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FAST-HANDOFF SUPPORT IN IEEE 802.11 WIRELESS NETWORKS

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ABSTRACT

With the advance of wireless local area network (WLAN) technology, handoff support has become one of the most important issues in IEEE 802.11 WLANs. However, the current IEEE 802.11 specification does not provide the fast handoff required for real-time multimedia applications. To support fast handoff in IEEE 802.11 networks, a number of fast-handoff schemes have been proposed in the literature. In this article we review these fast-handoff schemes and analyze their advantages and disadvantages qualitatively. After that, important design considerations for mobility support in future IEEE 802.11 networks are suggested. Also, we introduce a fast-handoff framework which adaptively meets different application requirements via a cross-layer approach.

Public wireless local area network (WLAN) systems based on IEEE 802.11 are exponentially becoming popular in hot spot areas such as airports, campuses, convention centers, and so on. Unlike existing wireless Internet services based on cellular networks, public WLAN systems can provide high-speed Internet connectivity up to 11 Mb/s (IEEE 802.11b [1]) or 54 Mb/s (IEEE 802.11a/g [2, 3]). Originally, WLAN was designed as a network solution for eliminating the problem of tangled cables among network devices in an indoor environment, so that handoff support was not perceived as a critical issue. However, the advances of public Wi-Fi services and multimedia applications have raised an unforeseen problem, *handoff support* between access points (APs) [4, 5]. Due to insufficient handoff support in IEEE 802.11 networks, a significant disruption can be experienced while a handoff is performed. Table 1 summarizes the measured handoff delay reported in [6] and it indicates that the handoff delay is unsatisfactory to support multimedia applications in IEEE 802.11 networks. Consequently, supporting fast handoff in IEEE 802.11 networks has become a vital issue to achieve seamless mobile services.

Currently, several IEEE working groups (WGs) have endeavored to enhance and augm0ent IEEE 802.11, i.e., 11g for 2.4 GHz OFDM [3], 11e for quality of service (QoS) [7], 11i for security [8], 11f for inter-AP protocol [9], and so on [10]. Regarding handoff support, the 11i and 11f WGs have proposed several schemes to address security concerns and to support communications between the APs involved in a handoff event, respectively. More recently, two new IEEE 802.11 groups, 11k and 11r, have been launched for the purpose of radio-resource management and fast-handoff support, respectively. The draft 802.11k specification provides a radio resource measurement mechanism [11]. This measurement information can be used to obtain information on the currently available APs, before a handoff decision takes place. On the other hand, the 11r task group will define roaming algorithms to satisfy the stringent QoS requirements but, as yet, no tangible results have been forthcoming.

In addition to these standardization activities, many studies have been conducted in order to improve the handoff performance in IEEE 802.11 networks. The existing fast-handoff schemes have been evaluated by simulations or measurements on specific testbeds. However, to the best of our knowledge, no comparative study of these fast-handoff schemes has been reported. The main contributions of this article are to provide an update on the state of the art in representative fast-handoff schemes for IEEE 802.11 networks and to evaluate their advantages and disadvantages comprehensively. Also, based on the comparative study, we propose a fast-handoff framework to adaptively meet different applications' requirements in IEEE 802.11 networks.

The rest of this article is organized as follows. First, we

AP / MH	Cisco			Soekris			Lucent		
	P	A	R	P	A	R	P	A	R
Lucent	37.2	3.08	5.07	196.9	1.77	1.77	81.2	0	1.73
Cisco	399.8	3.56	4.13	349.9	4.48	1.79	347.3	1.485	1.09
ZoomAir	195.6	2.403	8.84	191.3	2.37	1.77	347.5	0	3.085

Table 1. *Handoff delay in different vendors (Unit: msec, P: probe delay, A: authentication delay, R: reassociation delay).*

provide an overview of the handoff procedure triggered in IEEE 802.11 networks. We summarize various fast-handoff schemes, depending on their objectives to reduce the handoff delay. After that, we evaluate their pros and cons qualitatively. Design issues for mobility support in IEEE 802.11 networks are presented and an adaptive fast-handoff framework based on a cross-layer approach is introduced. Finally, the concluding remarks are given.

Handoff Procedure in IEEE 802.11 Networks

As described in [6], the handoff process in IEEE 802.11 networks can be divided into two steps: *discovery* and *reauthentication*.

Discovery

Due to the mobility of a mobile host (MH), the signal-to-noise ratio (SNR) from the current AP can become degraded, and this triggers the initiation of a handoff procedure. Before closing the connectivity to the current AP, the MH needs to find potential APs with which to associate. This is accomplished by means of a medium access control (MAC) layer function called scanning.

There are two types of scanning in the IEEE 802.11 standard: passive and active. In the passive scan mode, the MH listens to the wireless medium for beacon frames. Beacon frames provide the MH with timing and advertising information. Using the information obtained from these beacon frames, the MH can choose an AP to associate with next. The current IEEE 802.11 standard supports multiple channels. Specifically, both the IEEE 802.11b and 11g standards operate in the 2.4 GHz ISM band and use 11 channels of the 14 possible channels, whereas the IEEE 802.11a standard operates in the 5 GHz ISM band in which a total of 32 channels are defined. During the passive scanning mode, the MH listens to each channel of the physical medium one by one, in an attempt to locate the next AP. Therefore, the passive scan mode incurs significant delay.

On the other hand, the active scanning mode involves the transmissions of probe request frames by the MH and the processing of the received probe response frames from the APs. After all channels have been scanned, the MH collects the information from all available APs and therefore the MH can select the next AP to associate. The detailed active scanning procedure is as follows [12]:

1 The normal channel access procedure, carrier sense multiple access with collision avoidance (CSMA/CA) is performed to gain control of the wireless medium.
2 The MH transmits a probe request frame containing the broadcast address as its destination.
3 A probe timer is started.
4 The MH waits for probe responses.
5 If no response has been received by *MinChannelTime*, the next channel is scanned
6 If one or more responses are received by *MinChannelTime*, the MH stops accepting probe responses at MaxChannelTime and processes all of the responses received by this time.
7 The above steps are repeated for the next channel.

Reauthentication

The reauthentication procedure[1] involves authentication and reassociation to the new AP and the transfer of the MH's credentials from the old AP to the new AP. Authentication is a process that the AP either accepts or rejects the identity of the MH. An MH begins the authentication process by sending an authentication request frame that informs the AP of its identity. Then, the AP responds with an authentication response frame indicating its acceptance or rejection. Once a successful authentication has been accomplished, the MH can send a reassociation request frame to the new AP, which then replies with a reassociation response frame containing an acceptance or rejection notice.

