Fast Millimeter Wave Assisted Beam-Steering for Passive Indoor Optical Wireless Networks

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***Abstract*—In light of the extreme radio congestion, the time has come to consider the upper parts of the electromagnetic spectrum. Optical beam-steered wireless communications offer great potential for future indoor short-range connectivity, due to virtually unlimited available bandwidth and lack of interference. However, such networks require fast automatic beam-steering solutions. In this letter, we propose a novel optical beam-steering approach that exploits coarse grained millimeter wave localization to significantly reduce optical beam-steering time. We formulate it as a search problem that is NP-Hard to solve optimally. Moreover, we present the MMW-OBS heuristic that efficiently solves it in real-time. Results show that MMW-OBS provides total steering times below 1 second using state of the art millimeter wave localization, which is already sufficient to support sporadically mobile devices.**

***Index Terms*—Beam-steering, indoor optical beam-steered networks, millimeter wave communications, RF indoor localization**

I. Introduction

The largely congested radio spectrum already struggles to fulfill increasing user requirements. As such, the time has come to seriously consider optical wireless communication (OWC) systems, which operate in the upper parts of the electromagnetic spectrum [1].

The main OWC contender at the moment is Visual Light Communication (VLC), which can re-utilize existing LED illumination systems [1]. However, due to their omni-directionallity and the fact that light intensity decreases with the square of the distance, it is unfit for very high throughput connectivity at a reasonable range. This can only be realized by directional collimated optical beams [2]. Technologies such as micro-electro-mechanical system (MEMS)-actuated mirrors [3], spatial light modulators (SLMs) [4], and optical switches for coarse steering together with SLMs [5] have been used for this purpose. However, these approaches require one separate steering device per beam, which makes them highly complex and unable to scale to many beams. Koonen *et al.* recently proposed a passive 2D beam-steering approach [2]. This hybrid system uses narrowly confined optical infrared beams accurately directed to the devices, achieving ultra-high data rates (a minimum of 10 Gbps per beam [2]), for the downstream. For upstream communication and coarse-grained user localization, a shared millimeter wave 60 GHz radio is envisioned. This approach differs from all previous ones, as the full ultra-high downstream capacity of the infrared beam is available to each device, and no contention or interference with other devices occurs. Such a hybrid 60GHz–infrared OWC has already been successfully demonstrated for static scenarios, where the beam can be manually steered to the device [2]. However, there is need for fast and efficient automatic beam-steering solutions in order to support dynamic and mobile devices.

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In this letter, we propose such a beam-steering algorithm (MMW-OBS). It aims to minimize the total steering time, by determining the optical wavelength that best corresponds with the current device location as fast as possible aided by the coarse-grained location information obtained from the 60 GHz radio. Our results show that MMW-OBS is highly robust in face of localization errors and noise, and can be used to effectively provide seamless optical connectivity to dynamic and mobile devices.

II. Hybrid indoor optical wireless network

The room area is divided in small (overlapping) cells. In each of these, an infrared pencil radiating antenna (PRA) and a millimeter wave (mmw) radio access point (AP) are installed on the ceiling. They provide service to the devices within the coverage area. Devices are equipped with an infrared receiver and a mmw antenna for downlink and uplink communications, respectively. As each position is in range of multiple PRAs, line-of-sight communication can be guaranteed even in case of an obstacle. The PRAs are connected via high-speed optic fiber to the central communication controller (CCC) installed outside the area. The CCC controls the communication and the wavelength of each of the lasers connected in the system. In addition, it manages handovers among PRAs when line-of-sight is lost or a device moves. A PRA is a passive structure composed of a pair of crossed diffraction gratings that point the transmitted infrared beam (from the connected tunable laser) to a specific location determined by the wavelength [2]. Due to hardware limitations, a beam can only be tuned to a finite number of wavelengths, resulting in a 2D-grid of overlapping beam locations. For a more in-depth description of the architecture of this system, the reader is referred to previous work [2].

