Efficient Handover for Mobile Device in Beam-Steered Infrared Light Communication with Vision-based Localization

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Abstract *We propose and experimentally verify an extrapolation algorithm based on the polynomial regression to trigger efficiently handover in beam-steered infrared light communication systems. Error-free connection is demonstrated for a wireless device while moving. The proposed mechanism also reduces significantly the number of handover failures.*

Introduction

Currently, the relentless proliferation of wireless applications such as the Internet of Things, virtual reality, video streaming has put an enormous burden on indoor wireless networks. While radio-frequency communications are overloaded due to spectrum congestion, beam-steered infrared light communication (BS-ILC) is emerging as a promising technology that can unlock the path to exponential capacity growth. By employing narrow well-directed beams in the 1460–1625 nm range, BS-ILC can obtain performance targets for 6G mobile communications such as data transmission rate of terabits per second, sub-millisecond latency, and densely populated environments[1],[2]. Previously, we introduced a BS-ILC system based on arrayed waveguide grating router (AWGR) and a vision-based localization to find the target direction of steered beams[3]. We also introduced an auto-aligned receiver to obtain a sufficient link budget for a high data rate[4].

As a next step, this study focuses on mobility management that allows wireless user devices (UDs) to move from cell to cell and maintain service continuity. Although the small footprint of steerable beams offers advantages in data rate and energy consumption, this narrow communication cell brings the challenge of frequent handovers during UD's movement. In this paper, we analyse the impact of cell deployment and localization latency on the probability of handover failures. Then we propose a polynomial extrapolation algorithm using the Vandermonde matrix to compensate for the localization latency. Experimental results illustrate that the proposed handover mechanism can provide error-free connections to UDs during the movement.

System model

Fig. 1 shows the beam steering module concept using an AWGR. Output fibers of the AWGR are assembled into a honeycomb matrix array spaced at a pitch Δy which fits into the aperture of a lens with the focal length f. Let b is the distance between the user plane and the lens, p is the relative defocusing parameter (which can be defined by the distance v between the array and lens as $p = 1 - v/f$) and α is the divergence angle of the single mode fiber. Then, using paraxial geometric optics, the footprint radius R_{cell} of communication cell, distance d_{c-c} between the center of two cells, the width w of the overlapping area and the fill factor f_{f-f} at the user plane are given:

$$R_{cell} = \tan\alpha\,\big(f + p(b-f)\big);\, d_{c-c} = \frac{\Delta y}{f}(b-f)$$

$$w = 2R_{cell} - d_{c-c}, \qquad f_{f-f} = \frac{2\pi R_{cell}^2}{\sqrt{3}d_{c-c}^2}$$

Fig. 2 illustrates the impact of the defocusing parameter and 2D arrangement on the communication cell deployment at the user plane. At the distance $b = 1.8m$, fiber spacing $\Delta y = 2.51mm$ and lens focal length $f = 51.2mm$, the distance between the center of two cells stays the same while the cell diameter is proportional to the defocusing. From $p \geq 0.21$, the PRA can cover all the user plane and the width w starts increasing.