Figure 1 illustrates the message flow during a handoff. The handoff process starts with a probe request message and ends with a reassociation response message originating from the AP. The entire handoff delay can be divided into three delays: *probe delay*, *authentication delay*, and *reassociation delay*.

Probe Delay

The probe delay is dependent on which scan mode is used (i.e., passive or active mode). The average probe delay in the passive scan can be represented as a function of the beacon interval and the number of channels available. Specifically, if the beacon interval is 100 msec, the average probe delays of IEEE 802.11b with 11 channels and 802.11a with 32 channels are 1100 msec and 3200 msec, respectively. Note that the channel switching delay is negligible, that is, about 40–150 usec [13].

On the other hand, the probe delay bound of the active scan mode can be determined by the *MinChannelTime* and *MaxChannelTime* values, which are device-dependent. The current active scanning procedure requires for an MH to scan all available channels (i.e., 11 channels for IEEE 802.11b and 32 channels for IEEE 802.11a). Therefore, the probe delay bound, T_A, of the active scan can be expressed as

[1] *The association refers to a procedure to make a logical connection by an MH, which is invoked once when the MH enters a WLAN system for the first time. On the other hand, the reassociation is a procedure that an MH provides information to the WLAN system withwhich the MH was previously associated.*

$$N \times MinChannelTime \leq T_A \leq N \times MaxChannelTime;$$

where N is the number of channels available.

The most intuitive method for reducing the probe delay is to reduce the number of channels to be probed.

Namely, the probe delay can be reduced by probing only selected channels rather than all channels. Another method is to refine the *MinChannelTime* and *MaxChannelTime* values for the purpose of reducing the channel waiting time. Research work based on these methods will be introduced later.

AUTHENTICATION DELAY

The authentication delay is incurred by the exchange of the authentication frames. In general, two authentication approaches are widely accepted. One is the open-system authentication, in which the AP always accepts an MH without any authentication procedure. Optionally, MAC address filtering can be employed with the open-system authentication, but this is not a part of the IEEE 802.11 standard. The other is the shared-key authentication method based on wired equivalent privacy (WEP) [14], which requires that both the AP and MH implement WEP. The shared-key authentication requires four message exchanges as follows:

1 The MH requests authentication to the AP by sending a `Challenge-Request` message
2 The AP sends a random number to the MH through a `Challenge-Response` message.
3 The MH signs this random number using WEP, which is a pre-shared secret key, and sends a Response message back to the AP.
4 The AP verifies that the random number has been signed by the correct key, by calculating the signature itself and comparing the computed and the received values. Once the key has been verified by the AP, it authenticates the MH by sending an `Approval` message.

The authentication delay is proportional to the number of messages exchanged between the AP and MH. Therefore, the shared-key authentication results in longer authentication delay than the open-system authentication. Furthermore, if an IEEE 802.11 network utilizes enhanced authentication schemes described in the IEEE 802.11i standard (e.g., IEEE 802.1x and EAP-TLS [15]), more message exchanges are required. For instance, recently deployed public WLAN systems (e.g., NeSpot in Korea [16]) employ the 802.1x-based authentication scheme. Consequently, the problem of reducing the authentication delay is likely to become an even more challenging issue in future WLAN systems.

REASSOCIATION DELAY

Reassociation is the process of moving an association from an old AP to a new AP within an extended service set (ESS). An ESS is a set of one or more interconnected basic service sets (BSSs), where a BSS is a service coverage of an AP. The reassociation delay is incurred due to the exchange of the reassociation frames. Upon the successful completion of the authentication process, an MH sends a reassociation request frame to the AP and receives a reassociation response frame, and completes the handoff. Over the air, the reassociation procedure is almost the same as the association procedure. On the backbone network, however, APs may interact with each other to deliver frames related to the reassociation. Namely, future implementations may also include additional inter-AP protocol (IAPP) [9] messages during the reassociation phase, which may further increase the reassociation delay.

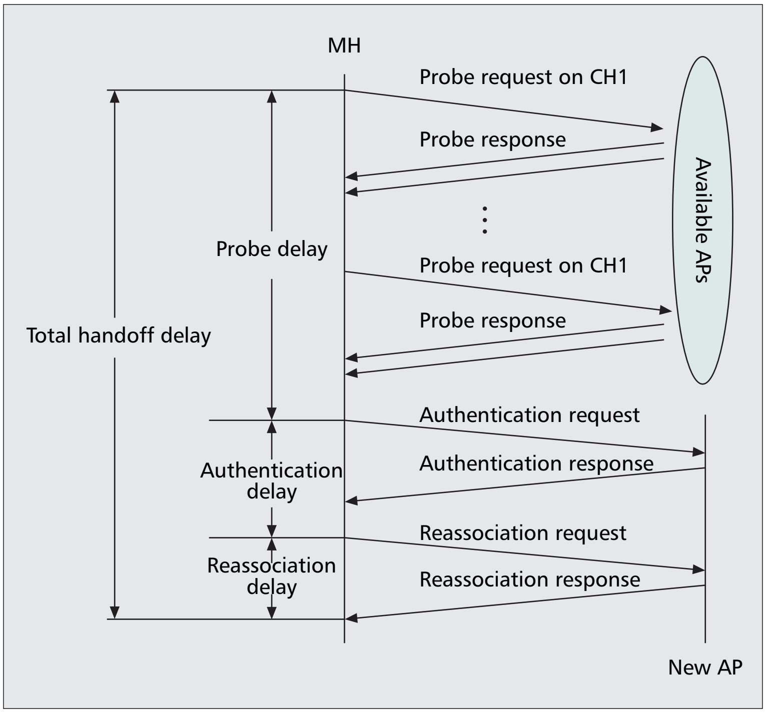


Figure 1. *Handoff message flow in IEEE 802.11 networks.*

FAST HANDOFF SCHEMES: STATE OF THE ART

A number of schemes have been proposed to reduce the handoff delay in IEEE 802.11 networks. Among them, we select representative ones and describe them in two categories: *reducing the probe delay* and *reducing the authentication/reassociation delay*. Note that the authentication and reassociation procedures have similar operations and therefore we consider these two procedures into one.

REDUCING PROBE DELAY

As indicated in [6], the probe delay is the main contributor to the handoff delay, and hence it is crucial to reduce the probe delay.

