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Topology-aware handoff scheme for surveillance patrol robot

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Abstract With the advances in wireless communication technology and artificial intelligence, robots are gradually being introduced as a part of our life. Similarly to most mobile devices, mobile robots suffer from handoff latency. This paper proposes TASPR, a Topology-Aware Surveillance Patrol Robot, which can integrate the robotic status and topology information to assist handoff between access points (APs). TASPR uses Topology-Aware Hand-Off Scheme (TAHOS) to find the most promising AP from a list of candidate APs. When TASPR decides to initiate a handoff procedure, it analyzes moving direction, received signal strength and topology information to filter out unnecessary scannings. Thus, TAHOS has less handoff latency compared to conventional handoff procedure and neighbor graph algorithm (NGA).

Keywords Artificial intelligence · Intelligent robot · Wi-Fi · 802.11 · Handoff

1 Introduction

The advent of robots is becoming an intrinsic part of everyday life and has gained immense popularity in recent years [27, 28]. As a robot equipped with sensors can be programmed to track a moving object actively, its mobility is a promising solution to organizing a smart and secure home. The previous research [1] proposed a SIP-enabled Surveillance Patrol Robot (SSPR), which is equipped with a set of sensors and a camera, and is aware of session initiation protocol (SIP). SSPR can patrol the home space periodically. When SSPR senses a moving object, it will start tracking. Meanwhile, SSPR will initiate a SIP call to the default mobile device through wireless technology such as Wi-Fi. The householder can get the status of house through his/her mobile device. Furthermore, when SSPR follows the object from one room to another, the wireless link may break and result in the disconnection of audio and video streams. With mobility support in SIP, SSPR could perform a handoff from the original access point (AP) to another with better signal strength.

However, when the robot moves from one AP coverage to another, the robot may take a few seconds

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to establish a new session, causing the loss of some important information during these seconds. This latency can be attributed to 802.11 handoff procedure. The handoff procedure consists of two phases: discovery and commit phase. The authors in [2] implied that the discovery phase accounts for most of delay in the handoff procedure, which is the most promising part for improvement. Several solutions [3–17] have been proposed to address the scanning mechanism. These approaches focus on minimizing the disconnected time while the wireless station (STA) changes the associated AP. In the original IEEE 802.11 standard, the STA has to scan all channels. Some of the proposed approaches [3–9] introduce a selective channel scanning method for fast handoff based on the neighbor graph. STAs use neighbor graph algorithm (NGA) to selectively scan channels according to the neighbor graph. Such graph records the adjacency relations between APs and the channel used by each AP. With the neighbor graph, an STA can determine the candidate channels to scan and check whether it has received all responses from the APs in a particular channel. As a consequence, the number of channels the STA should scan decreases and so does the waiting time for staying in a dedicated channel.

Although an STA with neighbor graph can choose the desired channels to scan, this kind of scheme introduces extra overhead in dynamically maintaining the neighbor graph. This is because a neighbor graph is a data structure that abstracts the handoff relationships between APs, and an STA has to broadcast probe requests on each channel to collect the neighbor information. Furthermore, neighbor graph only records the adjacency of APs. The geographical location of each AP is not taken into consideration. Since the deployment of APs is usually static, such geographical information could be used to assist the discovery of candidate APs.

To improve the mobility and applicability of SSPR, this study proposes a Topology-Aware Surveillance Patrol Robot (TASPR). TASPR integrates the robotic status and topology information of APs and uses Topology-Aware Hand-Off Scheme (TAHOS) to assist handoff between APs. When a TASPR is activated, it retrieves the geographical information of APs from a server and then uses the signal strength of each AP to estimate its location. Besides, TASPR monitors the variation of signal strength to predict its moving direction and find the possible APs for handoff. In addition, TASPR compares its robotic status with the predicted direction to filter out the sudden change of signal strength caused by interference. When TASPR maintains a constant direction with stable velocity, the signal strength should increase or decrease in a polynomial fashion. The unexpected change of received power can be viewed as a jammed signal and should be ignored by TASPR. Furthermore, with the geographical information of APs, TASPR can determine the most suitable AP to probe and start performing a handoff. In the case where geographical information is not available, TASPR adopts an improved version of NGA to scan the candidate AP. Unlike the conventional NGA, which uses the neighbor graph to probe all candidate APs, TASPR adopts a weighted neighbor graph to find its candidate APs. Then TASPR monitors the variation of signal strength along with the robotic status to find the most appropriate AP for scanning. As a result, both methods of TAHOS can reduce the handoff latency and the audio and video streams will continue after handoff. Since a home robot can reinforce its capability through the integration of artificial intelligence and wireless communication technology, TASPR will make a home smarter and safer.