The three steps of the connection setup procedure between device and PRA are depicted in Figure 1. First, the device registers with the 60 GHz millimeter wave network, consisting of

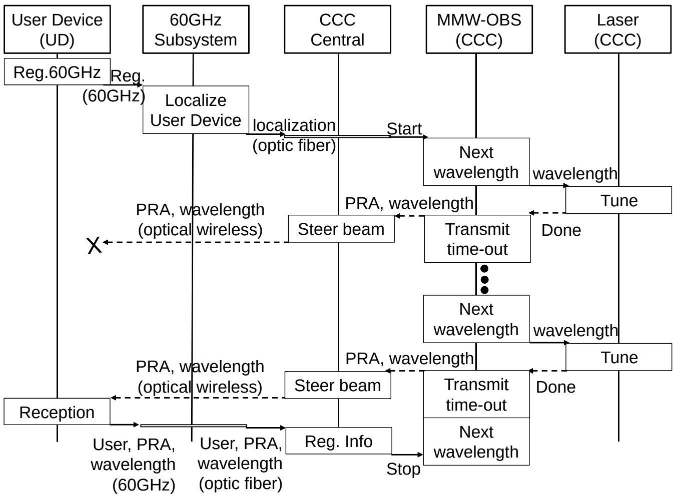

Fig. 1: Sequence diagram of the connection setup process: (i) when a device enters the coverage area it first registers via the 60 GHz network, (ii) the 60 GHz subsystem performs a coarse localization of the user, and (iii) the CCC will try to steer the infrared beam to the precise location of the user.

an initial beaconing state, followed by a beam forming phase to establish the best transmission sector of the antenna [6]. Second, the 60 GHz subsystem attempts to localize the device. This localization is envisioned to be performed by means of null steering [7], i.e. the detection of nulls of power between parallel antennas, in order to obtain accuracies of the order of 100mm. This is in line with the current state-of-the-art for line-of-sight localization [8]. The user location estimate and a unique identifier (e.g., MAC address) are finally sent to the CCC. Third, based on the localization, the CCC tunes the attached laser to different wavelengths until the optical receiver of the device is found. At each selected wavelength, the CCC transmits a message with device ID, PRA ID and used wavelength, and waits for a time-out before proceeding to the next wavelength. If the device successfully decodes the message, it sends a response to the CCC over the 60 GHz network with the succeeding wavelength and IDs to complete the handshake. The goal of the beam steering algorithm is to determine the optimal order in which to test the different wavelengths, as to minimize the total connection setup time.

III. Problem Formulation

The beam-steering problem can be modeled (and optimally solved) as a search problem. As multiple PRAs can perform beam-steering in parallel, we provide a formulation for a single PRA without loss of generality. Let us first define the inputs, before defining the search problem itself. The laser can be tuned to a finite set of wavelengths Λ. Each wavelength $\lambda \in \Lambda$ maps to a unique location l_λ. This mapping $\mathcal{L} : \lambda \mapsto l_\lambda$ can be determined a-prior during system calibration. For example, $\mathcal{L}$ can be obtained through active measurements in the physical location, determining where the wavelengths in Λ generate spots on the surface area. In a more sophisticated environment, it could be partially generated during system calibration and then dynamically improved as new positions are discovered. The tuning time $\tau_{\lambda_i,\lambda_j}$ of the laser from wavelength λ_i to λ_j is a linear function of their distance and tuning delay tt_l, or $\tau_{\lambda_i,\lambda_j} = |\lambda_i - \lambda_j| \times tt_l$. The tuning delay tt_l represents the time required by the laser to move one nanometer (nm) and depends on the hardware. The third and final input represents the estimated device position l_{mmw} as determined by 60 GHz localization. However, radio localization introduces an error, which is represented by a cumulative error distribution function (CDF) [8], which models the uncertainty of the estimated device location. From this, a Gaussian probability distribution can be derived, centered on the estimated device location l_{mmw} (i.e., with normalized mean $\mu_{mmw} = 0$) and variance σ^2_{mmw}. This distribution gives the probability $P(\lambda)$ that the location l_λ associated with a wavelength λ is the actual device location. It can be modeled as the instantaneous value of the Gaussian probability density:

$$P(\lambda) = f\left(d_\lambda | \mu_{mmw} = 0, \sigma^2_{mmw}\right) = \frac{1}{\sqrt{2\pi\sigma^2_{mmw}}} e^{-\frac{d^2_\lambda}{2\times\sigma^2_{mmw}}} \quad (1)$$

The value of d_λ represents the distance between l_λ and l_{mmw}. Using the beam direction, these locations can be projected onto the z-plane of the surface area, giving $l_\lambda = (x_\lambda, y_\lambda)$, $l_{mmw} = (x_{mmw}, y_{mmw})$ and $d_\lambda = \sqrt{(x_{mmw} - x_\lambda)^2 + (y_{mmw} - y_\lambda)^2}$.

