Beam Search Strategy for MillimeterWave Networks with Out-of-Band Input Data

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***Abstract*—Beam training in dynamic millimeter-wave (mm-wave) networks with mobile devices is highly challenging as devices must scan a large angular domain to maintain alignment of their directional antennas under mobility. Exploiting the fact that mobile devices will typically integrate multiple chipsets, we study a set of non-mmwave input data that can be leveraged jointly to provide faster beam search and better data rate. We leverage these findings to introduce SLASH, an algorithm that adaptively narrows the sector search space and accelerates link establishment, link maintenance and handover between mm-wave devices. We evaluate SLASH both with simulations and experiments in a 60-GHz testbed. SLASH can increase the data rate by more than 64% for link establishment and 67% for link maintenance with respect to prior work.**

I. Introduction

Exact beam alignment of the highly directional antennas of mm-wave communication systems is necessary to achieve high data rates or even just a sufficient link margin for communication. The need for fast and efficient beam training strategies has stimulated a variety of research studies, both theoretical and experimental [1]–[10]. There was substantial progress in terms of beam training efficiency compared to the original brute force or (optionally) hierarchical training of IEEE 802.11ad, for example through compressive beam training approaches [9], [11] that only need to scan a subspace of the available antenna beams. Nevertheless, particularly dense deployments with many devices or networks with high mobility remain a challenge. In dense networks with small cell sizes, handovers occur frequently, and a device may need to beam train with potentially many APs to determine to which APs it has the best link quality. In this case, it has been shown that using context information can help provide beam steering information to speed up the link establishment without the need for explicit beam training [10], [12].

However, past works have mainly considered in isolation out-of-band inputs. Motivated by these considerations, we investigate how to jointly use out-of-band input data, in particular the orientation of the mobile device and its distance and angle to the AP as measured with sub-6GHz legacy WiFi, for speeding up the beam search at mm-wave frequencies for problems such as i) how to maintain beam alignment under device rotation over a very short period of time, ii) reduce beam training delay exploiting angle information with sub-6GHz legacy WiFi and reciprocal channel at mmwave frequency, and iii) increase the data rate during the handover process to other APs in range using knowledge of the estimated distance with time measurements extracted with sub-6GHz legacy WiFi.

Our contributions are as follows.

- We design SLASH, a beam search strategy that exploits out-of-band context input that can be easily available in today's devices (Sec. III). In particular, for link establishment we use angle of arrival information as input to narrow down the sector search space, exploiting the relationship between the quasi-reciprocity of the mm-wave channel to further speed up the link establishment. For link maintenance, we propose a fast strategy to maintain the mm-wave link by tracking the device rotation under user mobility. For handover, we use the distance to proactively select the AP to connect to.
- We conduct our studies with both simulations and experiments with a 60 GHz testbed to validate our approach, and we compare SLASH both to the 802.11ad standard and prior work. Our study indicates that SLASH is very effective in increasing the data rate with respect to prior work (Sec. V).

II. Motivation

mm-wave communication supports physical data rates of several Gb/s using highly-directional phased antenna arrays [13]. Examples of technology using mm-wave are the IEEE 802.11ad standard for Wireless Local Area Networks (WLANs) in the 60 GHz band [14] and 5G cellular networks for licensed mm-wave bands [15]. The communication between AP and User Equipment (UE) in mm-wave requires:

Link Establishment: beam training is needed to find the Angle of Departure (AoD) at the transmitter and the Angle of Arrival (AoA) at the receiver in order to select an antenna sector pair that allows to establish communication and maximizes the received power.[1]

Link Maintenance: after beam training, environment variations and UE mobility and rotation can cause swift changes of the link quality, and continuous beam adaptation is needed to maintain a high data rate.

AP handover: mm-wave network deployments are dense, and multiple APs are presented in the area. Handover procedure must be triggered if there exists an AP that could provide a higher data rate.

[1]Note that, in this paper, we interchangeably use the terms sector and beams.