The remainder of this paper is organized as follows: we first describe the distance calculation and location estimation methods and then introduce the weighted neighbor graph and channel selection scheme. In the following section, we will describe the design of TASPR and present the simulation results. Finally, we summarize our findings and provide suggestions for further research in the final section.

2 Mathematical formulation

2.1 Distance calculation and location estimation

Since TASPR needs to find its location, it measures the received signal first. With the signal strength of each AP, TASPR can calculate the distance between an AP and itself. Furthermore, with such distance information between TASPR and APs, TASPR can estimate its location in response to the locations of APs. TASPR can retrieve the signal strength from the received signal strength indicator (RSSI) of beacons or probe response frames in 802.11. There are two scanning method defined in 802.11. Active scanning occurs when the STA changes its IEEE 802.11 radio to the channel being scanned, broadcasts a probe request, and then waits to hear any probe responses (or periodic beacons) from APs on that channel with a matching BSSID. The IEEE 802.11 standards do not specify how long an STA should wait, but 10 ms is a representative period. Passive scanning is performed by simply changing the IEEE 802.11 radio to the channel being scanned and waiting for a periodic beacon from any APs on that channel. By default, APs send beacons every 100 ms. Since an STA may take 100 ms to hear a periodic beacon broadcast, most STAs prefer an active scanning. Therefore, TASPR can retrieve the signal strength through active or passive scanning.

With the received signal strength, TASPR can then calculate the distance by using Free Space Propagation Formula [18–20]. The free space propagation formula is used to predict received signal strength when the transmitter and receiver have an unobstructed line-of-sight path between them. Here we assume that both transmitting antenna and receiving antenna are located in an otherwise empty environment. Neither absorbing obstacles nor reflecting surfaces are considered. The antennas of TASPR and APs are omnidirectional. The received signal power S_r at TASPR is

$$S_r = S_t G_t G_r \left(\frac{\lambda}{4\pi D_j}\right)^2, \tag{1}$$

where S_t is the transmitted power from the AP, G_t and G_r are the gains of the transmitting and receiving antennas, respectively, λ is the wavelength, and D_j is the distance between the jth AP and TASPR. The power drops as the inverse square of the distance. Given that each AP has a known fixed location and each AP is assumed to have identical signal strength, the distance D_j between TASPR and the jth AP can be represented as

$$D_j = \sqrt{\frac{S_t}{S_r} G_t G_r \left(\frac{\lambda}{4\pi}\right)^2}. \tag{2}$$

After obtaining the distance information between TASPR and APs, TASPR can then use the geographical information to estimate its location with respect to each AP [21]. Here we assume TASPR and all APs are on the same plane. One of the most common methods for TASPR to estimate its location is *lateration*, which evolved from triangulation. With the calculated distance information (D_j) and the geographical information which contains the known positions (x_j, y_j) of the anchors (i.e., APs), we can derive the following series of equations:

$$\begin{aligned}
&(x_1 - x)^2 + (y_1 - y)^2 = D_1^2,\\
&(x_2 - x)^2 + (y_2 - y)^2 = D_2^2,\\
&\vdots\\
&(x_j - x)^2 + (y_j - y)^2 = D_j^2,
\end{aligned} \tag{3}$$

where the unknown position (x, y) is the location of TASPR. We can further subtract the last equation in (3) from the first $j-1$ equations to linearize equations in (3):

$$\begin{aligned}
&x_1^2 - x_j^2 - 2(x_1 - x_j)x + y_1^2 - y_j^2 - 2(y_1 - y_j)y\\
&\quad = D_1^2 - D_j^2,\\
&x_2^2 - x_j^2 - 2(x_2 - x_j)x + y_2^2 - y_j^2 - 2(y_2 - y_j)y\\
&\quad = D_2^2 - D_j^2,\\
&\vdots\\
&x_{j-1}^2 - x_j^2 - 2(x_{j-1} - x_j)x + y_{j-1}^2 - y_j^2\\
&\qquad - 2(y_{j-1} - y_j)y\\
&\quad = D_{j-1}^2 - D_j^2.
\end{aligned} \tag{4}$$

