Indoor WLAN Deployment Optimization Based on Error Bound of Neighbor Matching

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Abstract. In this paper, we propose a novel indoor Wireless Local Area Network (WLAN) deployment optimization approach based on the error bounds of Neighbor Matching Algorithms (NMAs). We derive out the closed-form solution to the localization errors of NMAs with respect to the environmental size, interval of Reference Points (RPs), number of neighbors, and locations of Access Points (APs). Based on the requirement of localization precision, as well as networking overhead, we optimize the networking parameters, like the interval of RPs, number of neighbors, and locations of APs. Finally, the extensive experiments are conducted to demonstrate that the proposed approach can effectively improve the localization precision of NMAs in indoor WLAN environment.

Keywords: WLAN · Network optimization · Location fingerprinting · Neighbor matching · Error bound

1 Introduction

As the demand for the real-time location information increases remarkably, the Location-based Services (LBSs) have attracted significant attention in recent decade. The accurate localization in outdoor environment can be realized by using the well-known Global Positioning System (GPS), whereas the localization accuracy decreases seriously in indoor environment since the signal from the satellites is blocked by the buildings [1]. At the same time, there is growing interest in the indoor localization techniques which are based on the existed indoor high-speed wireless access networks, like the Wireless Local Area Network (WLAN) [2], Zigbee, and Radio Frequency Identification (RFID). Due to the consideration of the cost overhead and localization accuracy, the WLAN technique is more favored by the current indoor localization systems.

Compared to the conventional trilateration based localization approach, the location fingerprint based localization approach is preferred in WLAN localization. In the typical location fingerprint based localization system [3,4], the grids of Reference Points (RPs) are first required to be calibrated. Second, the location fingerprints which are typically the vectors of Received Signal Strength (RSS)

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mean from each hearable Access Point (AP) is collected at every RP. The set of location fingerprints is recognized as the radio map. Finally, when a location query occurs, the estimated location can be reported by matching the newly collected RSSs against the radio map.

Up to now, there is a batch of studies focusing on the design of localization algorithms, like the Nearest Neighbor (NN), K-nearest Neighbor (KNN) [5], weighted KNN (WKNN) [6], which are also known as the Neighbor Matching Algorithms (NMAs). NMAs are easily applied and featured with low computation overhead, practicability, and high-precision [7]. The KNN returns the location estimate as the average of the coordinates of the K neighbors corresponding to the smallest RSS distances to the newly collected RSSs. The NN is a special case of KNN as the number of neighbors equals to 1. The difference between the KNN and WKNN is that the latter one returns the location estimate as the weighted coordinates of the K neighbors, while the weights of neighbors are determined by the distances between the location fingerprints and newly collected RSSs. Since the NMAs are easily applied and featured with low computation overhead, practicability, and high-precision, we focus on deriving the error bounds of NMAs to investigate the theoretical relation between the localization error and networking parameters.

The remainder of the paper is organized as follows. The theoretical analysis for the error bound of NMAs is presented in Sect. 2. The analytical results are provided in Sect. 3. Finally, Sect. 4 concludes the paper.

2 Error Bound

In this paper, we focus on the analysis towards the theoretical relation between the localization errors of NMAs and networking parameters, and meanwhile derive out the closed-form solutions to the error bounds.

2.1 AP Located on the Boundary

Figure 1 shows a straight corridor with the Line-of-sight (LOS) from the AP. The N RPs (with $\bullet$'s) are uniformly calibrated with the same interval, R, in this environment (with the length of $N \times R$). The user location is described as

$$x = r_i + \sigma, 0 \leq \sigma \leq R \text{ and } 0 < i < N \tag{1}$$

We rely on the logarithmic loss model [8] to characterize the signal propagation property, as shown in (6).

$$P = P(d_0) - 10\beta \log_{10}(d/d_0) \tag{2}$$

where P and $P(d_0)$ are the RSSs collected at the locations with d and d_0 meters from the AP respectively; and β is the path loss exponent. On this basis, the distance of the RSSs collected by the user and at the n-th RP is calculated by

$$\Delta P_n = |S_n - S_u| == \begin{cases} 10\beta \log\left(n/(i+\sigma/R)\right), n \geq i+1 \\ 10\beta \log\left((i+\sigma/R)/n\right), n \leq i \end{cases} \tag{3}$$