Evaluation of handover in BS-ILC system

We introduced the accurate localization based on

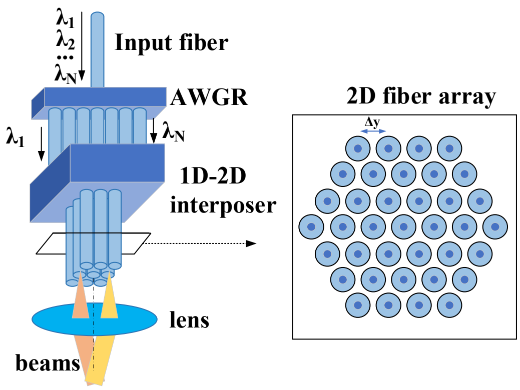

Fig. 1: Beam steering module

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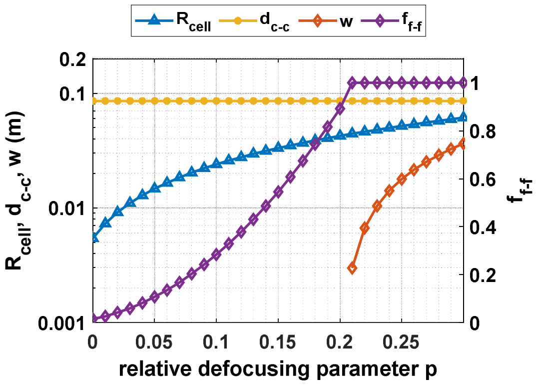


Fig. 2: Impact of defocusing on cell deployment.

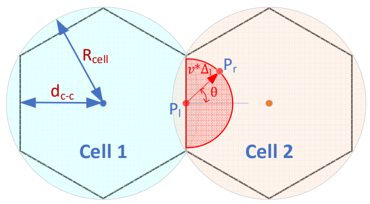


Fig. 3: Simulation scenario.

a vision technology to find the position of UDs at the user plane[3]. But the localization latency occurs due to the image transmission delay and the image processing time. Let define $C\{P\}$ as a conversion function that returns a cell number that the distance from the UD's position P to the cell's center is less than R_{cell}. To analyse the impact of the localization latency on the probability of handover failures, we assume that the user device is moving from cell 1 to cell 2 at a random speed v and random direction θ with the probability density function $f_\theta(\theta) = \frac{1}{\pi}, \quad -\frac{\pi}{2} \leq \theta \leq \frac{\pi}{2}$. A good handover decision is triggered at the time that the UD crosses the middle of two cells. When the UD is found by the vision-based localization at $P_l(d_{c-c}, 0)$ and $C\{P_l\} = 1$, the UD is already at $P_r(x_r, y_r)$ because of the localization latency Δl (as shown in Fig. 3). Therefore, the probability of handover failures is

$$f = \begin{cases} 1 & C\{P_r\} = 2 \\ 0 & C\{P_r\} = 1 \end{cases} \rightarrow f = \begin{cases} 1 & l = \sqrt{x_r^2 + y_r^2} \geq R \\ 0 & l = \sqrt{x_r^2 + y_r^2} < R \end{cases}$$

with $l = \sqrt{d^2 + (v\Delta l)^2 + 2dv\Delta l\cos(\theta)}$.

Then the cumulative density function of handover failure is given by:

$$P = \begin{cases} 1 & R^2 < d^2 + (v\Delta l)^2 \\ 2\arccos\left(\frac{R^2 - d^2 - (v\Delta l)^2}{2dv\Delta l}\right) & \sqrt{d^2 + (v\Delta l)^2} < R < d + v\Delta l \\ 0 & R > d + v\Delta l \end{cases}$$

Fig. 4 shows the handover failure probability as a function of the UD's speed. As can be seen, the analytical results in the above equation closely match the Monte Carlo simulation. Also, the number of handover failures decreases when

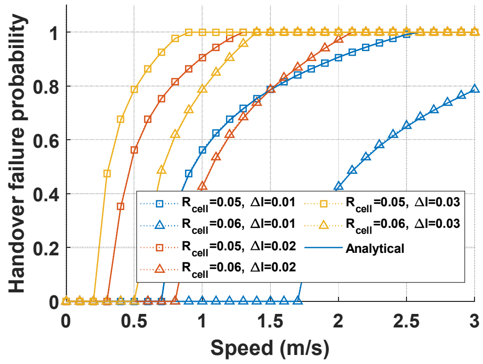


Fig. 4: Probability of handover failures.

the localization latency decreases and the footprint radius increases. However, an increase of footprint radius causes a decrease of signal-to-noise ratio (SNR) and an increase of interference, and therefore we believe that reducing the localization latency is more promising.