A. Beam training

Frequently performing a time-consuming beam training procedure leads to high latency and overhead, which wastes network resources and deteriorates the system performance. We take as reference the IEEE 802.11ad beam training.[2] The 802.11ad standard handles the beam training procedure via a Sector Level Sweep (SLS) strategy to discover the AP-UE sector pair providing the highest received signal strength (RSS). SLS comprises two phases: (i) AP SLS and (ii) UE SLS. During the AP SLS phase, the AP exhaustively switches across all the available sectors – ideally covering the entire 360° azimuth – and transmits training frames marked with sector identifiers. The UE receives those frames with a quasi-omnidirectional antenna pattern and identifies the AP sector with the highest RSS. The same process is repeated in the subsequent UE SLS phase, where the UE trains its sectors and the AP receives quasi-omnidirectionally. Once a connection is established, the link quality degradation due to user mobility is handled through either beam refinement and tracking, or through a full beam training procedure, that attempt to determine a new combination of beams with improved link quality. According to the standard, the beam refinement phase searches around the current sector pair in order to determine a new combination of beams with improved link quality.

B. Out-of-band inputs for beam training

In order to reduce the beam training delay, we investigate how well the AoD/AoA pair providing the highest RSS can be estimated by means of sub-6 GHz WiFi technology, when mm-wave and sub-6 GHz WiFi coexist in the same multi-band device.[3] Previous approaches in this area are affected by three main problems.

Errors in the angular estimation. In case of mobile devices, energy and form factor constraints limit the number of antennas to one or two, even in mobile chipsets of the last generation [18]. Even if APs may be equipped with low-order MIMO transceivers in typical form factors, the median error in the angle estimation of 802.11 frames received by mobile devices with one antenna is about 20 degrees [19], [20], i.e., even in this case significant further refinement is necessary to ultimately align the antenna beams. This motivates trying alternative approaches that are less demanding in terms of hardware requirements. For this, we envision to exploit legacy sub-6 GHz technology that can provide Channel State Information (CSI) to infer the direction of the target device (see e.g. [10]).

Inferring angular rotation. The client rotation must be compensated for any variation of the angle with respect to the spatial reference system and the chosen antenna sector must be adjusted accordingly, otherwise the mm-wave link quality would suffer dramatically. For this purpose, we use additional inertial sensors such as compass and gyroscopes.

Handover procedure at mm-wave. The client may be connected to the AP until the connection is below the sensitivity before triggering a new search for APs in range. This can cause outage in the communication. For this we propose to exploit legacy sub-6 GHz technology that can provide distance estimates. For instance, the Fine Time Measurement (FTM) is a protocol that has been standardized in the 802.11-2016 and it is now entering in the market. FTM estimates the distance between the AP and the mobile at sub-6 GHz frequency, even without associating the mobile to the AP [21].

[2]mm-wave in 5G is under standardization, with beamforming operations for both data and control planes [15], [16]

[3]The sub-6 GHz WiFi radio can also serve as a fallback in case no mm-wave link can be established [15], [17].

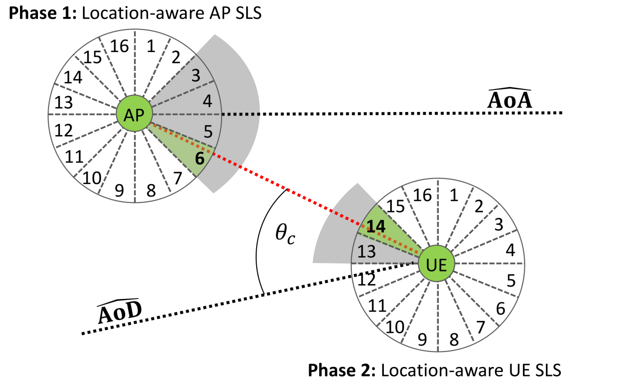


Fig. 1. Schematic representation of the working principle for link establishment.

III. SLASH

In this section, we present SLASH, a beam search strategy for mm-wave link establishment and maintenance which exploits input from inertial sensors and sub-6 GHz angular information provided by [10]. For link establishment, we assume that the LOS/quasi-LOS path is the one with the highest RSS between the AP and the UE. As shown in recent studies, when LOS/quasi-LOS is blocked, mm-wave suffers from outage and significant throughput degradation and the traffic is re-directed to sub- 6 GHz WiFi [17], [22]. For link maintenance, the rotation can be estimated in presence or absence of the mm-wave LOS/quasi-LOS path. Compared to existing works in the literature which limit their investigation only to downlink transmissions [10], [12], [23], we consider both the AP SLS and UE SLS phases.

A. Link establishment

For the link establishment, we propose a beam search algorithm to adaptively narrow the sector search space according to the median angle error presented in [10]. We assume that AP and UE employ directional sector antennas of beamwidths α_{AP} and α_{UE}, respectively, to communicate at mm-wave frequencies.