After reordering equations in (4), we then derive a polynomial presentation in the form of $Ax = b$:

$$\begin{aligned}
A &= \begin{bmatrix} 2(x_1 - x_j) & 2(y_1 - y_j)\\ 2(x_2 - x_j) & 2(y_2 - y_j)\\ \vdots & \vdots\\ 2(x_{j-1} - x_j) & 2(y_{j-1} - y_j) \end{bmatrix},\\
b &= \begin{bmatrix} x_1^2 - x_j^2 + y_1^2 - y_j^2 + D_j^2 - D_1^2\\ x_2^2 - x_j^2 + y_2^2 - y_j^2 + D_j^2 - D_2^2\\ \vdots\\ x_{j-1}^2 - x_j^2 + y_{j-1}^2 - y_j^2 + D_j^2 - D_{j-1}^2 \end{bmatrix}.
\end{aligned} \tag{5}$$

The above equation can be solved by using the least-square method, which is

$$\hat{x} = \left(A^T A\right)^{-1} A^T b. \tag{6}$$

In order to verify the result generated from (6), we can perform a redundant sanity check by computing the residue (*resi*) between the given distances (D_k) and the distance from each AP to the estimated location $\hat{x}$:

$$resi = \frac{\sum_{k=1}^{j}(\sqrt{(x_k - \hat{x})^2 + (y_k - \hat{y})^2} - D_k)}{j}. \tag{7}$$

Since a large residue (*resi*) implies the inconsistency of the equations, we should reject the location $\hat{x}$ when the length of the residue exceeds the radio range.

2.2 Weighted neighbor graph and channel selection

In the case where geographical information is not available, TASPR will construct a weighted neighbor graph to assist its scanning. According to [3–9], a neighbor graph is an undirected graph with each edge representing a mobility path between APs. Therefore, given a set of edges, the neighbor of each edge represents a potential next AP. Assume $\mathbf{AP} = \{AP_1, AP_2, \ldots, AP_k\}$ is a set of APs in the wireless network environment. The mobility pattern (i.e., association pattern) of TASPR R during a finite period of time can be expressed as

$$\Gamma(R) = \langle AP_{R1}, AP_{R2}, \ldots, AP_{Rk}\rangle, \tag{8}$$

where k is the number of APs that served TASPR and AP_{Ri} is the ith AP. For simplicity, we assume that each successful transition between the previous AP and current AP is done by reassociation. We can then construct a neighbor graph G for an individual TASPR from the sequence $\Gamma(R)$:

$$G(R) = (V, E), \tag{9}$$

where V is the set of APs and E stands for the relations between APs:

$$E = \bigl\{(AP_i, AP_{i+1}) | AP_i \text{ and } AP_{i+1} \text{ are successive in } \Gamma(R)\bigr\}. \tag{10}$$

According to the Locality Mobility Principle [22], each edge reflects a handoff relationship between APs. The individual neighbor graph is a directed graph that reflects the mobility pattern of a TASPR in the wireless network environment. With the set of individual neighbor graphs, we can construct a whole neighbor graph NG_{whole}:

$$NG_{\text{whole}} = \bigcup_{R \in \text{TASPR}} G(R). \tag{11}$$

When finding a candidate AP for handoff, there are two main factors that affect probing latency: (i) the number of channels to probe, i.e., probe-channel count, and (ii) waiting time on each probed channel, i.e., probe-waiting time [2]. With prior knowledge of the neighbor graph, the probe-channel count and probe-waiting time can be reduced. The algorithm proposed in [4] constructs a partition of neighbor APs based on their channel assignments. Let the neighbor channel count be the number of distinct channels used by neighbor access points. The neighbor channel count is of course always less than or equal to the number of independent channels. With such partition information, STA removes wasted channels or empty channels and probes only non-empty (AP existing) channels. This kind of probing is also known as minimum-channel probing. For a better performance in NGA, an optimal channel assignment should avoid assigning the same channel to neighbors. The difference between neighbor channel count and the number of independent channels grows as the number of independent channels increases. The authors in [4] show that the benefit of minimum-channel probing increases as the number of independent channels increases.