The search problem itself is characterized by a set of states, actions, a path cost, and a goal. For the beam-steering problem, a state $s_n = [\lambda_1, ..., \lambda_n]$ represents an ordered set of wavelengths to be tested by the CCC. The possible actions at state s_n encompass the selection of one additional wavelength $\lambda_{n+1} \in \Lambda \setminus s_n$, resulting in a new state $s_{n+1} = [\lambda_1, ..., \lambda_{n+1}]$. The goal is to find a state that consists of all wavelengths. As beam-steering aims to minimize the total steering time, the cost associated with a state should represent the average total steering time to find the device when testing wavelengths in the order associated with that state. This cost $g(s_n)$ depends on the localization error probability $P(\lambda)$, the time-out τ_{to} to test a wavelength, and the laser tuning time $\tau_{\lambda_i,\lambda_j}$:

$$\begin{aligned} g(s_n) = &P(\lambda_1) \times \tau_{to} + \sum_{i=2}^{n} \left[\left(1 - \sum_{j=1}^{i-1} P(\lambda_j) \right) \right. \\ &\left. \times P(\lambda_i) \times \left(i \times \tau_{to} + \sum_{j=1}^{i-1} \tau_{\lambda_j,\lambda_{j+1}} \right) \right] \end{aligned} \quad (2)$$

To find the optimal goal state, a search algorithm additionally requires an estimate of the cost to reach the goal from the current state s_n. This cost $h(s_n)$ is modeled as the minimum average steering time required to find the device when testing all wavelengths not in s_n:

$$\begin{aligned} h(s_n) = \min_{\lambda \in \Lambda \setminus s_n} &\left[\left(1 - \sum_{i=1}^{n} P(\lambda_i) \right) \times P(\lambda) \times \left((n+1) \right. \right. \\ &\left. \left. \times \tau_{to} + \sum_{i=1}^{n-1} \tau_{\lambda_i,\lambda_{i+1}} + \tau_{\lambda_n,\lambda} \right) + h(s_n \cup \{\lambda\}) \right] \end{aligned} \quad (3)$$

Based on these cost functions $g(s_n)$ and $h(s_n)$, any existing optimal tree-search algorithm, such as iterative deepening or A^*, can be used to optimally solve the above defined search problem. As output, these algorithms give the goal state s_n that contains all wavelengths in Λ in the order that leads to the lowest average steering time $g(s_n)$. Given W possible wavelengths, the worst case time and space complexity are $\mathcal{O}\left(W^W\right)$ and $\mathcal{O}(W)$ respectively. As such, finding the optimal solution is practically infeasible, due to the exponential computational complexity.

IV. MMW-OBS ALGORITHM

In this section we present MMW-OBS, a beam-steering heuristic that aims to solve the presented search problem in real-time, using a greedy approach. First, it splits the wavelengths into groups with near-equal probability of corresponding to the device location. Second, it tests the wavelengths within each group, minimizing the intra-group steering time.

A. Probability Group Generation

First, the probability of each possible location l_λ is calculated using Eq. 1. Then, the set of wavelengths Λ is divided in a disjoint list of probability groups $[\Lambda_0, \Lambda_1, ..., \Lambda_n]$. The wavelength with highest probability $\lambda^{best} = \arg\max_{\lambda\in\Lambda} P(l_\lambda)$ is added to Λ_0, as well as all other wavelengths λ that have a success probability within a threshold θ of λ^{best}, or

$$\Lambda_0 = \left\{\lambda | P\left(\lambda^{best}\right) - P(\lambda) \leq \theta\right\} \tag{4}$$

Similarly, the process is repeated for each disjoint set $\Lambda_i\,(i > 0)$, but only for the remaining wavelengths in $\Lambda \setminus \bigcup_{j=0}^{i-1} \Lambda_j$. This is repeated n times, until each wavelength is assigned to a set Λ_i. The threshold θ provides a trade-off between only considering the localization probability $P(\lambda)$ (i.e., $\theta = 0$), the steering time $\tau_{\lambda_i,\lambda_j}$ (i.e., $\theta = 1$), or a combination of both.

B. Find User Location

Figure 2 shows the "Find User Location" process in pseudocode. The algorithm iterates over the probability groups in ascending order (line 2), starting with the one containing the λs with highest probabilities (Λ_0 at the start). Subsequently, for each probability group Λ_i, the initial wavelength $\lambda^{current}$ is selected as the one with a probability at most θ^{init} worse than the best λ^{best} in terms of probability, but with the overall shortest tuning time from where the laser is currently tuned (lines 3–5). The use of θ^{init} ensures that if several wavelengths have a very similar probability, the one with the best tuning time is used. Next, the laser is tuned to the selected wavelength (line 8) and the system checks for connectivity (line 9). If it does, the algorithm ends (line 10). Otherwise, the next wavelength is selected from the current group Λ_i as the one with the shortest tuning time from $\lambda^{current}$ (line 12). This is repeated until the group is empty (line 13).