Starting with AP SLS as first stage, the AP can exploit the system to retrieve the UE's estimated direction $A\hat{o}A$. Then, fixing the location angle error θ, the angular portion $\nabla\Theta^{AP} = 2\theta$, centered around the line of the UE's estimated direction, is used to determine the subset of sectors to probe during AP SLS. As shown in the example in Fig. 1, the AP transmits training sequences to probe from beams 3 to 6, while the UE receives omnidirectionally and performs RSS measurements.

Quasi-reciprocity and position of the UE. The concept of channel quasi-reciprocity, the similarity of the downlink and uplink channels, is usually used for channel estimation [24]. We exploit it in a different way: for the UE SLS phase, we probe the sectors in the direction of the AP, $A\hat{o}D$, but given that the AP SLS already resolved the angle error at the AP side, we can take this into account to further reduce the number of sectors in the uplink to probe. For the implementation, we set $\nabla\Theta^{UE} = \frac{\nabla\Theta^{AP}}{2} = \theta$ for the UE SLS phase. For instance, considering the example in Fig. 1, the correcting effect of AP SLS allows to exclude sectors 11 and 12 from the UE SLS, leaving just two beams (13 and 14) to be probed instead of four. At the end of the two phases, the AP-UE sector pair providing the highest RSS (beams 6 and 14 in the example) is used for data transmission.

Algorithm 1 outlines the pseudo-code of SLASH-LE. Concretely, during the AP SLS phase, the UE is in omnidirectional reception mode, while the AP switches through the $I = \lceil \Theta^{\text{AP}}/\alpha_{\text{AP}} \rceil$ transmit sectors B_i^{AP}, $i = 1, 2, ..., I$, falling within the angular portion $\triangledown\Theta^{\text{AP}} = 2\theta$, which can be denoted by the set

$$\mathcal{B}_{\text{AP}} = \left\{ B_i^{\text{AP}} \text{ falling in } \Theta^{\text{AP}}, i = 1, 2, ..., I \right\} . \quad (1)$$

The UE performs RSS omnidirectional measurements over the set of beams trained by the AP and selects the B_{best}^{AP} as the beam providing maximum RSS. In the subsequent UE SLS phase, the UE uses the positioning system to estimate the AP position and corrects it by the angle θ_c inferred from the AP SLS results. Training packets are transmitted by the UE switching across the $J = \lceil \Theta^{\text{UE}}/\alpha_{\text{UE}} \rceil$ sectors B_j^{UE}, $j = 1, 2, ..., J$, falling within the angular portion $\triangledown\Theta^{\text{UE}} = \theta$, which can be denoted by the set

$$\mathcal{B}_{\text{UE}} = \left\{ B_j^{\text{UE}} \text{ falling in } \Theta^{\text{UE}}, j = 1, 2, ..., J \right\} . \quad (2)$$

As before, the AP performs RSS omnidirectional measurements over the set of UE transmit sectors and selects B_{best}^{UE} as the beam providing maximum RSS. At the end of the procedure, AP and UE enter the data transmission phase where the selected beams B_{best}^{AP} and B_{best}^{UE}, respectively, are used to communicate.

B. Link maintenance

We propose an algorithm to maintain the mm-wave communication and update the current sector using data from the gyroscope of the smartphone for rotation estimation. As we consider static APs, UE rotations imply that only the antenna sector at the UE side needs to be updated. The key is that, while the optimal beam for the AP may not change a lot (especially if the mobile device is not very close to the AP), this is not the case with the mobile device, where each rotation can significantly impact the optimal beam.

The main algorithm steps are as follows:

- During UE mobility, as soon as the system observes a drop in signal quality, the estimated angular rotation since the last link maintenance is determined.
- If the angular velocity indicates a change in direction, the two candidate sectors are trained following a UE SLS-like approach.
  - The new direction with the highest RSS is selected for mm-wave communication. Any error in the estimated angular velocity is immediately solved using the direction with the highest mm-wave RSS as feedback loop.
- If the angular velocity indicates no changes in direction and the mm-wave link quality is low, SLASH monitors the distance estimates between from the UE to the AP.
  - Beam refinement/tracking as defined by the 802.11ad standard is used when the distance estimates indicates that the UE is connected to the closest AP (cf. Section II-A). We emphasize that this procedure is different from the full SLS.
  - A handover procedure is instead triggered when the distance estimates indicate that there is a closer AP.

