# AOA-Based Localization and Tracking in Multi-Element VLC Systems

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***Abstract*—Visible light communication (VLC) is an emerging technology that is expected to be widely used for indoor wireless communications. Accurate localization of VLC equipment has a wide variety of applications in indoor scenarios, where GPS receivers do not work. This paper proposes a new and effective method for localization of VLC devices based solely on the connectivity information. Due to narrow field of view characteristics of connected LEDs, angle of arrival to an access point can be estimated accurately. Exploiting such features, a least square estimator is developed for location estimation, and a Kalman filter is utilized for improving the tracking performance of a mobile device. Simulation results show that average localization accuracies on the order 0.2 meters can be achieved in various different access point topologies.**

***Index Terms*—Free space optics (FSO), Kalman filter, least squares estimator (LSE), light emitting diode (LED), optical wireless communications (OWC), tracking, visible light communication (VLC).**

## I. Introduction

Recently, rapid increase of number of mobile devices pushed the radio frequency (RF)-based wireless technologies to their limits. These RF spectrum crunch along with the old capacity gap between the RF wireless last mile and the optical fiber Internet backbone speeds have motivated the research community to look for solutions and alternative spectrum resources. A promising approach is to use the optical spectrum bands to complement the legacy RF technologies [1]. The concept, known as *optical wireless communication* (OWC) or *free-space-optical communication* (FSO), loads the directional optical beams via non-negative modulation techniques (e.g., On/Off Keying (OOK)) and demodulates the light beam on a passive receiver which is typically a photo-detector (PD). When visible optical spectrum band is used, OWC/FSO translates into a particular form known as visible light communication (VLC).

VLC is of interest particularly because its transmitters are light emitting diodes (LEDs), which are also the same devices used for solid-state lighting (SSL). The integration of VLC and into SSL modules presents a great opportunity for a range of applications going beyond just lighting and illumination. One of them is to localize user equipment (UE) where GPS or other RF-based localization technologies may not work accurately. VLC-based localization is of particular interest for indoor settings where LED-based lighting exists.

The idea of VLC-based localization was introduced earlier for the dual-purpose use of indoor lighting fixtures [2]–[4].

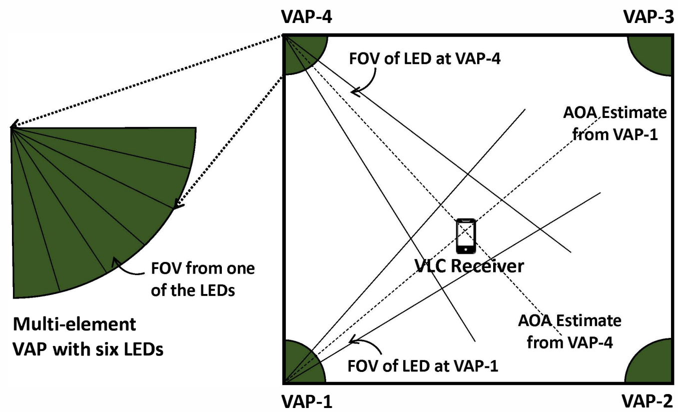



Fig. 1. AOA-based localization in multi-element VLC systems. The VLC receiver will capture the signals from one of the LEDs in each multi-element VAP. The AOA for each VAP is taken as the central line of the FOV from each connected LED. A least square estimator can be used to find the location of the VLC receiver using all AOA estimates and VAP locations.

These studies performed the localization based on multi-lateration of light beams from *four* anchors within a room. Time difference of arrival (TDOA) from the anchor VLC-capable lighting fixtures was used to identify the location of a UE within the room. Since light beams can be made directional, VLC allows angle-of-arrival (AoA) detection if multiple LEDs, a.k.a. multi-element, are used in such a way that each LED is oriented to a different direction. By arranging LEDs in a circular/spherical placement, a receiver UE can differentiate the angle at which a light beam is coming from. Our earlier work prototyped multi-element FSO structures [5] and showed that they can effectively be used for AoA detection as long as the receivers have a directional field-of-view (FOV).