Given W possible wavelengths, and n probability groups with at most V wavelengths each, the worst case time and space complexity of MMW-OBS are $\mathcal{O}\left(n \times V^2\right)$ and $\mathcal{O}(W)$, making it feasible to find a solution in real-time.

1: **function** FINDUSERLOCATION($[\Lambda_0, ..., \Lambda_n]$, $\lambda^{current}$)
2:   **for** Λ_i in $[\Lambda_0, ..., \Lambda_n]$ **do**
3:     $\lambda^{best} = \arg\max_{\lambda\in\Lambda_i} P(l_\lambda)$
4:     $\Lambda^{init} = \left\{\lambda | \lambda \in \Lambda_i \wedge P\left(l_{\lambda^{best}}\right) - P(l_\lambda) \leq \theta^{init}\right\}$
5:     $\lambda^{current} = \arg\min_{\lambda\in\Lambda^{init}} |l_\lambda - l_{\lambda^{current}}|$
6:     **repeat**
7:       $\Lambda_i = \Lambda_i \setminus \{\lambda^{current}\}$
8:       STEERTO($\lambda^{current}$)
9:       **if** CONNECTEDTOUSER == TRUE **then**
10:         **return** $\lambda^{current}$
11:       **else if** $\Lambda_i \neq \emptyset$ **then**
12:         $\lambda^{current} = \arg\min_{\lambda\in\Lambda_i} |\lambda^{current} - \lambda|$
13:     **until** $\Lambda_i \neq \emptyset$
14:   **return** $\varnothing$

Fig. 2: Pseudocode for the "Find User Location" step

V. EXPERIMENTAL EVALUATION

This section first describes the implementation of the system in the ns-3 network simulator. Then, we provide a discussion on the results obtained from the MMW-OBS algorithm.

A. Simulation setup

The hybrid indoor optical wireless network setup discussed in Section II, was implemented in the ns-3 network simulator. For the millimeter wave communication stack, we used the open source implementation of IEEE 802.11ad by Assasa *et al.* [6]. The Gaussian error distance distribution of 60 GHz localization was derived from experimental results found in literature [8]. The optical wireless channel implementation was based on the calculations done by Koonen *et al.* [2].

The parameters of the system are derived from recent work [2], with a beam spot diameter D_b of 30 mm, tuning time $tt_l = 5$ ms/nm, and a PRA coverage area of 1.5x1.5 m^2 covered by 2500 possible wavelengths between 1505 nm and 1630 nm. The PRA and AP are attached to the ceiling at height 2.5 m. The connection time-out τ_{to} is set to 20 ns, enough for the device to receive the necessary information (i.e., PRA and device ID, and wavelength) and decode it. Finally, the optimal values of θ and θ^{init} were experimentally determined to be 0.05 and 10^{-7} respectively.

During the experiment, the device was placed at 250 different evenly spread out positions, to ensure independence of the results towards the actual device location. At each position, the experiment was repeated 30 times, with randomly sampled localization errors from the same error distribution. Various localization error distributions are evaluated, ranging from the ideal situation ($\sigma^2_{mmw} = 0.1$) up to a worst-case ($\sigma^2_{mmw} = 8100$). The used evaluation metric is the total steering time, which is calculated as the difference between the time when the device is found and when the steering started. As a benchmark, we compare to a pure optical approach, in which the wavelengths are sequentially explored from spot 0 up to 2499.

B. Results and discussion

Table I presents the overall results for the 14 values of the variance on the localization error σ^2_{mmw}, as well as the all optical benchmark. In the ideal case ($\sigma^2_{mmw} = 0.1$ mm^2),

TABLE I: Average steering time in milliseconds of the MMW-OBS algorithm for different distributions of the 60GHz localization error and the all optical approach.