Algorithm 1 SLASH-LE

Input: θ, α_{AP}, α_{UE}

Phase I: Direction-aware AP SLS

UE in omnidirectional reception mode
Estimate AoA from CSI: $\hat{AoA}$
$\Theta^{\text{AP}} = [\hat{AoA} - \theta, \hat{AoA} + \theta]$
Define $\mathbf{RSS}_{\text{UE}}$ vector
$I = \lceil \Theta^{\text{AP}}/\alpha_{\text{AP}} \rceil$
$\mathcal{B}_{\text{AP}} = \left\{ B_i^{\text{AP}} \text{ falling within } \Theta^{\text{AP}}, i = 1, 2, ..., I \right\}$
for $i = 1 : I$ **do**
    AP sends a beacon through sector $B_i^{\text{AP}} \in \mathcal{B}_{\text{AP}}$
    UE stores the measured RSS as $\mathbf{RSS}_{\text{UE}}[i]$
end for
$B_{best}^{\text{AP}} = B_i^{\text{AP}} \in \mathcal{B}_{\text{AP}}$ — $\mathbf{RSS}_{\text{UE}}[i] = \max(\mathbf{RSS}_{\text{UE}})$
return B_{best}^{AP}

Phase II: Direction-aware UE SLS

AP in omnidirectional reception mode
Estimate AoD from CSI: $\hat{AoD}$
Compute θ_c
$\Theta^{\text{UE}} = [\hat{AoD} - \theta_c - \theta/2, \hat{AoD} - \theta_c + \theta/2]$
Define $\mathbf{RSS}_{\text{AP}}$ vector
$J = \lceil \Theta^{\text{UE}}/\alpha_{\text{UE}} \rceil$
$\mathcal{B}_{\text{UE}} = \left\{ B_j^{\text{UE}} \text{ falling within } \Theta^{\text{UE}}, j = 1, 2, ..., J \right\}$
for $j = 1 : J$ **do**
    UE sends a beacon through sector $B_i^{\text{UE}} \in \mathcal{B}_{\text{UE}}$
    AP stores the measured RSS as $\mathbf{RSS}_{\text{AP}}[j]$
end for
$B_{best}^{\text{UE}} = B_j^{\text{UE}} \in \mathcal{B}_{\text{UE}}$ — $\mathbf{RSS}_{\text{AP}}[j] = \max(\mathbf{RSS}_{\text{AP}})$
return B_{best}^{UE}

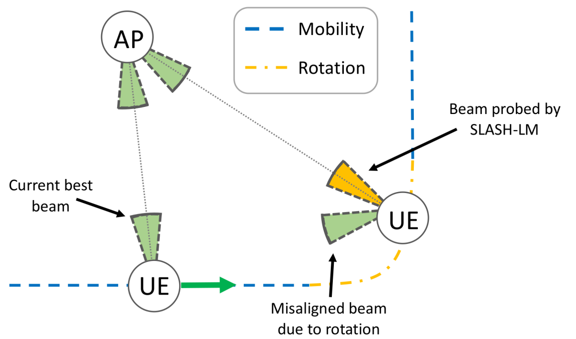


Fig. 2. Illustrative example of link maintenance using SLASH.

IV. Testbed

Our measurements are conducted in an indoor space with an open area and offices covering a total area of 300 m^2. Concrete walls separate the offices from the open area, and significant multipath is present in the area. The map of the scenario is shown in Fig. 3, where red circles mark the AP positions and green crosses mark two random selected UE positions (UE_1 and UE_2). All APs and UEs are equipped with both 60 GHz and sub-6 GHz WiFi.

A. Experiments for Link Establishment

To perform experiment for the link establishment phase, each AP and UE is equipped with both 60 GHz and legacy WiFi radio technologies. An illustration of the setup of the AP

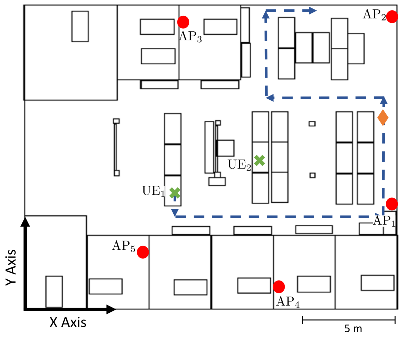


Fig. 3. Indoor environment considered for static and mobile tests.