In [17], Velayos *et al.* proposed a fast-handoff detection scheme (referred to as the *tuning scheme*). In this work, they used the frame loss distribution caused by collisions, in order to determine the optimal handoff trigger timing to a new AP. To reduce the handoff detection time, the MH starts the channel probe procedure as soon as it deems that collision can be excluded as a reason for the frame transmission failure. In other words, based on the probability distribution, if a frame and its next two consecutive retransmissions fail, the MH concludes that the frame failure is caused by the MH's movement (not by collision) and therefore a further handoff process is required. In addition, they leveraged the active scan mode and derived new values for *MinChannelTime* and *MaxChannelTime* from their measurement results and analytical models. Specifically, they used smaller values of 1 ms and 10.24 ms for *MinChannelTime*

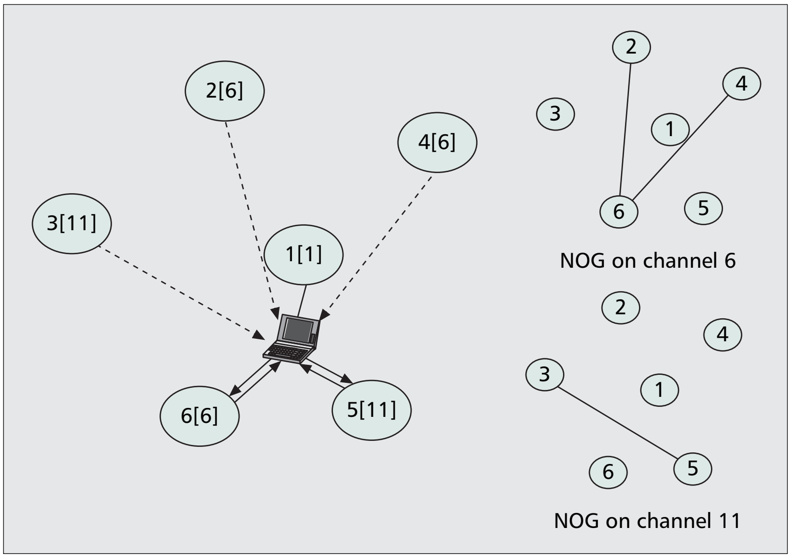


Figure 2. *NG-pruning scheme.*

and *MaxChannelTime*, respectively. By using these reduced timer values, the tuning scheme can reduce the channel probe delay.

Reference [18] presented a novel discovery method using a neighbor graph (NG) and a nonoverlap graph (NOG). This scheme (referred to as the *NG-pruning scheme*) focuses on reducing both the total number of channels to be probed and the waiting time on each channel. They suggested two algorithms: the NG and NG-pruning algorithms. The rationale behind these algorithms is to ascertain whether or not a channel needs to be probed (by the NG algorithm) and whether the MH has to wait more probe response messages on a specific channel before the expiration of *MaxChannelTime* (by the NG-pruning algorithm). The NG abstracts the hand-off relationship between adjacent APs. Using the NG, the set of channels on which neighboring APs are currently operating and the set of neighbor APs on each channel can be learned. Based on this information, an MH can determine whether or not a channel needs to be probed. On the other hand, the NOG abstracts the nonoverlapping relation among the APs. Two APs are considered to be nonoverlapping if and only if the MH cannot communicate with both of them simultaneously with acceptable link quality. For instance, if the distance between AP_i and AP_j is far, an MH can associate with only one of them. In this case, AP_i and AP_j are nonoverlapping each other. Therefore, if the MH has received a probe response frame from AP_i, this implies that the MH cannot receive a response frame from AP_j by the principle of nonoverlapping. By means of the NOG, the MH can prune some of the APs which are nonoverlapping with the current AP group that has already responded.

Figure 2 illustrates the operation of the NG-pruning scheme. The unbracketed and bracketed numbers represent the AP identifier and channel number used by the AP, respectively. In this example, only three channels (i.e., 1, 6, and 11) are used and the current AP (AP_1) has five neighboring APs (AP_2 to AP_6). The neighbor information can be learned by the construction of the NG. By using this neighbor information, the MH knows that the number of channels it has to probe is just two (i.e., channels 6 and 11). On the other hand, individual NOGs are constructed on each channel (i.e., one NOG on channel 6 and the other NOG on channel 11). First, suppose that the MH is probing on channel 6. When it receives a probe response message from AP_6, the MH decides that it is unnecessary to wait for additional probe response messages on channel 6. This is because AP_6 is nonoverlapping with AP_2 and AP_4, even though they use channel 6. After probing channel 6, the MH sends a probe request message on channel 11. Then, the MH receives a probe response message from AP_5 and stops probing on this channel because AP_3 using channel 11 is nonoverlapping with AP_5.

In [12], a selective scanning algorithm with a caching mechanism was proposed (referred to as the *channel mask scheme*). In the channel mask scheme, only a well-selected subset of all available channels is probed. Channel selection is performed by means of a channel mask that is built when the driver is first loaded at the MH. Specifically, full-scan is triggered at first and the channel mask is then constructed by the information obtained in the first full-scan. In IEEE 802.11b, only three channels do not overlap among all 11 channels. Hence, in a well-configured wireless network, all or most of the APs operate on channels 1, 6, and 11. Consequently, the channel mask is formed by combining three frequent channels (i.e., 1, 6, and 11) and the channels scanned at the first full-scan. By using this channel mask, an MH can reduce the amount of unnecessary time that it spends probing nonexistent channels among neighboring APs. To further reduce the handoff delay, a cache mechanism was also introduced. The basic idea of the caching mechanism is for each MH to store its handoff history. When an MH associates with an AP, the AP is inserted into the cache maintained at the MH. When a handoff is needed, the MH first checks whether there is an entry corresponding to the current AP's MAC address in the cache. If there is a matched cache entry, the MH can associate with the AP without any further probing procedures.

Figure 3 illustrates the operation of the channel mask scheme. Each MH has its own channel mask, which is built during the network setup phase. At the same time, each MH has its own cache table that is constructed and updated dynamically by handoff events. Namely, when an MH associates with an AP, the AP's identifier (i.e., MAC address) is stored in the cache as a key. In addition, two APs with the best received signal strength (RSS) are stored in the cache. When a handoff is needed, the MH first checks the entries in its own cache table using the current AP's MAC address as the search key. If there is a cache entry for the current AP (i.e., cache hit), the MH tries to associate with the first AP that has the highest RSS. If the association is successful, the handoff is finished and therefore the handoff latency can be significantly reduced. Otherwise, the association to the second AP is tried. Only when the first and second associations fail, the MH performs selective channel probing using the channel mask. In Fig. 3, only three channels are used, so that it is sufficient for the MH to probe the three channels even if a cache miss occurs.

