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Research Article

An 802.11k Compliant Framework for Cooperative Handoff in Wireless Networks

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In IEEE 802.11-based wireless networks, the stations (STAs) are associated with the available access points (APs) and communicate through them. In traditional handoff schemes, the STAs get information about the active APs in their neighborhood by scanning the available channels and listening to transmitted beacons. This paper proposes an 802.11k compliant framework for cooperative handoff where the STAs are informed about the active APs by exchanging information with neighboring STAs. Besides, the APs share useful information that can be used by the STAs in a handoff process. In this way, we minimize the delay of the scanning procedure. We evaluate the performance of our mechanisms through OPNET simulations. We demonstrate that our scheme reduces the scanning delay up to 92%. Consequently, our system is more capable in meeting the needs of QoS-sensitive applications.

1. Introduction

The IEEE 802.11 [1] *wireless local area networks (WLANs)* were originally designed to give a solution to the significant problem of tangled cables of the end user devices. The stations (STAs) are wirelessly connected to the available access points (APs) and the APs are connected to a wired backbone network. The evolution of these networks include *mesh networks* where a wireless backbone is set up in order to support end-to-end wireless user communication [2].

No matter whether the backbone is wired or wireless, the STAs must somehow associate with an AP in order to get network connection. During the handoff procedure, a STA must scan all the available channels for a specific period of time in order to be aware of all the active APs in the neighborhood. Then, it must decide which AP is the optimal for the handoff following some optimization criteria and start a negotiation with this AP in order to become part of the network.

The described procedure introduces significant delays. Under the existing technology, the STA must spend enough time in each channel in order to be sure that it is aware of all the available APs that operate in the specific channel. Moreover, it must repeat this process for all available channels. The average scanning delay is 250–500 msec (depending on the 802.11 hardware that is used) [3]. These delays generate a significant problem in the association procedure. The situation is even worse if we consider that the same schemes are used in the handoff phase. Ideally, in a handoff scenario we would like the STA to move from one cell to the other seamlessly. It is obvious that this is impossible with the existing technology due to the delays we described earlier.

In this paper we propose a cooperative handoff framework that can be applied in both *WLANs* and *wireless mesh networks*, and speeds up the basic handoff procedure. The scheme is independent from the underlying association/handoff decision protocol that is used in the network. In this framework we utilize mechanisms for information sharing and radio measurement defined by 802.11k [4]. The STAs that initialize a handoff procedure take advantage of 802.11k-based mechanisms and cooperate with neighboring STAs/APs in order to exchange significant information. In this way we avoid sequential channel scanning and AP probing. The main outcome of our framework is that it eliminates the delays that are introduced in the system during the 802.11-based scanning/probe phases. Therefore, it efficiently supports seamless STAs handoff from one cell to another.

The rest of the paper is organized as follows. In Section 2 we present a brief background and the state of the art. Section 3 presents in detail our 802.11k compliant cooperative handoff framework. In Section 4, we describe the evaluation results of the proposed mechanisms. Finally, in Section 5 we conclude and we pave the way for our future research directions.

2. Background and Related Work

IEEE 802.11 defines association/handoff procedures based on *Received Signal Strength Report Indicator (RSSRI)* measurements. The unassociated STAs or the STAs that are trying to reassociate with a new AP, initialize a scanning process to find the available APs that are placed nearby. During this scanning process, the STAs sequentially switch to the available operational frequencies in order to probe the APs and receive their information. They measure the *RSSRI* values of each AP and associate with the AP that has the highest *RSSRI* value (the strongest received signal). The authentication process follows.

Several studies have proven that the *RSSRI*-based association/handoff mechanism can lead to poor network performance while the networks resources are not utilized efficiently [3, 5]. Therefore, the research community focuses on designing new association/handoff methodologies that will provide better resource utilization in the network. In our previous work [6] we have introduced new dynamic association and reassociation procedures that use the notion of the "*airtime cost*" in making association/handoff decisions. This metric reflects the uplink/downlink channel conditions and the traffic load in the network. The cross-layer extension of this mechanism takes into consideration the routing-based information from the mesh backbone. Consequently, the STAs are based on this information to optimize their association/handoff decision.

In [7], the authors study a new STA association policy that guarantees network-wide max-min fair bandwidth allocation in the network. The system presented in [5] ensures fairness and QoS provisioning in WLANs with multiple APs. The work in [8] proposes an improved client association and a fair resource sharing policy in 802.11 wireless networks. In [9], the authors propose an association scheme that takes into account the channel conditions (the channel information is implicitly provided by 802.11h [10] specifications). In [11] the problem of optimal user association to the available APs is formulated as a utility maximization problem. The work in [12] proposes a new mechanism where the traffic is split among the available APs in the network and the throughput is maximized by constructing a fluid model of user population that is multihomed by the available APs in the network.