Design of handover mechanism

We propose an extrapolation algorithm based on the polynomial regression to find a best fit for the time-series of the position. The expected positions p_x and p_y in the x- and y- coordinates at the time t_k can be modeled as an nth degree polynomial, yielding the polynomial regression model:

$$p_x(t_k) = w_{x,1}t_k^n + w_{x,2}t_k^{n-1} + \cdots + w_{x,n}t_k + w_{x,n+1}$$

$$p_y(t_k) = w_{y,1}t_k^n + w_{y,2}t_k^{n-1} + \cdots + w_{y,n}t_k + w_{y,n+1}$$

with w_x and w_y are the least-squares fit polynomial coefficients, and n is the degree of polynomial fit. We optimize the polynomial coefficients using the Vandermonde matrix as:

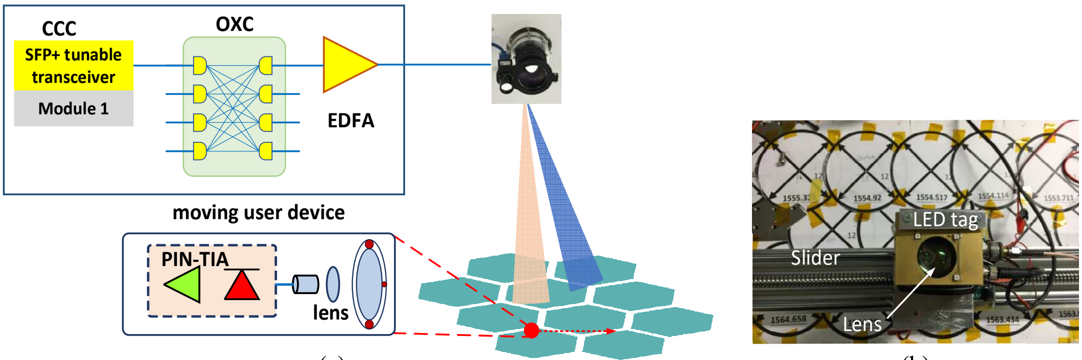
$$\begin{pmatrix} t_1^n & \cdots & 1 \\ \vdots & \ddots & \vdots \\ t_M^n & \cdots & 1 \end{pmatrix} \begin{pmatrix} w_{x,1} & w_{y,1} \\ \vdots & \vdots \\ w_{x,n+1} & w_{y,n+1} \end{pmatrix} = \begin{pmatrix} p_x^1 & p_y^1 \\ \vdots & \vdots \\ p_x^M & p_y^M \end{pmatrix}$$

$$\rightarrow \overline{\boldsymbol{w}}_{xy} = (\boldsymbol{T}'\boldsymbol{T})^{-1}\boldsymbol{T}'\overline{\mathbf{P}}$$

with M is the number of time-series data. Thus, the real-time position is given by $p_{x,real-time} = p_x(t_k + \Delta t)$ and $p_{y,real-time} = p_y(t_k + \Delta t)$.

Experiments and Results

Fig. 5a shows the experimental setup to evaluate the mobility management in the BS-ILC system that we have previously demonstrated successfully simultaneous 10GbE transmissions by two IR beams, each with high-definition video[5]. At the CCC, SFP+ tunable transceivers modulate the downstream data with an ITU grid channel spacing of 50 GHz. At a reach of 1.8m, each PRA covers a wide area of 1.6m×1.6m at the user plane, the cell diameter illuminated by each beam is about 11cm, and the largest width



(a) (b)

Fig. 5: (a) Setup diagram with BL-ILC system and vision-based localization; (b) Optical receiver on the slider.

of the overlapping area between two cells is 1cm. As shown in Fig. 5b, a low-cost camera is installed next to the PRA; three IR-LEDs (each with a diameter of 2.8mm and spaced by 2.5cm) are placed circularly around one user device's aperture as shown in Fig. 5c. The frame rate of the camera is 200fps, so UD's position is updated every 5ms. The localization latency is observed at 20ms[3]. The receiver is mounted on the top of a 2D motorized slider, then is controlled to move with an arbitrary trajectory.