In [19], a new handoff scheme, called *SyncScan*, was proposed to reduce the probe delay. Unlike the existing probe procedures defined in IEEE 802.11, SyncScan allows an MH to monitor the proximity of nearby APs continuously. In other words, the MH regularly switches to each channel and records the signal strengths of the channels. By doing so, the MH can keep track of information on all neighbor APs. Moreover, through continuous monitoring the signaling quality of multiple APs, a better handoff decision can be made and the authentication/reassociation delay can be also reduced. To minimize the packet loss during the periodical monitoring, the power saving mode (PSM) in the IEEE 802.11 specification is utilized. Since SyncScan is based on the regular monitoring of

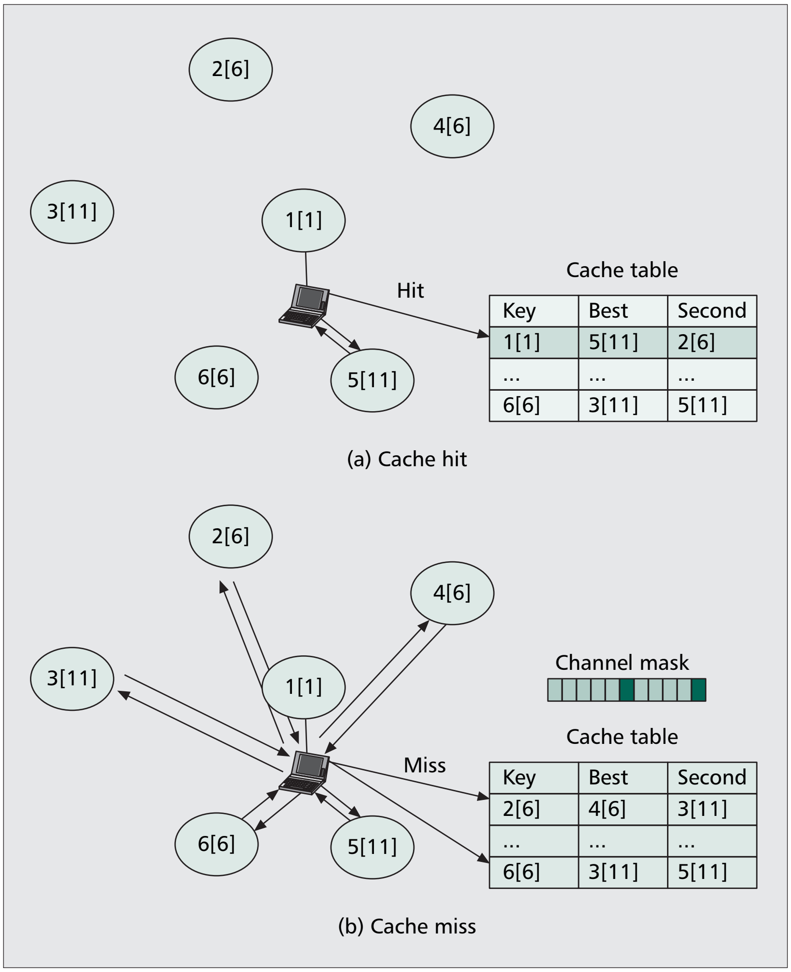


Figure 3. *Channel mask scheme.*

APs, time synchronization is a critical issue. For synchronization with APs, the network time protocol (NTP) can be leveraged. On the other hand, if multiple APs use the same channel and they generate beacons at the same time, a randomization technique can be employed.

Figure 4 shows the timing diagram in SyncScan, where d is a stagger parameter that determines the beacon broadcasting timing. For instance, APs operating on channel 1 broadcast beacon frames at time T, while APs on channel 2 will do the same at time $T + d$, APs on channel 3 will send beacon frames at time $T + 2d$, and so on. By this schedule, the MH switches from the current channel c to the channel $c + 1$ and receives beacon frames from APs on the channel $c + 1$. This operations are continuously repeated; hence, the MH learns information on neighbor APs. Consequently, SyncScan enables an MH to determine the time when a handoff should be triggered, which reduces the handoff delay.

Brik *et al.* introduced a handoff scheme utilizing multiple radios called *MultiScan* [20]. Similar to Sync-Scan, MultiScan obtains information on neighbor APs by scanning opportunistically. However, MultiScan requires an additional radio interface for the channel scanning. In MultiScan, the primary interface is associated with the current AP and used for data transmission. At the same time, the secondary interface is performing the channel scanning. If a handoff to a new AP is required, the second interface is associated with the new AP while the primary interface is still employed for data transmission. After the completion of a new association by the secondary interface, interface switch from the secondary interface to the primary one is triggered. As a result, the formerly secondary interface becomes primary for data transmission and the formerly primary interface is used for channel scanning. Consequently, MultiScan achieves a *make-before-break* handoff by using multiple radio interfaces.

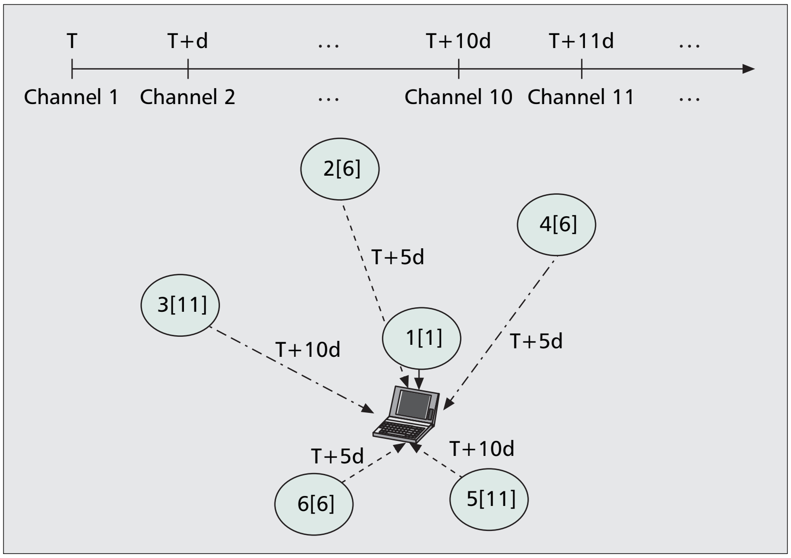
Reducing Authentication/Reassociation Delay

Even though the probe delay takes a large portion of the total handoff delay, the authentication/reassociation delay should be also reduced to achieve seamless mobile services. Actually, in public WLAN services, the authentication scheme based on the centralized authentication server is widely adopted for the sake of secure service and efficient accounting. In such an environment, the authentication/reassociation delay may be higher than those observed in the case where the open authentication procedure is employed [21]. An overview of different fast authentication methods in IEEE 802.11 networks is presented in [22] with an analysis in terms of network architectures and trust models. In this article we describe several schemes focusing on the communication model.