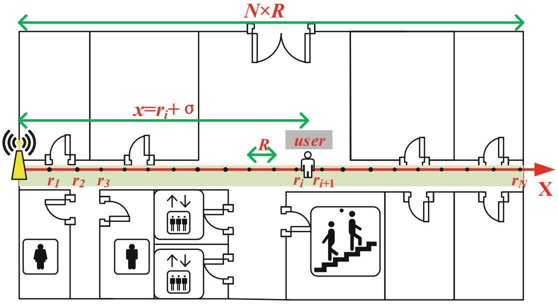


Fig. 1. AP located on the boundary.

KNN. When $K = 1$, only the i-th or $(i+1)$-th RP can be selected as the estimated location since the location fingerprints at other RPs are farther away from the RSS collected by the user. Based on this, we derive out the results in Table 1.

Table 1. Results under $K = 1$ in KNN

Value of σ	$0 \le \sigma \le (-i+\sqrt{i^2+i})R$	$(-i+\sqrt{i^2+i})R < \sigma \le R$
Relations of ΔP_n	$\Delta P_i \le \Delta P_{i+1}$	$\Delta P_{i+1} < \Delta P_i$
Neighbors	The i-th RP	The $(i+1)$-th RP
Localization error	$er_1 = \lvert r_i - x \rvert = \sigma$	$er_2 = \lvert r_{i+1} - x \rvert = R - \sigma$
Error bound	$ER_1 = \sum_{i=1}^{N} \int_0^{(-i+\sqrt{i^2+i})R} \sigma d\sigma + \int_{(-i+\sqrt{i^2+i})R}^{R} (R-\sigma)\, d\sigma$	

When $K = 2$, based on (3), we can easily obtain that the location fingerprints at the $(i-1)$-th, i-th, $(i+1)$-th, and $(i+2)$-th RPs are with the smallest distances from the RSS collected by the user. Thus, we derive out the results in Table 2.

Table 2. Results under $K = 2$ in KNN

Value of σ	$0 \le \sigma \le (-i+\sqrt{i^2+2i})R$	$(-i+\sqrt{i^2+2i})R < \sigma \le R$
Relations of ΔP_n	$\Delta P_i \le \Delta P_{i+1} < \Delta P_{i-1} < \Delta P_{i+2}$	$\Delta P_{i+1} \le \Delta P_{i+2} < \Delta P_i < \Delta P_{i-1}$
Neighbors	The i-th, $(i+1)$-th RPs	The $(i+1)$-th, $(i+2)$-th RPs
Localization error	$er_1 = R/2$	$er_2 = (3R-\sigma)/2$
Error bound	$ER_2 = \sum_{i=1}^{N} \int_0^{(-i+\sqrt{i^2+2i})R} \frac{R}{2} d\sigma + \int_{(-i+\sqrt{i^2+2i})R}^{R} \frac{3R-\sigma}{2} d\sigma$	

When $K = k$ (k is odd), by using the mathematical induction, we can derive out the error bound in (4). Table 3 illustrates the neighbors and the corresponding localization errors under different values of σ. In Table 3, we set $k_1 = (k-1)/2$ and $k_2 = (k+1)/2$ respectively.

$$ER_{\text{odd\_}(1,N)} = \sum_{i=1}^{N} \int er_1 d\sigma + \cdots + \int er_{m+1} d\sigma \cdots + \int er_{(k+3)/2} d\sigma \tag{4}$$

where $er_{m+1} = 1/k(1-2m)\sigma + kmR + (k_2 - m)(k_1 - m)R$, $m \in \{0, \cdots, k_2\}$.

Table 3. Results under $K = k$ (K is odd) in KNN

Value of σ	Neighbors	errors
$0 \leq \sigma < (-i + \sqrt{(i-k_1)(i+k_2)})R$	The (i-k_1)-th, $\cdots$, (i+$k_2 - 1$)-th RPs	er_1
$\cdots$	$\cdots$	$\cdots$
$(-i + \sqrt{i(i+k)})R \leq \sigma \leq R$	The $(i+1)$-th,$\cdots$, $(i+k)$-th RPs	er_{k_2+1}

Similarly, when $K = k$ (k is even), we derive out the error bound in (9) based on the result of errors corresponding to different values of σ in Table 4. In Table 4, we set $k_3 = k/2 - 1$ and $k_4 = k/2 + 1$ respectively.