In this paper, we leverage the AoA detection and consider a room with *multi-element VLC-capable* lighting fixtures. Our method needs at least *two* anchor nodes, and uses the AOA information from all the connected LEDs. Only downlink part of the communication is considered as VLC because there is an important tendency to use hybrid VLC and RF, such that VLC will be used for downlink only when it is available. It is to overcome connectivity issues of VLC. Therefore in our scenario, access points (AP) are VLC transmitters and UEs are VLC receivers. After getting localization information, Kalman filter is applied for mobile user scenario to improve precision of the results. Kalman filters are also commonly used for improving tracking accuracy of wireless equipment for indoor and outdoor scenarios [6], [7].

The remainder of this paper is organized as follows. The VLC localization scenario is described in Section II, and an AOA-based least squares location estimator is developed in Section III. Section IV introduces Kalman filtering for improving localization accuracy. Simulation results are provided in Section V, and the last section concludes the paper.

## II. VLC Localization Scenario

In this paper, we consider a VLC localization scenario as shown in Fig. 1. There are multi-element visible light access points (VAPs) which involve $N_{\mathrm{E}}$ LED transmitters. These VAPs are placed at different locations in the room. Our preliminary study in this paper considers a two dimensional topology, where the VAPs are assumed to be on the same horizontal plane as the VLC receiver. Each LED in a VAP is assumed to have an equal FOV angle of $\alpha_{\mathrm{FOV}}$.

At a given time, the receiver is connected to only one of the LEDs at a given VAP. The unique identity of an LED and its corresponding VAP is assumed to be decodable at the receiver, which can simply be achieved by sending a different header from each LED. Since each LED is directed to a different angle, collectively, the LEDs of each VAP span the whole room. Moreover, locations of the transmitters and direction angles of each LED are assumed to be known at the receiver, which can be shared by the VLC network through periodic broadcast messages (similar to broadcasting of system information messages to user equipment from LTE base stations [8]).

The localization approach we consider in this paper is based purely on the connectivity information of the VLC receiver to LEDs at different VAPs. From connectivity information, the angle of arrival (AOA) from a transmitter is estimated to be the line extending from the center point of the FOV of the corresponding LED, as shown in Fig. 1. When the receiver is connected to a specific LED at a specific transmitter, it means it is within the line of sight (LOS) of that LED. When the receiver is within the LOS of a specific LED, it will locate itself on the line extending from the center angle of that LED. If it is connected to two different transmitters, it will locate itself on the intersection point of these two lines, as in Fig. 1. When there are more transmitters, and therefore more AOA information, least square estimator will be used as will be described in the next section to estimate the location of the VLC receiver.

## III. Least Squares Location Estimator

Given the two or more AOAs and the locations of the corresponding VAPs as shown in Fig. 1, the receiver can estimate its location using a least squares estimator (LSE), as will be described below [9], [10]. In Fig. 2, a representative scenario with four VAPs is shown, where $\alpha_i$ is the AOA from the $i$-th VAP, $(x_i, y_i)$ is the locations of the $i$-th VAP, and $(x, y)$ is the location of the device to be localized. From Fig. 2, for $i = 1, ..., 4$, we can write

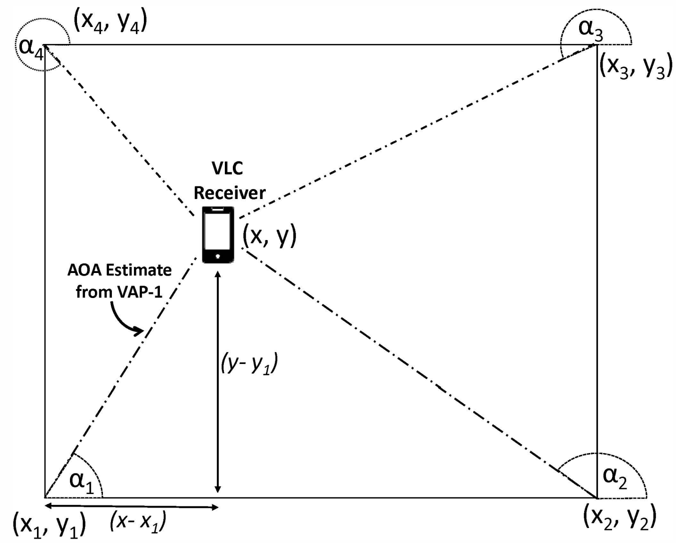



Fig. 2. AOA estimation parameters.