In [23], Pack *et al.* proposed a predictive handoff scheme for reducing the authentication/reassociation delay (referred to as the *FHR scheme*). In this scheme, an MH's authentication information is proactively distributed to multiple APs depending on the MH's mobility pattern and service class. To predict the MH's mobility pattern, a concept of frequent handoff region (FHR) was introduced. The FHR is a set of APs which have high possibilities of being visited by an MH in the near future. The FHR is constructed based on the handoff frequency and the MH's priority at the centralized system. The FHR can be easily implemented based on the IEEE 802.1x model [24]. From several measurement studies [5], the number of APs associated with an MH during its service time is typically bounded to two or three. Therefore, in the FHR scheme, the MH's authentication information is delivered to a subset of the adjacent APs which are located at a maximum two-hop distance from the current AP.

Figure 5 shows the operation of the FHR scheme. In this example, an MH associates with AP_4 at the login phase, and it forms a FHR consisting of AP_0, AP_4, AP_7, and AP_8. Therefore, the authentication information is distributed to four APs (i.e., AP_0, AP_4, AP_7, and AP_8) in advance. If the MH moves to one of the selected APs, no authentication procedure to the authentication server is needed. However, if the MH moves to another AP (e.g., AP_2 in Fig. 5b), which was not involved in the predictive authentication operation, new authentication and reassociation procedures have to be performed. In addition, after performing handoff to AP_2, a new FHR consisting of AP_1, AP_2, AP_3, and AP_5 has to be constructed.

Instead of using the centralized system, a proactive scheme based on a distributed cache structure was introduced in [25]. This scheme is called the proactive neighbor caching (PNC) scheme. The PNC scheme uses a neighbor graph, which dynamically captures the mobility topology of a wireless network for the purpose of prepositioning an MH's context. The PNC scheme ensures that the MH's context is always dispatched one-hop ahead, and therefore the handoff delay can be substantially reduced. Here, the context includes informa-



■ **Figure 4.** *SyncScan operation.*

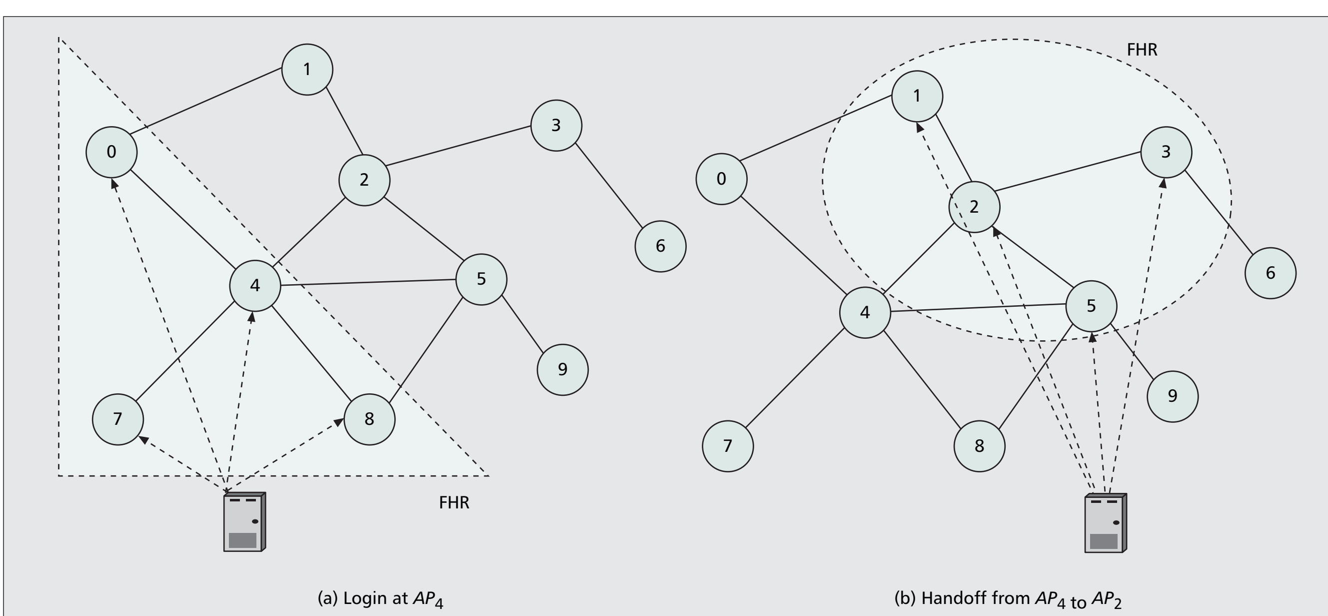
tion regarding the MH's session, quality of service (QoS), and security [26]. The neighbor graph is constructed using the information exchanged during the MH's handoff, and it is maintained at each AP in a distributed manner. The propagated MH's context is stored in the cache. The cached MH's context may be replaced by a cache replacement policy (e.g., least recently used (LRU) scheme) if there is no remaining capacity in the cache. Recently, the PNC scheme has been included in the IAPP specification [9], which is a standard protocol for communications between APs.

The operation of the PNC scheme is illustrated in Fig. 6. When an MH logs in to AP_4, this AP propagates the MH's context to all neighboring APs (i.e., AP_0, AP_2, AP_5, AP_7, and AP_8). When the MH moves to AP_2, no further authentication procedure is performed because AP_2 has already received the MH's context. At the same time, the MH's contexts are removed from the other nonneighboring APs (i.e., AP_0, AP_7, and AP_8).