When selecting an AP to probe, there may be two or more possible candidates. This study adopts a weighted neighbor graph, which utilizes frequent handoff region (FHR) [12] to calculate the weight of each edge in E. The FHR is a subset of adjacent APs which are likely to move in the near future. Many handoff prediction algorithms, which are based on the mobility history collected from STAs with regularity, have been proposed [23]. Since most STAs move according to a specific regularity, it is possible to predict the mobility pattern using the previous patterns [23, 24]. However, most STAs in wireless network environment are visiting or temporary hosts without any regular mobility patterns. Therefore, it is not feasible to predict the mobility pattern from the mobile specific information. Instead of the mobile-specific prediction scheme, network-specific prediction scheme is a promising choise. In this prediction scheme, the handoff probability between APs is calculated according to the previous handoff ratio and residence time collected by a server (SIP Proxy Server in our design).

In the network-specific prediction scheme with FHR, each handoff event is recorded in the server. With event logs, it is possible to find out the handoff ratio per unit time between APs [24]. The handoff ratio is calculated as

$$H(m,n) = \sum_{k=1}^{N(m,n)} \frac{1}{R_k(m,n)}, \tag{12}$$

where $H(m,n)$ and $N(m,n)$ denote the unit handoff ratio and the number of handoff events from $AP(m)$ to $AP(n)$, respectively. Let $R_k(m,n)$ be the residence time in the kth handoff event from $AP(m)$ to $AP(n)$. The residence time is calculated as

$$R_k(m,n) = T_{\text{out}}(k) - T_{\text{in}}(k), \tag{13}$$

where $T_{\text{out}}(k)$ and $T_{\text{in}}(k)$ represent out-time and in-time of the kth handoff event, respectively. The weight values between APs are determined by the handoff ratio. The following equation calculates the link weight value $w(m,n)$ between AP(m) and AP(n) through weight function:

$$w(m,n) = \begin{cases} 0, & m = n, \\ \frac{1}{H(m,n)}, & m \neq n, AP(m) \text{ and } AP(n) \\ & \text{are adjacent,} \\ \infty, & AP(m) \text{ and } AP(n) \\ & \text{are not adjacent.} \end{cases} \tag{14}$$

The handoff ratio $H(m,n)$ in (12) is influenced only by the handoff events. As a result, the weight value in the path from $AP(m)$ to $AP(n)$ where $m = n$ is set to zero. In addition, if two APs are not adjacent, the weight value is infinite. Owing to traffic asymmetry, $w(i,j)$ and $w(j,i)$ are not equal.

3 Topology-aware surveillance patrol robot (TASPR)

In the proposed scheme, a server will record and keep topology information for each TASPR. This topology information contains both geographical information of each AP and weighted neighbor graph. Each TASPR can access and update such topology information through the Internet. When the robot is activated, it will initiate a request to the SIP Proxy Server for retrieving the topology information. As Fig. 1 illustrates, the request is embedded in the REGISTER message. After receiving such request, the Proxy Server will respond to TASPR with topology information appended to 200 OK message. When TAPSR has finished its handoff procedure, it uses a RESGISTER message to update its location information (attached AP) in the Proxy Server.