Table 4. Results under $K = k$ (K is even) in KNN

Value of σ	Neighbors	errors
$0 \leq \sigma < (-i + \sqrt{(i-k_3)(i+k_4)})R$	The (i-k_3)-th,$\cdots$, (i+$k_4 - 1$)-th RPs	er_1
$\cdots$	$\cdots$	$\cdots$
$(-i + \sqrt{(i-(k_3+1-n))(i+(k_4-1+n))})R$ $\leq \sigma < (-i + \sqrt{(i-(k_3-n))(i+(k_4+n))})R$	The (i-$k_3 + n$)-th,$\cdots$, (i+$k_4 + n - 1$)-th RPs	er_{n+1}
$\cdots$	$\cdots$	$\cdots$
$(-i + \sqrt{i(i+k)})R \leq \sigma \leq R$	The $i+1$-th,$\cdots$, $(i+k)$-th RPs	er_{k_4}

$$ER_{\text{even}\_(1,N)} = \sum_{i=1}^{N} \int er_1 d\sigma + \cdots + \int er_{n+1} d\sigma \cdots + \int er_{(k+2)/2} d\sigma \tag{5}$$

where $er_{n+1} = 1/k(-2n\sigma + n^2 + n + k^2/4)$, $n \in \{0, \cdots, k_4\}$.

2.2 WKNN

When $K = 1$, the WKNN becomes the KNN. When $K = 2$, based on the results in Table 2, we can easily derive out the error bound in Table 5.

Table 5. Results under $K = 2$ in WKNN

Value of σ	$0 \leq \sigma \leq (-i + \sqrt{i^2+2i})R$	$(-i + \sqrt{i^2+2i})R < \sigma \leq R$
Relations of ΔP_n	$\Delta P_i \leq \Delta P_{i+1} <$ $\Delta P_{i-1} < \Delta P_{i+2}$	$\Delta P_{i+1} \leq \Delta P_{i+2}$ $< \Delta P_i < \Delta P_{i-1}$
Neighbors	The i-th, (i+1)-th RPs	The (i+1)-th, (i+2)-th RPs
Localization error	$er_1 = w_1 r_i + w_2 r_{i+1} - x$	$er_2 = w_1 r_{i+1} + w_2 r_{i+2} - x$
where $w_1 = \frac{1/(R-\sigma)}{1/(R-\sigma)+1/(2R-\sigma)}$ and $w_2 = \frac{1/(2R-\sigma)}{1/(R-\sigma)+1/(2R-\sigma)}$		
Error bound	$ER_2 = \sum_{i=1}^{N} (\int_0^{(-i+\sqrt{i^2+2i})R} er_1 d\sigma + \int_{(-i+\sqrt{i^2+2i})R}^{R} er_2 d\sigma)$	

Since the weight of each neighbor in WKNN cannot be formulated by a general expression, there is no closed-form solution to the error bound of WKNN.

However, the weights of neighbors can be easily calculated as the number of neighbors and networking parameters are determined. Hence, we only focus on the error bound of KNN in the results that follow.

2.3 AP Located at a Random Location

Figure 2 shows the layout of environment as the AP is located at a random location. In this situation, the user location is described as

$$x = r_i - mR + \sigma, m \leq N/2 \tag{6}$$

where mR is the distance between the AP and left boundary.

By assuming that the antenna of AP is omnidirectional, we assume that the RPs with the same distance from the AP have the same probability to be selected as the neighbors. On this basis, there are three cases to be discussed respectively, i.e., $0 \leq m < k_1$, $k_1 \leq m < k$, and $m \geq k$. When $K = k$ (k is odd), we derive out the error bounds with respect to different cases in Table 6.

Thus, as the number of neighbors is odd, the error bound of WKNN is calculated by

$$ER_{\text{odd}} = Er_1 + Er_2 + Er_3 \tag{7}$$

Similarly, When $K = k$ (k is even), we derive out the error bounds with respect to different cases in Table 7.