Fig. 6a shows the movement of UD in the user plane as a circular path through 4 cells. Fig. 6b and 6c show the position of the UD in the x- and y-coordinates. While the raw position returned by the image processing algorithm is always delayed compared to the actual position, the proposed algorithm estimates exactly the UD's real-time movement. Fig. 6d shows the received power of the photodiode during the movement. The received power depends on the position of the UD in the cell. The received power is high at the cell center and is low near the cell edge. The proposed algorithm has successfully triggered handovers at the appropriate time as the smooth power transition from cell to cell. A shown in Fig. 6e, the photodiode can achieve the error-free with the received power higher than -19dBm. Thus, there is no error occurring for the UD along the circular movement when the connection is available. Please note that no large-bandwidth OWC receiver was available at the time of exepriments. The signal drop appears only due to the laser tuning time. Furthermore, we analyse the number of handover failures during this movement as shown in Fig. 6f, and the proposed algorithm can improve the performance by 8 times, a significant number of failure reduction.

Conclusions

We demonstrated handover mechanism for high-capacity indoor BS-ILC system with vision-based localization using an extrapolation algorithm. The user position is localized in real-time, triggering handover events in time. Our proposed solution shows a major improvement for the BS-ILC system to be used in indoor mobile settings.

This work has been carried out in the framework of the TU/e-KPN flagship Smart-One program.

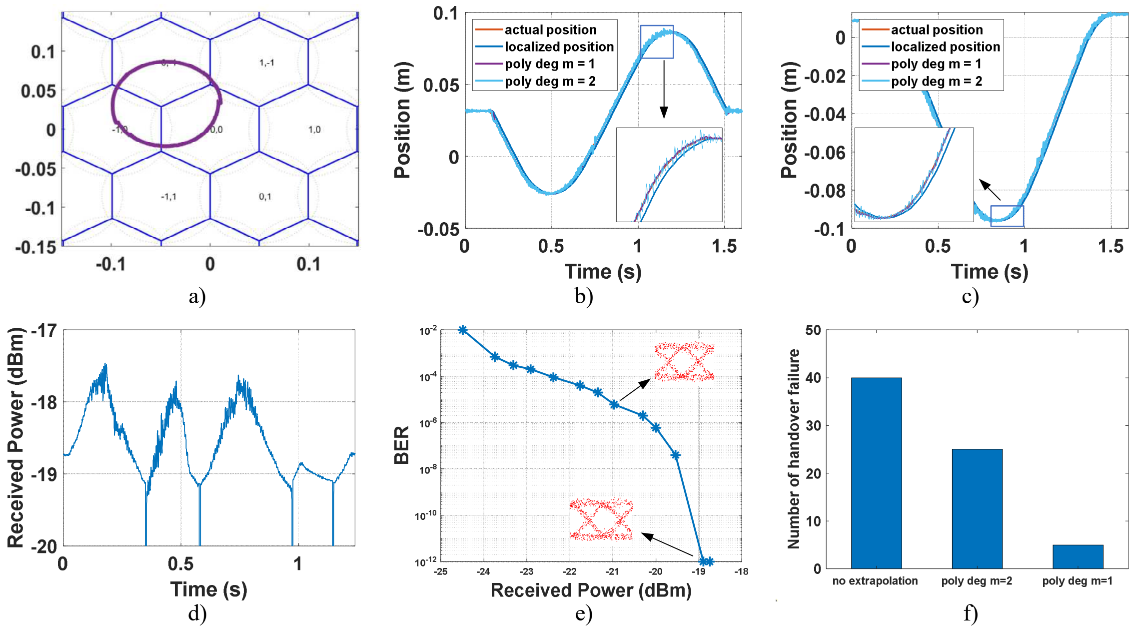


Fig. 6: (a) Circular movement in the user plane; User device position in the (b) y- (c) x-axis using the extrapolation algorithm; (d) Received power of user device during the movement; (e) BER of user device at 250Mb/s; (d) Number of handover failures.

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