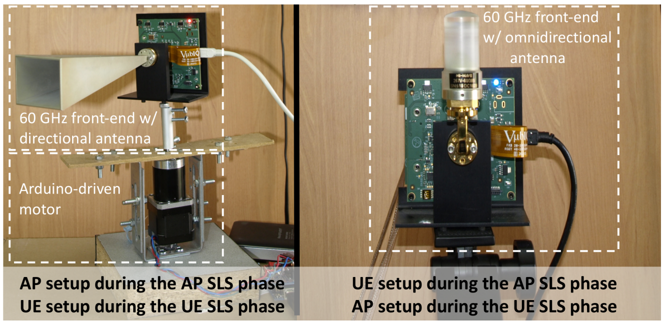


Fig. 4. The experimental setup used for 60 GHz RSS measurements once the connection has been established.

for these experiments is shown in Fig. 4. In order to follow the IEEE 802.11ad AP SLS and the UE SLS link establishment phases, in our system, the mm-wave transmitter is connected to an Agilent N5182A signal generator which constantly sends a probe signal and it is mounted on Arduino-driven stepper motors with an accuracy of 0.18 degrees in order to emulate electronically steerable phased antenna arrays. The receiver is connected to an Agilent N9010A signal analyzer to measure the RSS. In the AP SLS phase, the AP uses a Vubiq 60 GHz transmitter [25] set to 15 dBm and it is equipped with a 7°-beamwidth horn antenna. The UE uses a Vubiq 60 GHz receiver to receive the signal from the AP. It is connected to an omni-directional antenna and it has a noise floor equal to −87 dBm. The UE uses a Vubiq 60 GHz transmitter with power set to 30 dBm to tranmit to the AP using the same omni-directional antenna. The opposite configuration holds in the UE SLS phase.

B. Experiments after Link Establishment

In order to perform experiments for 60 GHz RSS measurements once the connection has been established, in our system, the mm-wave transmitter is connected to an Agilent N5182A signal generator which constantly sends a probe signal, and it is mounted on Arduino-driven stepper motors with an accuracy of 0.18 degrees in order to emulate electronically steerable phased antenna arrays. The receiver is connected to an Agilent N9010A signal analyzer to measure the RSS. This time, both AP and UE use a Vubiq 60 GHz transmitter [25] set to 15 dBm and equipped with a 7°-beamwidth horn antenna. It has a noise floor equal to −87 dBm. An illustration of the setup for these experiments is shown in Fig. 5.

C. Configuration for Link Maintenance

For tests in mobility with mm-wave, since our mechanical rotation does not allow our system to operate in real-time, we

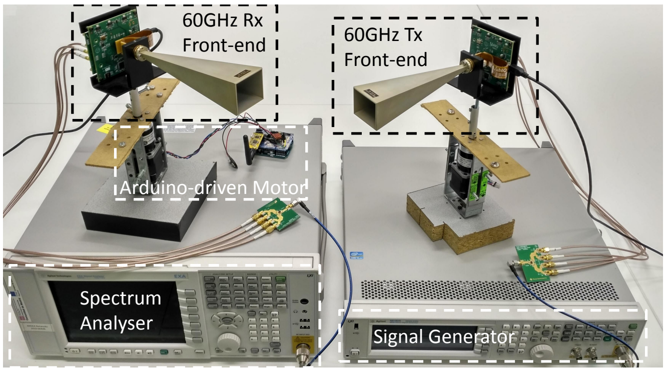


Fig. 5. The experimental setup used for 60 GHz RSS measurements once the connection has been established.

adopt the well known, ray-tracing based signal propagation tool WinProp and its integrated graphical editor for vector building databases, WallMan (Wall Manager), to reproduce the same office environment considered in Fig. 3. Other recent works in mm-wave networks have used a similar methodology [18], [26]. In this configuration, both the AP and the UE are equipped with a 7°-beamwidth antenna. Transmission power is set to 15 dBm and the noise floor is equal to −87 dBm. Finally, for our ray-tracing simulations, we consider only LOS transmission, first order reflection, and penetration through partitions, as these are the most dominant propagation mechanisms at mm-wave frequencies.