Thus, as the number of neighbors is even, the error bound of WKNN is calculated by

$$ER_{\text{even}} = Er_1 + Er_2 + Er_3 \tag{8}$$

Therefore, by assuming that the user locations obey the uniform distribution in the target environment, we can calculate the error bound in this situation as

$$ER_{\text{ave}} = \begin{cases} \frac{1}{N \cdot R} \cdot ER_{\text{odd}} & K = 2r - 1 \text{ and } r \in N^+ \\ \frac{1}{N \cdot R} \cdot ER_{\text{even}} & K = 2r \text{ and } r \in N^+ \end{cases} \tag{9}$$

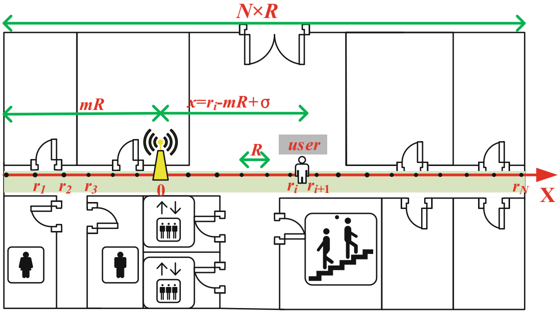


Fig. 2. AP located at a random location.

Table 6. Results under $K = K$ (K is odd) in WKNN

Case 1: $0 \leq m < k_1$
if $0 \leq i < k_1$ then $Er_1 = ER_{odd\_(1,k_1)} + ER_{odd\_(1,m)}$
if $k_1 \leq i < k_1 + m$ then $Er_2 = ER_{\mathrm{odd}\_(k_2,k_1+m)} + \sum_{k_2}^{k_1+m} \frac{(k-m-2-2i)(m-i+1)R}{2}$
if $k_1 + m \leq i$ then $Er_3 = ER_{\mathrm{odd}\_(k_1+m,N-m)}$
Case 2: $k_1 \leq m < k$
if $0 \leq i < k_1$ then $Er_1 = \sum_{i=1}^{k_1} \left[(k^2-1)/8 - i\right] R$
if $k_1 \leq i < m$ then $Er_2 = \sum_{k_1}^{m} \left[(k^2-1)/8 - i + 1/2(m-k_1-1)(m-k_1)\right] R$ $- \int (m-k_1)\sigma \mathrm{d}\sigma - \int (iR+\sigma) m d\sigma$
if $m \leq i$ then $Er_3 = ER_{\mathrm{odd}\_(m,N-m)}$
Case 3: $m \geq k$
if $0 \leq i < k_1$ then $Er_1 = \sum_{i=1}^{k} \left[(k^2-1)/8 - i\right] R$
if $k_1 \leq i < m$ then $Er_2 = \sum_{i=1}^{k} \int (iR+\sigma) d\sigma$
if $m \leq i$ then $Er_3 = ER_{\mathrm{odd}\_(m,N-m)}$

Table 7. Results under $K = K$ (K is even) in WKNN

Case 1: $0 \leq m < k_4$
if $0 \leq i < k_4$ then $Er_1 = ER_{\mathrm{even}\_(1,k_4)} + ER_{\mathrm{even}\_(1,m)}$
if $k_4 \leq i < k/2 + m$ then $Er_2 = ER_{\mathrm{even}\_(k_4,k_3+m)} + \sum_{k_4}^{k_3+m} \frac{(k-m-2-2i)(m-i+1)R}{2}$
if $k/2 + m \leq i$ then $Er_3 = ER_{\mathrm{even}\_(k_3+m,N-m)}$
Case 2: $k_4 \leq m < k$
if $0 \leq i < k_4$ then $Er_1 = \sum_{i=1}^{k_3} \left[(k^2-1)/8 - i\right] R$
if $k_4 \leq i < m$ then $Er_2 = \sum_{k_4}^{m} \left[(k^2-1)/8 - i + 1/2(m-k_4-1)(m-k_4)\right] R$ $- \int (m-k_4)\sigma \mathrm{d}\sigma - \int (iR+\sigma) m d\sigma$
if $m \leq i$ then $Er_3 = ER_{\mathrm{even}\_(m,N-m)}$
Case 3: $m \geq k$
if $0 \leq i < k_4$ then $Er_1 = \sum_{i=1}^{k} \left[(k^2-1)/8 - i\right] R$
if $k_4 \leq i < m$ then $Er_2 = \sum_{i=1}^{k} \int (iR+\sigma) d\sigma$
if $m \leq i$ then $Er_3 = ER_{\mathrm{even}\_(m,N-m)}$