The papers mentioned above study optimal STA association mechanisms in the network. On the other hand, a lot of attention has been given in reducing the delays introduced during the association/handoff procedure. The authors in [3] describe in detail the main factors that cause those delays.

(i) *Probe or scanning delay.* During the first step in the association/handoff procedure that is determined by 802.11 a STA have to scan for available APs: (a) passively, by listening to their beacon frames or (b) actively, by probing the APs. These are time consuming procedures since the STA must scan all the available channels (12 for 802.11a) in order to find active APs. Furthermore, the STA has to follow the beacon intervals for data synchronization reasons. Scanning delay constitutes a major portion of the handoff delay.

(ii) *Association/Handoff delay.* When a STA associates with an AP, it has to exchange *association frames* with this AP. Similarly, when a STA moves from an AP to a new AP, it has to exchange *reassociation frames* with the new AP.

(iii) *Authentication delay.* A STA has to exchange *authentication frames* in order to be authenticated by the new AP.

The following approaches attempt to reduce those delays and they are closely related to our work in this paper. The authors in [3] propose a technique to eliminate the probe phase delay of the association process. The work in [13] proposes a selective scanning algorithm and a caching mechanism in order to reduce the delay introduced by the scanning phase. Selective scanning uses a channel mask and therefore the STAs scan a small subset of the available channels (using this channel mask). In particular, when a STA scans APs, a new channel mask is built based on the current scanning status. In the next handoff, during the scanning process, this channel mask will be used. Consequently, only a well-selected subset of channels will be scanned. In [14], the authors formulate the association problem using neighbor and nonoverlap graphs. In [15], multiple radios are used in order to implement more effective/fast handoff mechanisms. Management frame synchronization is the basic part in the proposed mechanism presented in [16] while monitoring of the wireless communication links is the basic component of the proposed handoff mechanism in [17]. In [18], the authors present a proactive association scheme based on a distributed cache structure that speeds up the association procedure. Another approach that reduces the handoff delay is proposed in [19]. In this work the channel scanning is performed proactively and smart triggers reduce service disruption time in the system. The authors in [20] present a new mesh network architecture called SMesh. In this architecture they provide fast handoff procedures. In [21], the authors design client-driven handoff techniques that support vehicular mobility in multihop wireless mesh networks. In their work, they use channel quality measurements in the handoff decisions and they employ mechanisms to control handoff frequency. An interesting approach called Cooperative Roaming (CR) is proposed in [22]. This work is very relevant to our work,

	Element ID	Length	Measurement token	Measurement report mode	Measurement type	Measurement report
Octets:	1	1	1	1	1	Variable

Figure 1: Measurement report element.

while the authors introduce cooperation in order to perform layer 2 handoff, layer 3 handoff, and authentication. In their approach the STAs subscribe to multicast groups in order to spread useful information in the network. Our work focuses especially on mesh networking deployments, where a large number of clients must be supported and the provided QoS should be high. In these highly congested environments multicast communication is inefficient. Consequently, in our work we follow a different approach in which we utilize 802.11k measurement techniques that are adaptively applied in mesh deployments and can be applied in WLANs too. Finally, in [23] there is an interesting study of different fast handoff mechanisms.

Our work in this paper eliminates the delays in the first part of the handoff procedures (scanning and probing delays). It is worth mentioning that in our 802.11k compliant *client-based* framework the STAs "govern" the handoff procedures. This differentiates our work from other approaches in literature (like in [20]) where the APs are the responsible entities for the execution of the association/handoff procedures.

3. A Cooperative Handoff Framework

In this section, we present a 802.11k compliant framework for cooperative handoff. The main contribution of this scheme is the provisioning of fast handoff procedures that take full advantage of the cooperation between STAs and APs in the network. The underlying association/handoff decision protocol can utilize the capabilities of this framework and improve its performance. The proposed framework focuses on wireless mesh networks where the APs communicate through a wireless backbone network, but it can be applied in multicell wireless networks (WLANs) where the inter-APs communication can be supported through their wired connections.

3.1. IEEE 802.11k Framework. *IEEE 802.11k* [4] is a *Radio Resource Management* standard that provides measurement information for APs and STAs in the network. In particular, 802.11k determines *Radio Measurement* mechanisms that enable STAs/APs to observe and gather data about the radio link performance and the radio environment. There are special *Radio Measurement* periods where the STAs/APs execute these procedures in order to get informed about the communication conditions in their neighborhood. During those *Radio Measurement* periods the STAs/APs switch to a control channel in order to communicate and share information. Our cooperative framework exploits the capabilities of the 802.11k-based mechanisms and provides efficient handoff procedures. In what follows, we describe two mechanisms that are utilized in our framework.