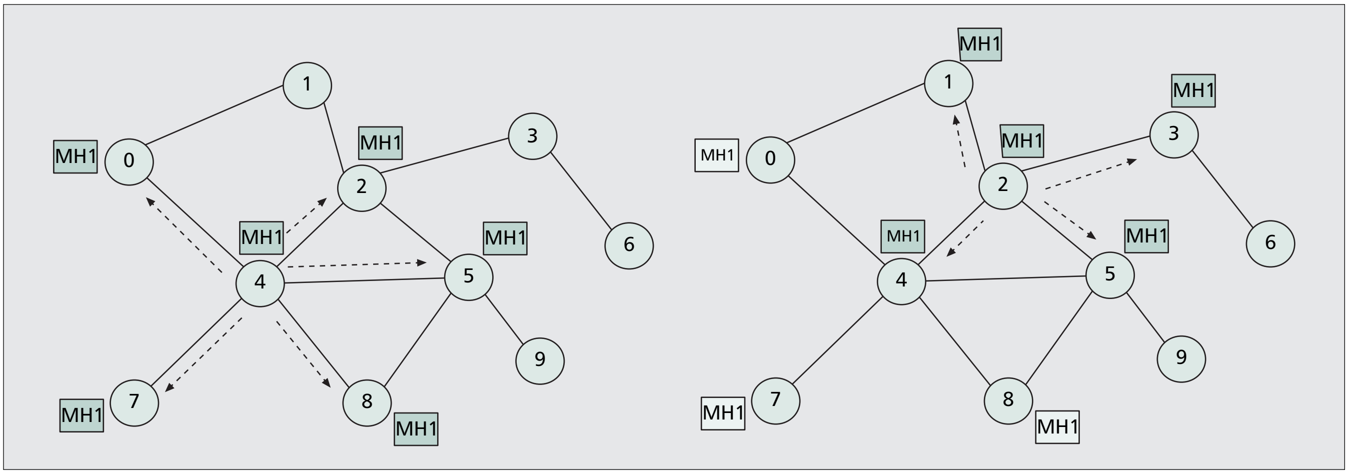
In the PNC scheme, an MH's context is propagated to all neighboring APs whenever a new (re)association is created. Therefore, the PNC scheme may result in high signaling overhead, especially when there are a large number of MHs in IEEE 802.11 wireless networks. Furthermore, previous measurement studies [4, 5] indicate that even in the case where a number of APs are deployed, a maximum of two or three APs are the main target points of the handoffs. Therefore, propagating the MH's context to a subset of neighboring APs may be sufficient to provide seamless mobility. To reduce the signaling overhead caused by context transfer, an enhanced neighbor caching scheme called the selective neighbor caching (SNC) scheme was proposed in [27]. The SNC scheme enhances the PNC scheme by adding a new concept of *neighbor weight*. The neighbor weight represents the handoff probability for each neighboring AP. Based on the neighbor weight, the MH's context is propagated only to the selected neighboring APs (i.e., those neighboring APs whose neighbor weights are equal to or higher than a predefined threshold). The neighbor graph and its neighbor weights can be easily constructed by monitoring the handoff patterns among the APs.

When we compare Fig. 7 with Fig. 6, the SNC scheme involves less context transfer operations. For example, when the MH is associated with AP_4, only three neighbor APs (i.e., AP_2, AP_5, and AP_8) receive the MH's context. If the MH hands off to one of the selected neighboring APs, the SNC scheme shows the same reduced delay as the PNC scheme, whereas the SNC scheme requires longer authentication/reassociation delay if the MH moves to a nonselected neighboring APs. The SNC can provide similar handoff performance if the threshold value is carefully selected. In addition, if the cache at the AP is limited, the SNC scheme is more preferable than the PNC scheme.

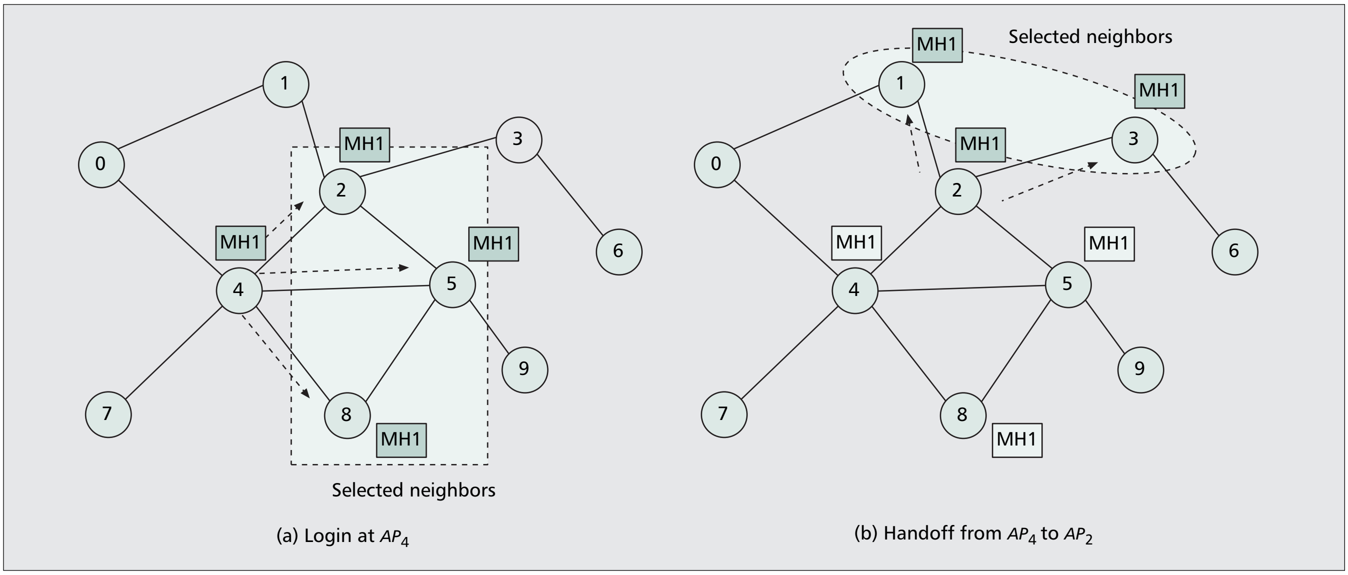
Putting It All Together: Qualitative Analysis



■ **Figure 5.** *FHR scheme.*



■ **Figure 6.** *PNC scheme.*



■ **Figure 7.** *SNC scheme.*

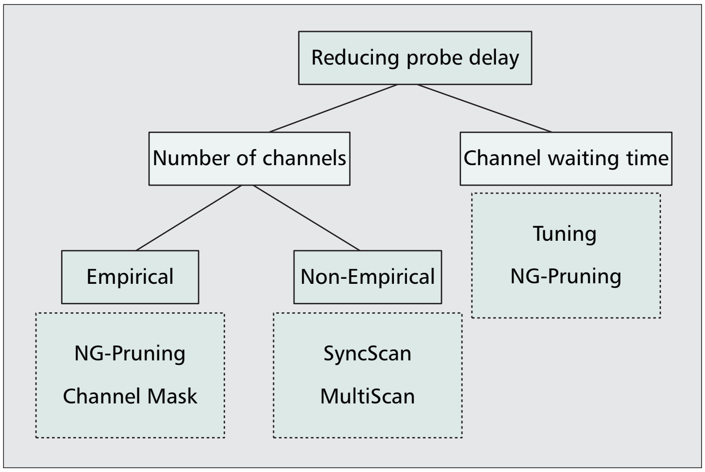
As mentioned above, reducing the probe delay is the most important requirement to achieve fast handoff in IEEE 802.11 networks. Figure 8 shows the classification for schemes to reduce the probe delay. Two different approaches are available for reducing the probe delay: limiting the number of channels to be probed and reducing the waiting time for each channel to be probed.