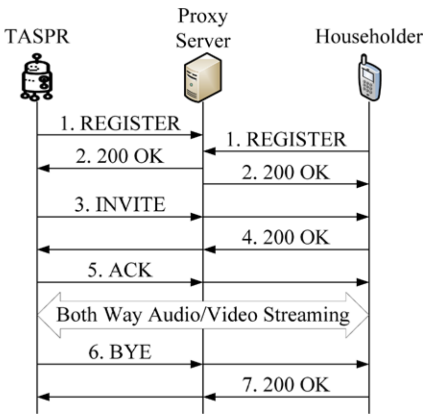


Fig. 1 Interaction between TASPR and the householder

After retrieving topology information, TASPR can start its Topology-Aware Hand-Off Scheme (TAHOS) for subsequent handoff events. This scheme consists of two methods for choosing a candidate AP. The first method (TAHOS I) uses the geographical information, estimated location and moving direction of TASPR to find possible candidates, while the other one (TAHOS II) uses the weighted neighbor graph.

In TAHOS I, if the geographical information of APs is available in the topology information, TASPR will estimate its location in response to the coordinate of each AP as shown in Fig. 2. The estimation method is illustrated in Sect. 2.1. Then TASPR starts monitoring the signal strength of each AP, comparing the variation of signal strength with the moving direction. As Fig. 3 illustrates, if TASPR moves towards the center of AP2 and AP3, the signal strength of AP2 and AP3 will increase smoothly while the signal strength of AP4 and AP5 will decrease. As long as TASPR knows its location in the coordinate system and captures the variation of the signal strength, TASPR can determine the candidate APs for handoff. As Fig. 3 shows, the candidate APs will be AP2 and AP3. However, the signal strength may be affected by the noise, and thus the received signal strength may not reflect the proper moving direction. This would be a problem to a conventional mobile device. As for TASPR, the moving direction can be retrieved through the communication interface on the robot. This paper adopts Pioneer P3-DX to design TASPR. The moving direc-

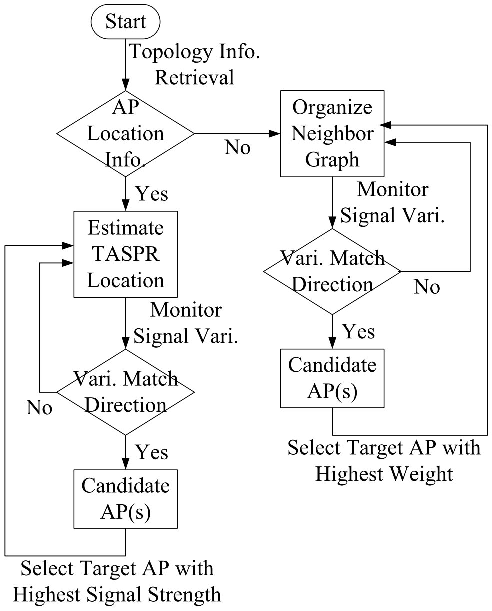
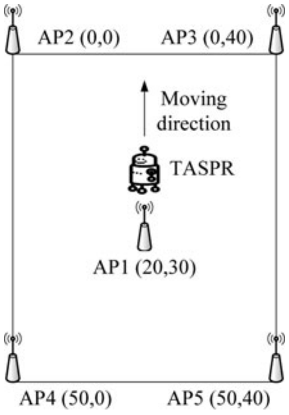


Fig. 2 Topology-aware handoff scheme

Fig. 3 Location information of each AP



tion can be read through ARIA library [25]. As long as TASPR compares the variation of signal strength with its moving direction, it can filter out the jammed signal. In the end, TASPR selects the AP with highest signal strength as the candidate AP for handoff.

In TAHOS II, the location information about each AP is not available. TASPR will use the weighted neighbor graph to assist selecting the candidate AP. This study assumes that the Proxy Server will record the AP in use and the subsequent AP after handoff for each TASPR. When TASPR decides to perform a handoff, as Fig. 4 illustrates, there are four possible APs (three possible channels). In conventional NGA, TASPR will probe all channels dedicated to APs, i.e., channels 4, 6 and 11. However, TASPR in this case moves towards the center of AP2 and AP3 and, thus, AP4 and AP5 should not be probed. For instance, the conventional NGA may switch to channel 6 when probing AP4, which contradicts to TASPR's moving direction. In TAHOS II, TASPR uses its moving direction to filter out AP4 and AP5 according to the signal attenuation. In Fig. 4, the candidate APs are AP2 and AP3. Since TAHOS II adopts a weighted neighbor graph and the AP with higher handoff ratio has a higher weight, TASPR will select the AP with higher weight to probe.