D. ToF distance estimates

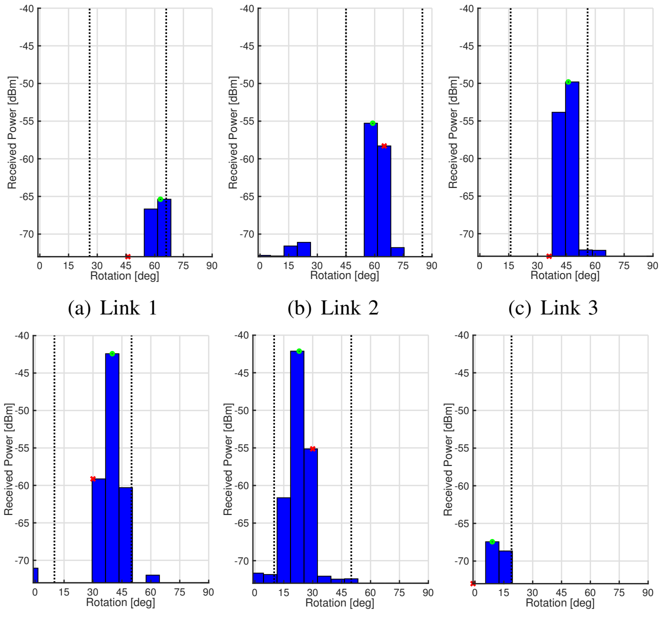
The ToF range is computed using regular 802.11 Probe Responses sent by the APs and acknowledged by the UE via 802.11 ACKs. At any point in time, the target device is associated to only one AP, as in typical 802.11 wireless networks. Our distance estimation system uses commercial Soekris net5501 embedded machines as APs. The APs are equipped with an 802.11b/g Broadcom AirForce54G 4318 chipset operating at 2.4 GHz and one omnidirectional antenna. The Broadcom chipset runs a customized firmware and b43 driver to measure the ToF for each Probe/ACK. The APs are connected over Ethernet to the Central Location Unit (CLU) implemented in C++, that stores and processes the raw ToF data and computes the distances. We calculate ranges using 20 samples per AP. Tests with the mobile user have been performed by a human carrying an unmodified Alcatel Pixi smartphone.

V. System Evaluation

In this section, we evaluate the performance of SLASH in static and mobile scenarios, comparing it against existing solutions in the literature.

A. Impact of the sub-6 GHz angle error on the mmwave RSS for link establishment

We experimentally investigate how errors in the UE direction estimate affect the 60 GHz RSS. This study is performed in a few representative links (6 out of 10) between the UE and the AP, using directional mm-wave antennas on both nodes (cf. Fig. 5). In order to evaluate the link quality for different levels of misalignment between AP and UE antenna, we start from an ideal situation where the nodes are perfectly aligned and measure the RSS when adding different rotation drifts at steps of 7° (corresponding to the antenna beamwidth).



(a) Link 1 (b) Link 2 (c) Link 3

(d) Link 4 (e) Link 5 (f) Link 6

Fig. 6. Measured RSS for different directional AP-UE 60 GHz links when varying the level of misalignment between transmit and receive antennas. In all tests, we use below 20 degrees of error as observed in past literature.

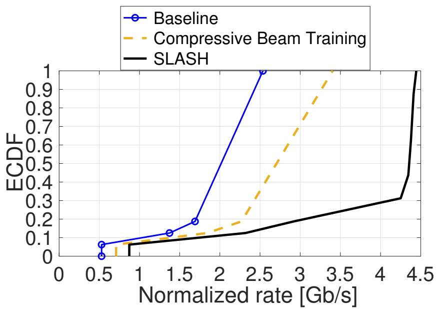


Fig. 7. ECDF of the normalized mm-wave data rate for different beam search strategies.

With the objective of better reproducing realistic scenarios, we randomly select the angle error between zero and 20 degrees as observed in past works that rely on one single antenna for sub-6 GHz legacy WiFi at the mobile device [19], [20]. In fact, in case of mobile devices, energy and form factor constraints limit the number of antennas to one or two, even in mobile chipsets of the last generation [10], [18]. Even if APs may be equipped with low-order MIMO transceivers in typical form factors, the median error in the angle estimation of 802.11 frames is limited by the number of antennas at the mobile side. This allows us to reproduce the effect resulting from a misaligned mm-wave link when the instantaneous output from the sub-6 GHz system is used to steer the devices' antenna beams.

The results are plotted in Fig. 6. The green circular markers refer to the ideal case with perfect knowledge of the AoD/AoA pair (i.e., assuming error-free sub-6 GHz location estimates). In the experiments, we only show the RSS values that are above the minimum sensitivity level required for correct frame reception. As shown in the figure, even few degrees of error in the angle estimation (red crosses) can result in steering in a direction without connectivity. For the rest of evaluation, we fix the location angle error θ for link establishment equal to 20°, from which Θ^{AP}=40° and Θ^{UE}=20°.