$$\frac{\cos\alpha_i}{\sin\alpha_i} = \frac{x - x_i}{y - y_i} \ , \tag{1}$$

which can also be written as

$$x \sin\alpha_i - x_i \sin\alpha_i = y \cos\alpha_i - y_i \cos\alpha_i \ . \tag{2}$$

Manipulating all the expressions in (2) for $i = 1, ..., N$ into matrix form, we may write

$$\mathbf{A}\mathbf{x} = \mathbf{b} \ , \tag{3}$$

where

$$\mathbf{A} = \begin{bmatrix} \sin\alpha_1 & -\cos\alpha_1 \\ \sin\alpha_2 & -\cos\alpha_2 \\ \vdots & \vdots \\ \sin\alpha_N & -\cos\alpha_N \end{bmatrix}, \mathbf{b} = \begin{bmatrix} x_1 \sin\alpha_1 - y_1 \cos\alpha_1 \\ x_2 \sin\alpha_2 - y_2 \cos\alpha_2 \\ \vdots \\ x_N \sin\alpha_N - y_N \cos\alpha_N \end{bmatrix}, \tag{4}$$

and $\mathbf{x} = [x \ y]^T$ denotes the unknown location of the VLC receiver. Then, the least square estimator (LSE) for the unknown mobile location $\mathbf{x}$ is given by [11], [12]

$$\hat{\mathbf{x}} = (\mathbf{A}^T\mathbf{A})^{-1}\mathbf{A}^T\mathbf{b} \ . \tag{5}$$

Note that using the received signal strength information from the LEDs (which follows a Lambertian law [5]), more accurate estimators such as maximum likelihood estimator can also be developed. The merit of the estimator in (5) is its simplicity, in which, only the connectivity information to individual LEDs in each VAP is utilized.

## IV. Tracking Users with Kalman Filters

In order to improve localization results for a mobile VLC receiver, Kalman filter is used. Let $(x_k, y_k)$ denote the location estimate of the mobile at time step $k$, $(V_k^x, V_k^y)$ denote the velocity of the mobile in $x$ and $y$ coordinates during time step $k$, and let $e_k^x$, $e_k^y$, $e_k^{V_x}$, $e_k^{V_y}$ represent the noise variables for the four different state variables. Moreover, let $(z_k^x, z_k^y)$ denote the LSE location estimate of the mobile at time step $k$ before applying the Kalman filter, and $v_k^x$, $v_k^y$ be the corresponding noise variables. Then, the prediction stage for the Kalman filter estimate for mobile location and velocity at time instant $k$ can be written as

$$\underbrace{\begin{bmatrix} x_k \\ y_k \\ V_k^x \\ V_k^y \end{bmatrix}}_{\hat{\mathbf{x}}_k} = \underbrace{\begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}}_{\mathbf{B}} \underbrace{\begin{bmatrix} x_{k-1} \\ y_{k-1} \\ V_{k-1}^x \\ V_{k-1}^y \end{bmatrix}}_{\mathbf{x}_{k-1}} + \underbrace{\begin{bmatrix} e_k^x \\ e_k^y \\ e_k^{V_x} \\ e_k^{V_y} \end{bmatrix}}_{\mathbf{e}_k}, \quad (6)$$

whereas the observation equations can be written as

$$\underbrace{\begin{bmatrix} z_k^x \\ z_k^y \end{bmatrix}}_{\mathbf{z}_k^{\text{est}}} = \underbrace{\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}}_{\mathbf{C}} \underbrace{\begin{bmatrix} x_k \\ y_k \\ V_k^x \\ V_k^y \end{bmatrix}}_{\hat{\mathbf{x}}_k} + \underbrace{\begin{bmatrix} v_k^x \\ v_k^y \end{bmatrix}}_{\mathbf{V}_k}. \quad (7)$$