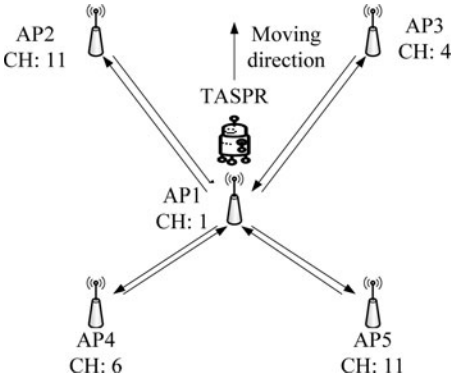


Fig. 4 Neighbor graph of TASPR

4 Performance evaluation

To study the feasibility of the proposed approach and compare it with the other alternatives, we constructed a simulation with simulator ns-2 [26] and an experiment with Pioneer P3-DX robot. The robot equips an onboard PC, which has a Wi-Fi interface and has a SIP UA installed for call setup. In this section, we first verify the feasibility of topology-aware handoff scheme with simulator ns-2 then we conduct a field test with Pioneer P3-DX robot.

4.1 Simulation results

As Fig. 5 illustrates, the setup of simulation contains four APs. For simplicity, the corresponding node (CN) and the home agent (HA) are not shown in the figure. At first, TASPR is attached to AP4. Then TASPR moves towards AP2. After leaving AP2, TASPR moves to AP1 followed by AP3. In the end, TASPR stops at AP3. This simulation starts a timer when TASPR decides to perform a handoff, and stops the timer when completing the layer-2 handoff procedure. The alternative scheme NGA adopts neighbor graph as shown in Fig. 6.

According to the simulation results (Table 1), both TAHOS I and TAHOS II have shorter handoff latency as compared to NGA.

- AP4 →AP2: At first TASPR moves from AP4 to AP2. When TASPR detects degradation of the communication quality, it considers to change AP and eventually decides to perform a handoff to a candidate AP that offers better signal quality. TASPR then initiates a handoff procedure to probe candidate AP. In this case, both NGA and TAHOS have only one candidate and thus, they have a similar amount of handoff latency.
- AP2 →AP1: After leaving AP2, TASPR moves towards AP1. When signal strength decreases, TASPR decides to perform a handoff. In this situation, there are two possible candidate APs, AP1 and AP4, according to the neighbor graph. Unlike NGA, TAHOS 1 and TAHOS 2 have only one candidate to probe. TAHOS 1 uses locations of APs, its location and signal strength to find the most appropriate one. TAHOS 2 uses weighted neighbor graph and the signal strength to find the candidate. In this case, there are two possible APs on the graph. When TASPR moves towards AP1, the signal strength of AP4 will decrease and thus conflict with TASPR's moving direction. As a result, only AP1 is the most appropriate one for handoff. In the end, NGA receives the highest handoff latency.
- AP1 →AP3: When TASPR decides to perform a handoff, there are three possible choices according to neighbor graph. As a result, NGA receives the highest handoff latency since NGA has to scan these channels. Both TOHAS 1 and TOHAS 2 have only one candidate. TOHAS 2 uses the variation of signal strength to filter out AP2 from the candidate list. The signal variations of AP3 and AP4 coincide with the moving direction. In this case, TASPR uses the weight to select the target AP. If the edge to AP3 has higher weight, AP3 will be the priority.