(i) *Beacon report.* A STA can receive a *beacon report* from the neighboring STAs in order to be aware of the communication conditions in its neighborhood. The STA can operate in an active way and broadcast a *beacon request* to the neighboring STAs. Afterwards the STA waits for a specific period (measurement period) in order to receive *beacons* from the neighboring STAs. In addition, a STA can operate in a passive way by listening to *beacons* that neighboring STAs send during the measurement periods. *Beacon* in its pure form carries information about the operating APs in the neighborhood, their communication channels, BSSID, and so forth. We must mention that 802.11k specifies measurement periods but it does not define the way to adjust their duration and how frequent they are initiated. Figure 1 depicts the general format of the *measurement report* defined in *802.11k* standard [4], which contains the *beacon report* (inside the Measurement Report field). *Beacon report* is depicted in Figure 2. More information about the details of the fields that are present in the *beacon report* can be obtained in [4].

(ii) *Neighbor report.* In this request/response mechanism a STA/AP can request information about the neighboring APs. *Neighbor report* supports communication and information exchange between APs in the network (this is not supported in *beacon report*). According to 802.11k a STA/AP can initiate a *neighbor report* process and send a *neighbor request* to the neighboring APs. The APs that "hear" this request react by sending a *neighbor report* that contains information stored in their Management Information Base (MIB). In addition, the APs can behave in a passive way during a *neighbor report* process. In other words during the measurement period all the APs in the network broadcast *neighbor reports* that contain information stored in their MIB. Therefore, an AP can "hear" the reports of its neighboring APs without initiating a request/response procedure. Figure 3 depicts the neighbor report element as defined in 802.11k [4].

3.2. Proposed Framework. In our framework we support information sharing between the STAs and the APs in the network, based on the aforementioned mechanisms that are defined in 802.11k. The first component in our framework is the ad-hoc cooperative procedure that STAs use in order

	Regulatory class	Channel number	Actual measurement start time	Measurement duration	Reported frame information
Octets:	1	1	8	2	1

	RCPI	RSNI	BSSID	Antenna ID	Parent TSF	Optional sub-elements
Octets:	1	1	6	1	4	Variable

Figure 2: Beacon report.

	Element ID	Length	BSSID	BSSID information	Regulatory class	Channel number	PHY type	Optional sub-element
Octets:	1	1	6	4	1	1	1	Variable

Figure 3: Neighbor report element.

to share information with their neighboring STAs. The second component is the cooperation between the APs in the network, where inter-AP communication is supported and the APs share information with their neighbors. The previous two procedures are totally independent and they are executed during the periodic measurement periods. Therefore, at the end of each measurement period the STAs and the APs are aware of the operational conditions of their neighboring STAs/APs. In case that a STA is searching for a new AP, it initiates a cooperative handoff procedure where the information that has been obtained during the last measurement periods is used.

The flow diagrams in Figure 4 depict the main steps of the information sharing procedures. We now give more details about the ad-hoc cooperative information sharing depicted in Figure 4(a) and the cooperation between the APs depicted in Figure 4(b).

3.2.1. Ad-hoc Cooperative Information Sharing

Step 1. STA switches to the control channel and "hears" the *beacons* that the neighboring STAs send during the measurement period. The STAs choose a random interval and broadcast a *beacon* when this interval expires. *Beacon* collisions are avoided by using this random interval mechanism. The length of the measurement period depends on the number of the STAs that are present in the network. During this measurement period a STA must acquire a uniform distribution of received *beacons* and minimize the collisions. The mechanism that defines the optimal measurement period is out of the scope of his paper.

Step 2. STA receives the *beacons* that the neighboring STAs send (during one measurement period). We divide the handoff related information that the *beacons* carry into two categories: (a) "objective" information: MAC address of the APs, their operational frequencies, and so forth, and (b) "subjective" information: communication load of the APs, channel conditions, error rate, transmission rate, and so forth. We call this information as "subjective" because each STA in the network experiences its own communication conditions and therefore it can provide a "subjective" view of the network in its proximity. We must mention here that the aforementioned information is stored into the basic fields of the *beacon* frame, depicted in Figure 2. Additionally, several fields can be appended in the *Optional Subelements* super field. In this way the *beacon* frame can be extended in order to carry extra information about the operational environment.

Step 3. For each received *beacon*, the STA checks the accuracy of the "subjective" information that is carried.

Step 4. STA stores only the "accurate information", in the way accuracy is defined in the following discussion.