Elements of $\mathbf{z}_k^{\text{est}}$ are $z_k^x$ and $z_k^y$, which are our estimates for $x_k$ and $y_k$ from their previous values. This is only a temporal estimate. At time $k$, we also get measurement values for $x_k$ and $y_k$, and they form our $\mathbf{z}_k^{\text{meas}}$. Then we calculate our final estimate with

$$\mathbf{x}_k = \hat{\mathbf{x}}_k + \mathbf{K}_k(\mathbf{z}_k^{\text{meas}} - \mathbf{z}_k^{\text{est}}), \quad (8)$$

where $\mathbf{K}_k$ is the Kalman gain. It can be iteratively calculated at each step by

$$\mathbf{P}_k = \mathbf{B}\mathbf{P}_k'\mathbf{B}^T + \mathbf{E}_x, \quad (9)$$
$$\mathbf{K}_k = \mathbf{P}_k\mathbf{C}^T(\mathbf{C}\mathbf{P}_k\mathbf{C}^T + \mathbf{E}_z)^{-1}, \quad (10)$$
$$\mathbf{P}_{k+1}' = (\mathbf{I} - \mathbf{K}_k\mathbf{C})\mathbf{P}_k, \quad (11)$$

where $\mathbf{E}_x$ and $\mathbf{E}_z$ are constant $4 \times 4$ and $2 \times 2$ estimated error matrices and $\mathbf{P}$ is the error covariance matrix which is updated twice in an iteration.

## V. Simulation Results

Computer simulations are performed to evaluate the performance of the considered AOA based localization and Kalman filter based tracking algorithms. We consider a $4 \times 6$ meter room as shown in Fig. 1, and calculate the root mean square error (RMSE) of localization. In case there is an obstacle between receiver and some of the VAPs, it will not be possible to use these VAPs for localization. We considered different scenarios as shown in Fig. 3, where there are different number of VAPs in the room.

First, in Fig. 4, we plot the RMSE of localization RMSE over different locations in the room, for $N_E = 3, 4, 5$. In each figure, there are regions separated with straight lines, and there is a darker region at the center of each region. When number of LEDs increases or number of VAPs increases, the overall localization error is seen to reduce significantly.

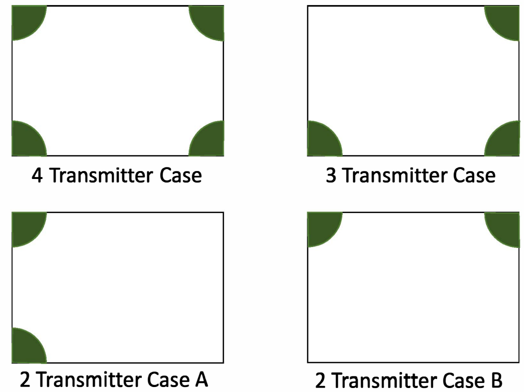



Fig. 3. Four different simulation scenarios where receiver can only reach some of the VAPs. Green quarter circles identify the location of the VAPs.

### A. AOA Based Localization

We consider the RMSE localization error, averaged over the whole room, in Fig. 5 for different transmitter and LED scenarios. With four transmitters at each corner, even with three LEDs, RMSE on the order of 0.6 m can be achieved. Accuracy is improved to 0.2 m error with the increasing number of LEDs. With three transmitters, accuracy is nearly 0.1 m less than four transmitter case. Worse localization RMSE results are observed in the two transmitter scenario. In Case A, in which distance between transmitters is 4 m, error is below 1 m with three LEDs. It decreases to 0.33 m with increasing number of LEDs. Case B shows similar performance with larger number of LEDs, while the performance becomes worse when the number of LEDs are three or four.

### B. Kalman Filter for Improved Tracking

To apply Kalman filter, we first introduce a sample path as shown in Fig. 6, get localization results along this path,

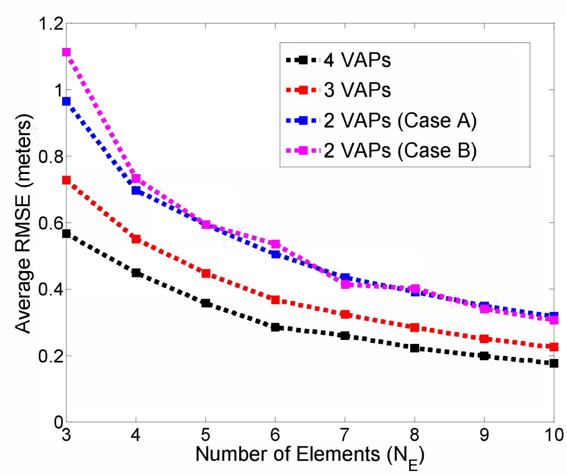
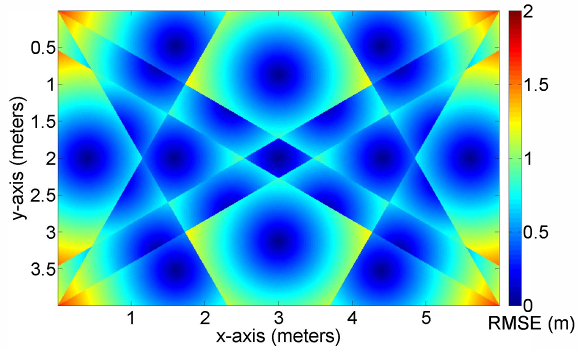
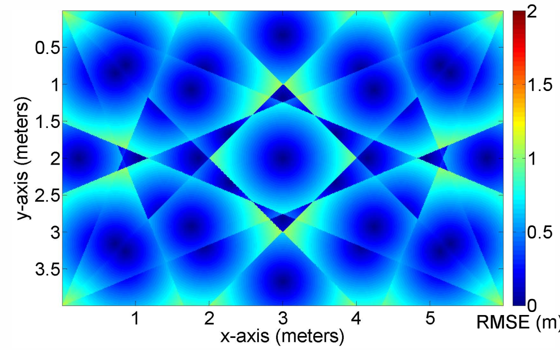