σ^2_{mmw} $[mm^2]$	s.t. $[ms]$	σ^2_{mmw} $[mm^2]$	s.t. $[ms]$	σ^2_{mmw} $[mm^2]$	s.t. $[ms]$
0.1	0.0024	**30**	0.0024	**60**	0.334
90	0.84	**120**	1.54	**150**	2.24
225	4.14	**600**	14.01	**900**	22.65
1200	26.92	**2400**	55.42	**3600**	245.3
4800	366.06	**8100**	682	***optical***	311.3

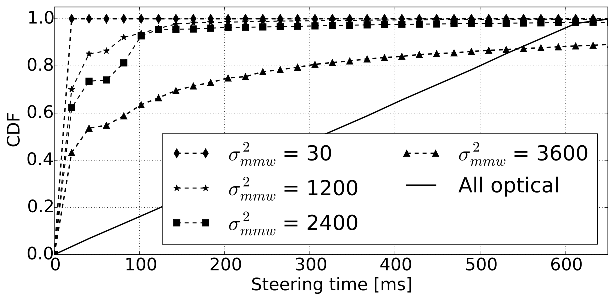

Fig. 3: Cumulative probability distributions (CDFs) for the cases $\sigma^2_{mmw} = 30$, $\sigma^2_{mmw} = 1200$, $\sigma^2_{mmw} = 2400$ and $\sigma^2_{mmw} = 3600$, compared to the all optical benchmark.

the steering time is in the order of microseconds. This means that the beam is successfully steered to the device at the first attempt (2.4 μs). However, as the localization error increases, the time taken by the algorithm to steer the laser beam to the device location increases as well. If we compare the results of MMW-OBS to the average all optical steering time of 311.3 ms, we can see that our approach finds the device on average significantly faster, except for very high variances on the localization error (i.e., $\sigma^2_{mmw} \geq 4800\ mm^2$).

To get a better view on worst-case performance, Figure 3 depicts a CDF for different localization error variances (namely, 30, 1200, 2400 and 3600) and compares them to an all optical approach. The all optical approach ignores the 60 GHz localization results and tests wavelengths sequentially, minimizing tuning time. Looking at the CDFs, MMW-OBS achieves better results than the all optical benchmark in all the cases except in the worst-case scenario in which the localization error is too high. For a variance up to $2400\ mm^2$, 85 % of the positions are found within the first 150m s. Even in the case of a variance of $3600\ mm^2$, MMW-OBS outperforms the benchmark optical solution for over 85 % of the tested device positions.

Finally, Figure 4 characterizes the steering time (y-axis) versus the actual localization error distance (x-axis), for the error distribution of $\sigma^2_{mmw} = 2400$. For benchmarking purposes, a dashed line can be found at the average state-of-the-art line-of-sight 60 GHz localization error of $120\ mm$ [8]. As it can be seen, for errors smaller than $75\ mm$, the steering time always remains under $150\ ms$. Even when the error increases up to $120\ mm$, the steering time is maintained below $1\ s$, which is still low enough to support sporadically mobile devices without significant service interruption. Finally, for a larger error of nearly $200\ mm$, the steering time is kept under 4 seconds. Such a steering time is within admissible boundaries

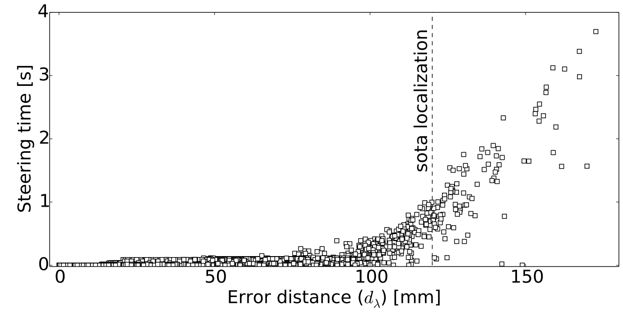

Fig. 4: Localization error distance (d_λ) versus steering time for $\sigma^2_{mmw} = 2400mm^2$. The dashed line represents the state-of-the-art average distance error of line-of-sight millimeter wave localization [8]

for automated re-connection to devices that rarely move (e.g., laptops and conferencing systems).

VI. Conclusion

Providing continuous service in indoor high-speed beam-steered optical wireless networks requires accurate beam-steering solutions. In this letter, we present an optimal formulation of the optical beam-steering problem with 60 GHz radio localization support. Moreover, the presented MMW-OBS heuristic provides a sub-optimal solution to this NP-Hard problem in real-time. Results show that using state of the art localization methods, the average beam-steering time remains under $1\ s$, which is fast enough to support sporadically mobile devices. Only for constantly moving devices highly accurate 60 GHz localization with an error less than $75\ mm$ would be needed. This leads to steering times of less than $150\ ms$.

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