B. *SLASH for a static user*

We consider a static user (UE_1 in Fig. 3) that performs the link establishment phase for all five APs, through the SLASH algorithm presented in Sec. III-A. We evaluate the ability of SLASH to accelerate the link establishment between AP and UE. We compute the normalized data rate as $R \cdot \frac{T}{T+\tau}$, where R is the achieved data rate, T = 2 ms is the data frame size, and τ is the beam search latency.

As a result of the successful beam search completion, the final data rate R over the directional 60 GHz link established between AP and UE can be computed for the configured beams B^{AP}_{best} and B^{UE}_{best}. More specifically, the *experimental RSS* values and the noise floor in a 2-GHz bandwidth at 60 GHz can be translated into an achievable bit-rate R following an IEEE 802.11ad specific rate table [14].

In order to measure the beam search latency, we consider the typical duration of training packets according to the 802.11ad standard (15.8 μs). In Fig. 7 we compare SLASH with other two different strategies, the IEEE 802.11ad as "Baseline" and [9] ("Compressive Beam Training"). "Compressive Beam Training" adapts compressive path tracking for sector selection. The ECDFs show that SLASH achieves a data rate that is 64% higher in median than "Compressive Beam Training". In practical cases, SLASH can achieve even higher performance than prior work, as it can exploit the estimated direction of the UE.

C. *SLASH for a mobile user*

We study the performance of SLASH with a user moving along the mobility pattern in Fig. 3, which includes straight-line paths and rotations. For the experimental trace, the mobile user holds the UE, walks along the trajectory at an approximated speed of 0.5 m/s and rotates at an approximated rotation speed of 0.35 rad/s. In the map in Fig. 3, we show the real trajectory of the user with the blue dashed line and we use an orange diamond for the position where the user performs a handover to the second AP. For this study, we consider two APs (AP_1 and AP_2) for the user to switch between, as the other three APs are in office rooms and they could not provide good coverage along the trajectory at mmWave frequency.

We evaluate the normalized data rate along the whole trajectory for four different algorithms. We recall that we resort to simulations using a trace-driven approach. The results are shown in Fig. 8, where "Constant Error Method" indicates the strategy in [27]. For the study, we use as input real distance estimates using WiFi Time of Flight (ToF) measurements from each of the APs (cf. Section IV-D). We also assume that the gyroscope that provides the rotation information is subjected to an error of a few degrees. The trace used for the evaluation is shown in the central plot in Fig. 8. SLASH tries to maintain the highest data rate, and the algorithm is called as soon as the RSS drops below the threshold for communication at the highest data rate. In addition, the user performs the handover to AP_2 using distance measurement inputs. Other strategies performs a handover only when the mm-wave link is below the threshold for communication. However, this does not occur in the open space under study. The plot shows the time when link maintenance is triggered due to the rotation. The "Baseline", "Constant Error Method" and "Compressive Beam Training" approaches are not able to detect rotation events and, therefore, need to resort to the same full beam search used for link establishment. During link maintenance,