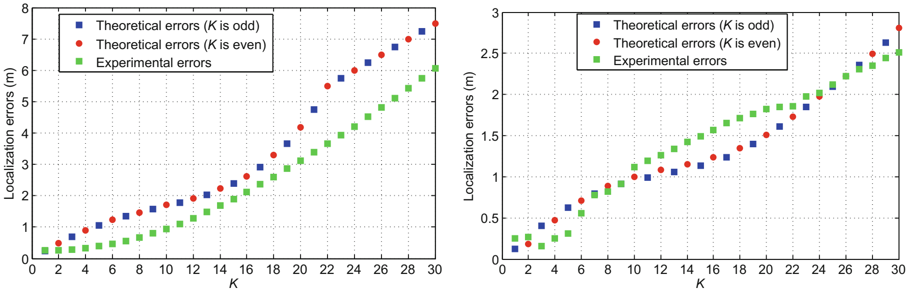
3 Experimental Results

3.1 Localization Errors

By setting $R = 1\,\mathrm{m}$ and $N = 60$, Fig. 3 compares the error bounds and simulated errors of the NMAs as the AP is located on the boundary (see Fig. 1). From this figure, we observe that the simulated errors are much close to the error bound. Furthermore, the WKNN generally exhibits higher localization accuracy compared to the KNN as expected [9].

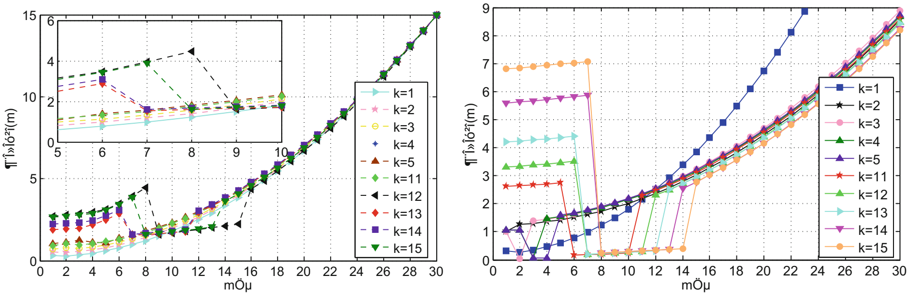
3.2 AP Locations

By setting $R = 1\,\mathrm{m}$ and $N = 60$, Fig. 4 shows the variation of error bounds with respect to the AP locations under different number of neighbors as the AP is located at a random location (see Fig. 2). From Fig. 4, we can find that the AP location has significant impact on the selection of the optimal number of neighbors corresponding to the lowest error bound. Due to the symmetry of the environment, the error bound reaches the maximum when the value m equals



(a) KNN. (b) WKNN.

Fig. 3. Comparison of the error bounds and simulated errors.



(a) KNN. (b) WKNN.

Fig. 4. Variation of error bounds under different values of m.

to 30. The sharp variation of error bounds around $m = 7\,\text{m}$ and $12\,\text{m}$ is resulted from the physical constraint of the environment.

4 Conclusion

In this paper, we proposed a novel indoor WLAN deployment optimization approach based on the localization error bounds of NMAs. We present the preliminary analysis on the closed-form solutions to the error bounds of NMAs in a typical indoor environment. The purpose of this analysis is to design the effective and efficient NMAs for the indoor WLAN localization. Furthermore, we discuss the impact of networking parameters, like the environmental size, interval of RPs, number of neighbors, and AP locations, on the error bounds of NMAs. For the future work, how to optimize the WLAN deployment by using the error bound criterion in multi-floor environment forms an interesting topic.

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