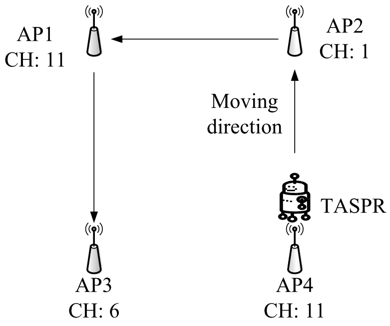


Fig. 5 Simulation environment

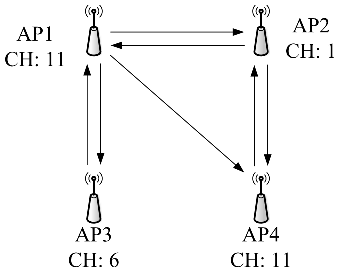


Fig. 6 Neighbor graph for simulation

4.2 Experiment results

To further verify the design of TASPR, we implemented TASPR with Pioneer P3-DX and construct an experiment environment (Fig. 7) for testing. The neighbor graph generated for experiment is shown in Fig. 8. At first, TASPR is attached to AP1. Then TASPR moves towards AP3. After leaving AP1,

Table 1 Simulation results

Moving direction	Scan with neighbor graph		Scan with TAHOS 1		Scan with TAHOS 2	
	# of probed AP	Handoff latency (ms)	# of probed AP	Handoff latency (ms)	# of probed AP	Handoff latency (ms)
AP4 →AP2	1	43	1	40	1	39
AP2 →AP1	2	66	1	44	1	45
AP1 →AP3	3	81	1	43	1	42

TASPR moves to AP2 followed by AP3. In the end, TASPR stops at AP3.

- AP1 →AP2: In the beginning of experiment, TASPR is attached to AP1. Then TASPR moves from AP1 to AP2. When TASPR decides to perform a handoff to a candidate AP with better signal quality, it initiates a handoff procedure to probe candidate AP. In this case, NGA, TAHOS 1 and TAHOS 2 have only one candidate and generate a similar amount of handoff latency.
- AP2 →AP3: When TASPR finds the signal degradation of AP2 and decides to perform a handoff, the neighbor graph (Fig. 8) illustrates three possible candidates. Since NGA has to scan such channels, it receives the highest handoff latency. When TASPR moves towards AP3, the signal strengths of AP2 and AP4 will decrease and thus conflict with TASPR's moving direction. In this case, TAHOS 1 uses locations of APs, its location and signal strength to find AP3 for handoff while TAHOS 2 uses neighbor graph and the signal strength (Table 2).

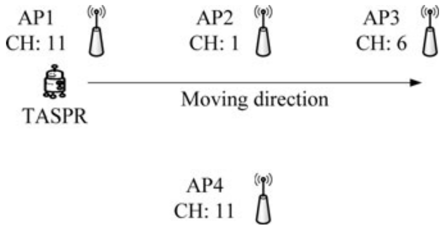


Fig. 7 Experiment environment

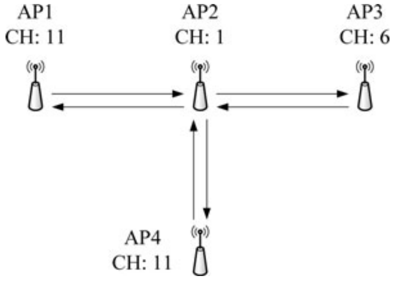


Fig. 8 Neighbor graph for experiment

5 Conclusions

We have proposed a design of TASPR to improve the handoff procedure of SSPR. TASPR can utilize the topology information including locations of APs and weighted neighbor graph to assist its handoff. The proposed handoff scheme TOHAS integrates robotic status and topology information to select the target AP in one shot. Simulation results confirm that TOHAS 1 and TOHAS 2 outperform NGA in terms of handoff latency.

In addition to layer-2 handoff, layer-3 handoff will generate enormous latency because layer-3 handoff involves the subnet change detection and IP address acquisition. There should be a cross-layer protocol to assist both layer-2 and layer-3 handoff.

TASPR is being implemented with Pioneer P3-DX. However, there are several sources of interfering signals, including microwave ovens, wireless phones, Bluetooth-enabled devices, and other wireless LANs, which may result in the signal estimation failure. There should be a correction technique to compensate the measurement of signal.

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Table 2 Experiment results

Moving direction	Scan with neighbor graph		Scan with TAHOS 1		Scan with TAHOS 2	
	# of probed AP	Handoff latency (ms)	# of probed AP	Handoff latency (ms)	# of probed AP	Handoff latency (ms)
AP1 →AP2	1	41	1	39	1	42
AP2 →AP3	3	79	1	40	1	41

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