Gigabit-per-second Wi-Fi. *IEEE Communications Magazine*, 52(12):132–141, 2014.

[6] S. K. Saha et al. X60: A Programmable Testbed for Wideband 60 GHz WLANs with Phased Arrays. In *Proc. of ACM WinTech*, 2017.

[7] J. Xiong and K. Jamieson. ArrayTrack: A Fine-Grained Indoor Location System. In *Proc. of USENIX NSDI*, 2013.