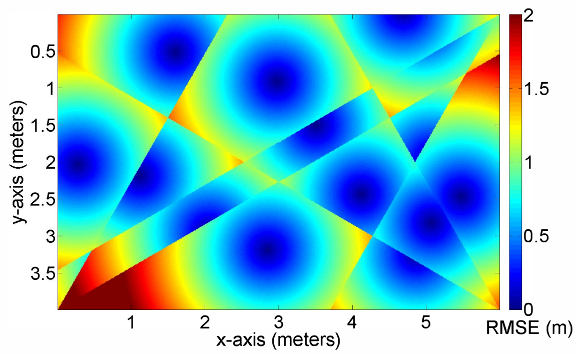

Fig. 5. Average RMSE for different number of LEDs.



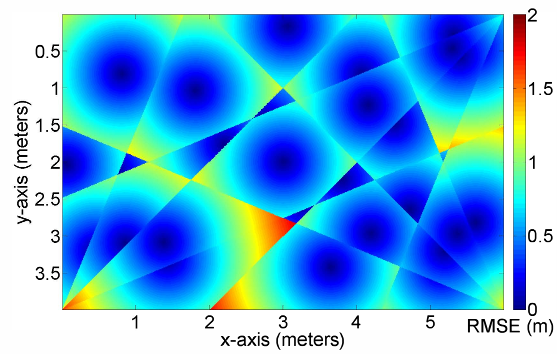

(a) 3 LEDs ($N = 4$).



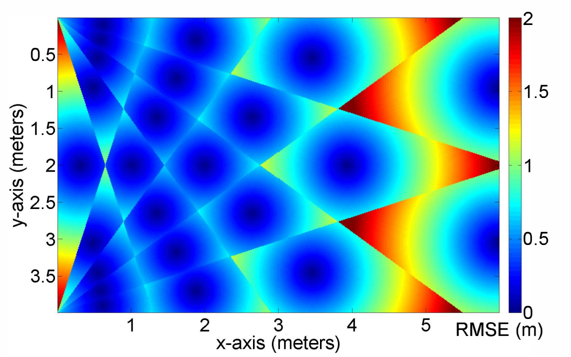

(b) 4 LEDs ($N = 4$).



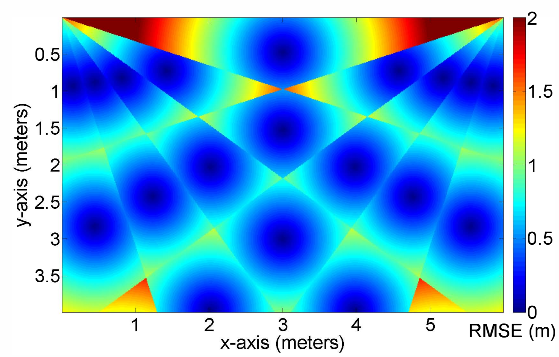

(c) 3 LEDs ($N = 3$).




(d) 4 LEDs ($N = 3$).




(e) 5 LEDs ($N = 2$, Case A).




(f) 5 LEDs ($N = 2$, Case B).