The tuning scheme is based on the latter approach. Specifically, the tuning scheme attempts to find more appropriate *MaxChannelTime* and *MinChannelTime* values to reduce the channel probing delay. The NOG in the NG-pruning scheme allows the channel waiting time to be reduced because the MH does not need to wait for further probe responses once it receives some probe responses from available APs. The channel mask scheme and the NG-pruning scheme limit the number of channels to be probed by introducing the channel mask/cache and the NG, respectively. These two schemes utilize empirical handoff information to construct the cache and the NG. SyncScan and MultiScan also reduce the number of channels to be probed; however, they are not dependent on the empirical handoff information. Instead, SyncScan and MultiScan collect information on nearby APs through continuous monitoring.

When IEEE 802.11 WLANs are deployed in public areas, secure and robust authentications become critical issues. However, more secure authentication schemes will incur longer authentication/reassociation delay. Hence, reducing the authentication/reassociation delay is as important as reducing the probe delay in such an environment. For the schemes reducing the authentication/reassociation delay, how to propagate the MH context is a criterion for classification.

The FHR and PNC schemes are based on a similar concept, that is, proactive propagation of the MH's context to the selected APs. However, these two schemes realize this concept in different manners. In the FHR scheme, the central system constructs the frequent handoff region by considering the mobility history and profile of the MHs. On the contrary, in the PNC scheme, each AP learns the mobility patterns of the MHs and configures the neighbor graph in a distributed manner. The SNC scheme is an extended version of the PNC scheme where only a subset of the neighbor APs keeps the MH's context.

Table 2 shows a comparison of schemes for reducing the probe delay in terms of compatibility, necessity of changes (AP side or MH side), implementation complexity, and signaling overhead. The tuning scheme requires only MH side modification and it does not lead to an incompatibility issue. Even though the tuning scheme can be easily implemented with low signaling overhead, how to select appropriate tuning values should be addressed more comprehensively. To support the



■ **Figure 8.** *Classification: reducing probe delay.*

NG-pruning scheme, both AP and MH should be modified even though a part of the NG-pruning scheme is the IEEE standard. The main drawback of the NG-pruning scheme is its high complexity and signaling overhead for NG and NOG maintenance. Hence, the implementation overhead and signaling overhead should be lessened to make this scheme more feasible. The channel-mask scheme is less complex than the NG-pruning scheme and it can operate in the existing IEEE 802.11 wireless networks. However, the caching and selection procedures are heuristic and therefore more refined algorithms should be exploited. SyncScan requires slight modifications to the AP to avoid packet loss due to periodical synchronization with APs, whereas MultiScan works well in the current IEEE 802.11 wireless networks. Both SyncScan and MultiScan are based on the passive scan mode, so that their signaling overheads are not high. Even though SyncScan can improve the handoff performance, it may result in packet reception latency due to probings on nearby APs. Therefore, more investigations on the parameter selection and performance in realistic environments are required. MultiScan removes the concerns in SyncScan, but it incurs high cost for multiple radios. In addition, the reduced handoff delay can be achieved at the expense of increased energy consumption due to multiple radios.

Table 3 compares the schemes for reducing the authentication/reassociation delay under the same criteria. The FHR scheme requires only the AP side modification. However, it is based on the central system, which can be a single point of bottleneck. The PNC scheme is included in the IEEE standard (i.e., IEEE 802.11f), so that no compatibility problem occurs. In addition, since its operations are fully distributed, there is no single point of bottleneck. However, the neighbor information is built in an incremental manner and therefore its initial performance is not good. Also, high signaling traffic can be induced even for static MHs. By introducing the weight matrix at the AP, the SNC scheme can reduce signaling overhead of the PNC scheme, and the SNC scheme can be implemented based on the PNC scheme without significant changes in the standard. However, an additional data structure should be constructed and maintained, and the SNC scheme only probabilistically lowers the authentication/reassociation delay.

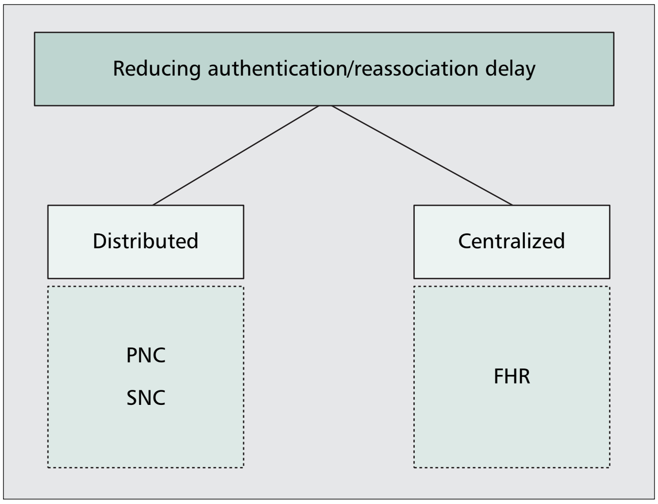
Perspective on Handoff Support in Future WLAN Systems

Even though a number of handoff schemes have been proposed for IEEE 802.11 wireless networks, seamless mobility support is still one of the most challenging issues. The handoff issue in IEEE 802.11 networks has been dealt with by the IEEE 802.11f working group. IEEE 802.11f defines an optional extension to IEEE 802.11 for AP communications among multi-vendor systems to support users' roaming and load balancing. Handoffs considered in the existing IEEE standards focus on only data traffic. Hence, the handoff delay is too long to support multimedia applications such as voice over IP. Recently, the IEEE 802.11r task group has been formed to develop a handoff solution at the IEEE 802.11 level. IEEE 802.11r specifies fast transition between BSSs, which allows seamless connectivity. However, IEEE 802.11r has not been standardized until now. On the other hand, the IEEE 802.21 working group is trying to develop standards to enable handoff and interoperability between heterogeneous network types, including both 802 and non-802 networks. In this section we first present important guidelines for handoff support in future WLAN systems, and then propose an adaptive fast-handoff framework.

Design Considerations

To support heterogeneous applications and users' demands, future mobility solutions in IEEE 802.11 WLANs need to meet the following requirements.