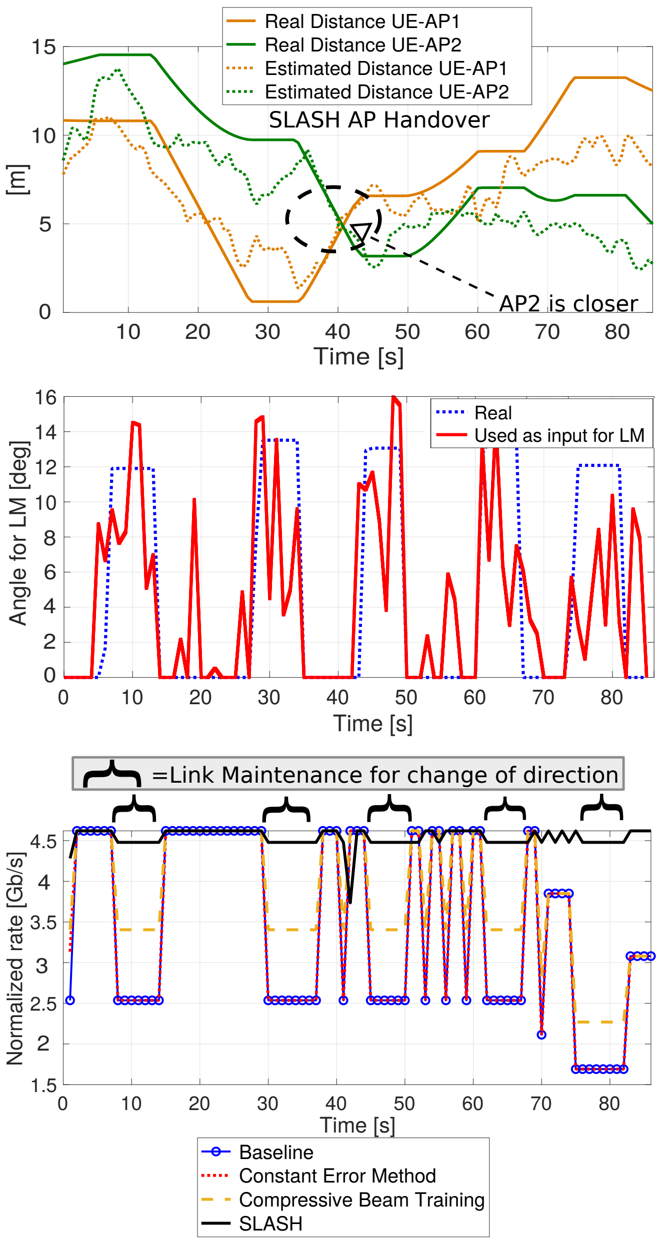


Fig. 8. Context-aware information, and data rate of SLASH and other algorithms.

SLASH achieves a data rate 67% higher than "Compressive Beam Training" and 121% higher than other strategies.

VI. Related work

The problem of fast mm-wave link establishment and maintenance is widely discussed in the literature. A comparative analysis of initial access techniques in mm-wave networks is presented in [1]. Simultaneous transmissions from multiple direction-coded beams to accelerate the beam search are exploited in [2], [3]. In [28] the authors use multi-lobe antenna patterns with random phase shifts for the beam training, which enables compressive sensing approaches to determine AoA and AoD. This approach requires arbitrary phase shifters over the antenna elements, which is not supported by standard off-the-shelf mm-wave devices that operate with how-resolution (2-bit) RF phase shifters [29].

In [4], a link-level measurement study of indoor 60 GHz networks using a software-radio platform revealed several challenges related to human blockage and device motion and how they affect the design of MAC protocols. Some of the findings of that work have been applied to extract context information from mm-wave networks in BeamSpy [30]. BeamSpy presents a beam tracking prediction mechanism based on the channel sparsity and spatial correlation of the 60 GHz link. The proposed approach works only in static conditions, while we target mobile users. Mm-wave and sub-6 GHz WiFi WiFi context information can complement each other and can enrich the set of inputs provided for the design of MAC protocols. [9] uses compressive sensing to sweep only through a subset of probing sectors.

Only very few works in the literature address the problem of fast beam search in realistic, dynamic scenarios with node mobility. In [5], a protocol for mobility resilience and overhead constrained adaptation for directional 60 GHz links is presented. A "beam sounding" mechanism is introduced to estimate the link quality for selected beams, and identify and adapt to link impairments. In [31] the authors develop a zero overhead beam tracking mechanism that uses two different beam patterns during the preamble of the frames. This allows to estimate user rotation and movement. The approach does not use context information from out-of-band channels, and it requires changes in the preamble structure. In [10] an algorithm that removes in-band overhead for directional mm-wave link establishment is proposed. However, the study focuses only on static scenarios without rotation, and requires at least five antennas in both the sub-6 GHz transmitter and receiver to achieve a similar angle error as in our system.

[6] relies on gyroscope sensors to reduce the beam search under mobility. They utilize the previously valid link knowledge to initialize a new beam search, and adaptively extend the search range to determine the new link. The coupling of legacy technology together with mm-wave frequencies in order to improve the beam search has been studied in some recent work. In [23], it is shown that beam training and cell discovery, respectively, can be accelerated assuming the availability of Global Positioning System (GPS) information about device locations.

VII. Conclusion

In this work we investigated how context information from various out-of-band inputs such as channel state information and time of flight from legacy WiFi devices as well as the inertial sensors from the mobile can be used jointly to speed-up the beam training process in mm-wave networks. We have then introduced SLASH, an algorithm to perform beam search for link establishment and maintenance. We have shown through extensive simulations and experiments that SLASH can significantly increase the data rate with mobile users compared to prior work. Our mechanism has the potential to be integrated in multi-band WiFi devices.

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