Fig. 4. RMSE of LSE location estimate over different locations in the room, for $N_{\mathrm{E}} = 3, 4, 5$ and for $N = 2, 3, 4$. Unit of colorbar is meters.

and apply the filter to smoothen the results. The speed of the mobile user is assumed to be constant. An illustration of how Kalman filter enhances the localization accuracy is further shown in Fig. 6. The actual path, localizaton results on the path, and the path after applying Kalman filter are illustrated.

The improvement provided by Kalman filter as a function of number of LEDs on each VAP is shown in Fig. 7 and Fig. 8. In both figures, the RMSE averaged over the sample path in Fig. 6. Results show that reasonable gains can be obtained using Kalman filters, while the gains are diminishing when larger number of LEDs are used at each VAP.

## VI. Conclusion

In this work, a new, effective, and low complexity approach for localization of indoor VLC devices is introduced, and potential improvements for tracking the mobile users with Kalman filters are described. In particular, a least square estimator is proposed for VLC localization, which exploits the connectivity information (and hence the AOA) of a VLC receiver with the visible light access points. Preliminary simulation results in various simulation topologies show that localization accuracies on the order of fractions of a meter are possible.

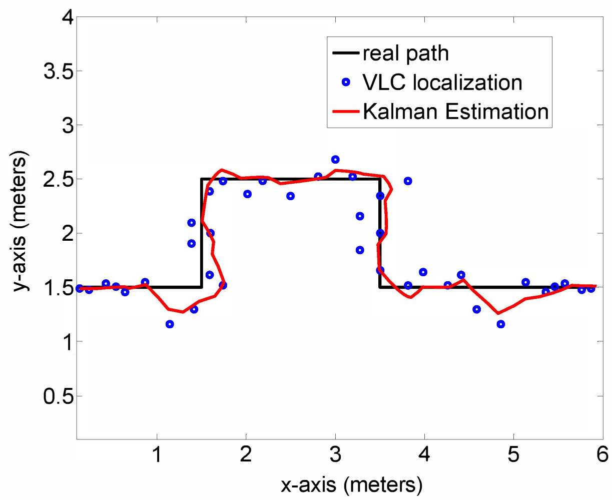



Fig. 6. VLC location estimation points throughout the path and the path after Kalman filter is applied (Movement is from left to right) (10 LEDs, $N_{\text{VAP}} = 4$).

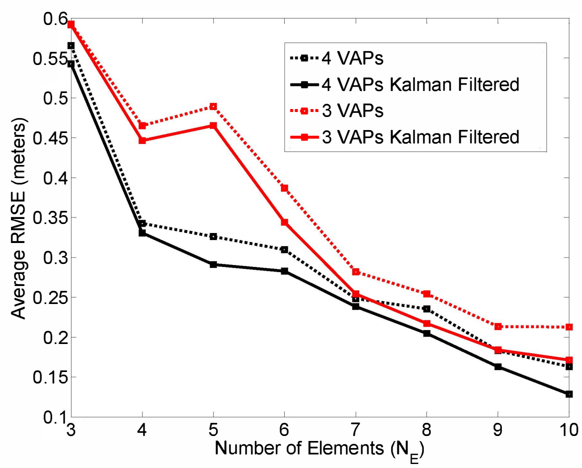



Fig. 7. RMSE over the path for 4 and 3 VAPs, with and without Kalman filter.

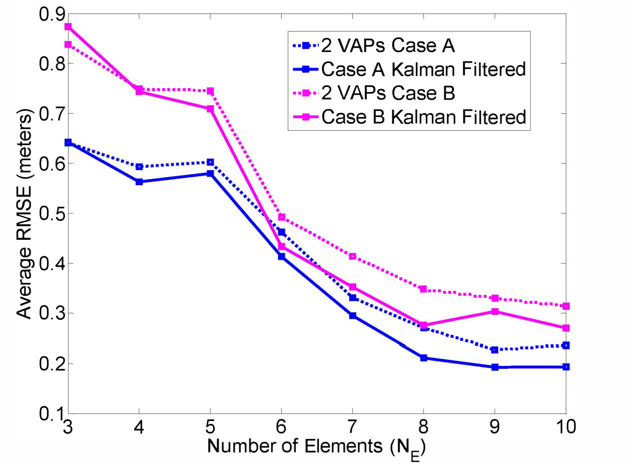



Fig. 8. RMSE over the path for 2 VAPs Case A and B, with and without Kalman filter.

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