- **Interoperability/backward compatibility**: With the popularity of the WLAN technology, a lot of APs have been already installed and many users are using WLAN services based on the IEEE 802.11b standard. Furthermore, many improvements are being made to the current IEEE standard. Therefore, future handoff schemes should be compatible with the legacy WLAN systems and standard activities.
- **Adaptability**: In future WLAN systems, a variety of applications will be supported and the handoff delay bounds of these applications are likely to differ depending on their characteristics. For example, elastic applications (e.g., web browsing) do not require a strict handoff delay bound compared with real-time (RT) applications [28]. Hence, to meet the various applications' requirements, the handoff scheme should be designed in an adaptive manner.
- **Extensibility**: In next-generation wireless networks, integrating WLANs with other heterogeneous networks is a



■ **Figure 9.** *Classification: reducing authentication/reassociation delay.*

Consideration	Tuning	NG pruning	Channel Mask	SyncScan	MultiScan
Compatibility	Yes	Partially	Yes	Partially	Yes
Necessity of changes	MH	MH/AP	MH	MH/AP	MH
Complexity of implementation	Low	High	Moderate	High	Moderate
Singling overhead	Low	High	Low	Moderate	Moderate

■ Table 2. *Comparison: reducing probe delay.*

hot issue. For example, cellular-WLAN integration networks provide wider coverage and seamless mobile services [29]. In addition, WLAN-based wireless mesh networks are promising network architectures [30]. Therefore, a mobility solution needs to be extensible to these new types of integrated networks.

Adaptive Fast Handoff Framework: A Cross-Layer Approach

As mentioned above, a variety of applications will be supported in future WLAN systems and they have different handoff delay bounds. For instance, RT applications require a strict handoff delay, whereas elastic applications are more sensitive to throughput rather than handoff delay. If these applications' requirements can be utilized for handoff support in IEEE 802.11 wireless networks, more desirable handoff performance will be achieved. In the proposed adaptive fast-handoff framework, the handoff related parameters (e.g., the number of channels to be probed, *MinChannelTime*/*MaxChannelTime*, the number of APs to be authenticated in advance, and so on) are dynamically determined depending on the applications' requirements.

Figure 10 illustrates the adaptive fast-handoff framework in IEEE 802.11 wireless networks. Let N be the the number of channels available. C represents the ordered channel set, where c_1 is the channel with the highest priority and c_N is the channel with the lowest priority. The priority refers to the degree of the possibility that an MH uses the channel at the next time. C can be constructed by considering the typical channel assignment policy and/or by utilizing other schemes such as NG-pruning scheme [18] and SyncScan [19]. Since c_1 has the highest priority, probing c_1 is firstly performed. If the signal-to-noise ratio (SNR) of channel c_1 is less than a predefined threshold δ, the next channel c_2 is probed. If the SNR of c_1 is higher than δ, the test on the handoff delay requirement is triggered. Let T_R be the handoff delay requirement determined by the application. In addition, let T_P and T_E be the average probe delay for a channel and the total elapsed time from the handoff trigger epoch, respectively. If $T_R - T_E$ (i.e., the remaining time by the excess of the handoff delay requirement) is less than T_P, the additional probe may result in the violation of the handoff delay requirement. Therefore, the overall probe procedure is terminated. Otherwise, the probing process continues.

As a result of the probe procedure, the MH obtains a set of neighbor APs. Then the MH authenticates and reassociates to the AP with the highest SNR. In this step, proactive authentication based on mobility estimation is performed. In other words, if the estimated mobility is high, the context regarding authentication/reassociation is propagated to more neighbor APs; otherwise, only less neighbor APs receive the context. This procedure can be accomplished by employing the SNC scheme.

The adaptive fast-handoff scheme reduces both the number of channels to be probed and the channel waiting time depending on the application requirement. In terms of reducing the authentication/reassociation delay, the context propagation procedure is performed in a distributed manner. However, with the help of the central system, cost-effective context transfer considering the mobility and network topology can be accomplished. Therefore, the adaptive fast-handoff scheme can be considered as a hybrid approach.

The adaptive fast-handoff framework has the following advantages:

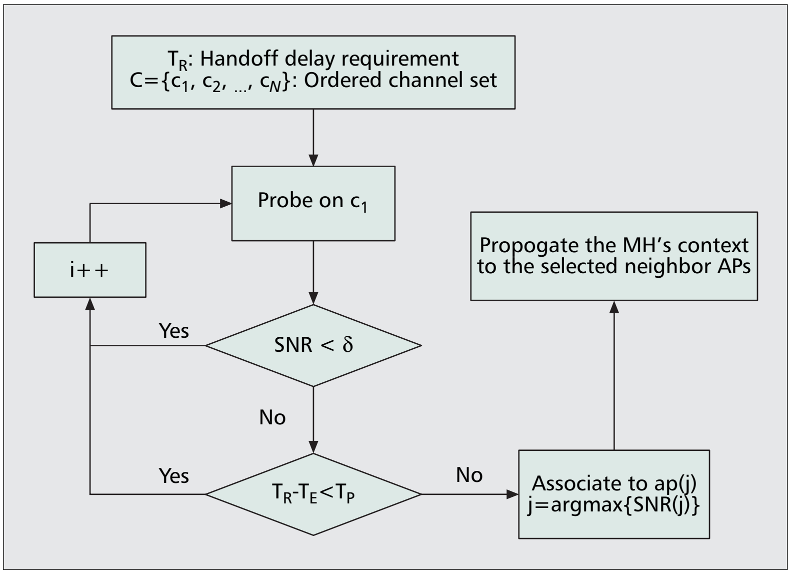
- It allows an MH to select the most appropriate AP with respect to its application. For RT applications, a tight delay requirement T_R can be adopted to minimize the handoff disruption time. On the other hand, elastic applications have loose delay requirements and therefore an AP with the highest SNR can be chosen through more channel probings
- In terms of authentication/reassociation delay, different numbers of APs are selected by considering mobility. Therefore, unnecessary context transfer can be minimized. In our future work, we will implement the prototype for the adaptive fast-handoff framework and conduct extensive performance studies.

Conclusion

In this article we have presented a survey of fast-handoff schemes in IEEE 802.11 wireless networks. We first classified different fast-handoff schemes into two classes, depending on their main goals in reducing the handoff delay. We also qualitatively analyzed their advantages and disadvantages. Since mobility support in IEEE 802.11 wireless networks is still a challenging issue, we suggested important guidelines that should be considered in emerging new fast-handoff schemes. Finally, an adaptive fast-handoff framework was introduced, which satisfies the given design considerations and therefore can be a reference model for designing new fast-handoff

Consideration	FHR	PNC	SNC
Compatibility	No	Yes	Partially
Necessity of changes	AP	AP	AP
Complexity of implementation	Low	Moderate	Moderate
Singling overhead	Low	High	Moderate

■ Table 3. *Comparison: reducing authentication/reassociation delay.*



■ **Figure 10.** *An adaptive handoff framework in IEEE 802.11 networks.*

schemes in IEEE 802.11 wireless networks. In our future work, we will develop a prototype for the adaptive fast-handoff framework in order to study its performance comprehensively.

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