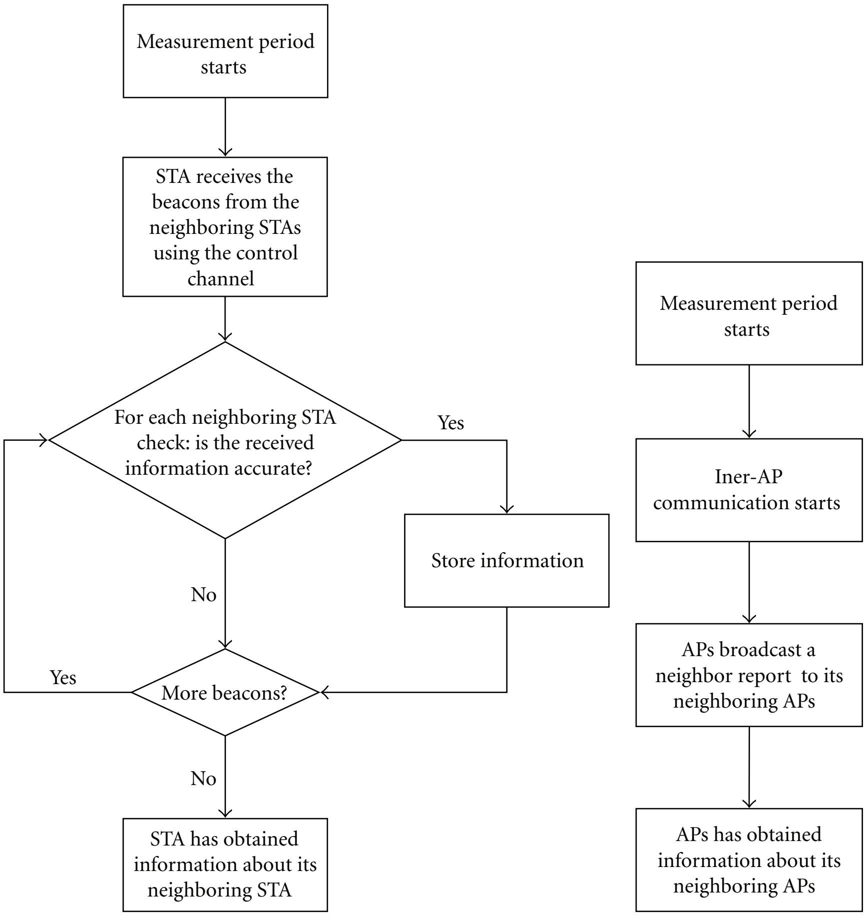
3.2.2. Cooperative Information Sharing between the APs

Step 1. APs choose a random interval and broadcast a *neighbor report* when this interval expires. *Neighbor report* collisions are avoided by using the random interval mechanism. The measurement period should be adjusted based on the number of the APs that are present in the system, in order to eliminate the collisions.

Step 2. APs passively "hear" the *neighbor reports* that the neighboring APs send. The *neighbor reports* carry "objective" information in its information fields (Figure 3).

Step 3. APs store the received information in order to be able to respond to a possible information request by a STA.

3.2.3. Accuracy of the "Subjective" Information. We claim that the "subjective" information that is carried in the beacon frames is accurate and therefore can be used by the STA that initiated the cooperative handoff procedure when the neighboring STAs are nearby. In other words, we support that "subjective" information can be fully adopted in case that the STAs are close to each other and therefore share



(a) Ad-hoc cooperative information sharing

(b) Cooperation between the APs

Figure 4: Cooperative information sharing during the measurement periods.

similar communication conditions with each of the available APs. An easy way to estimate the location/distance of the neighboring STAs is to measure the *Received Signal Strength Indicator (RSSI)* value of the transmitted signal. In order to estimate the distance from the *RSSI* value we use free space propagation model (line of sight) for simplicity reasons. In indoor environments this model is not precise but is still capable to approximate the STAs location. In free space propagation the *RSSI* is determined as

$$P_r(d) = P_0 - 20\log_{10}\left(\frac{4\pi d}{l}\right)\,\text{dBm}, \quad (1)$$

where $P_0 = 30\,\text{dBm}$ (theoretically the maximum transmission power in 802.11), and $l = (3 * 10^8\,\text{m/s})/2.4\,\text{GHz}$. Figure 5 depicts the relationship between *RSSI* and the distance of the STA that transmits the measured signal. In order to measure the information accuracy, we determine an *RSSI* threshold T_{RSSI}. Besides, we can deal with the *RSSI* fluctuations that occur in real-time deployments, by measuring the mean *RSSI* value of the signal transmitted by a STA (we use a short window to calculate the mean *RSSI* value). We assume here that the STAs/APs use the same transmission power and there is no power control in the system (pure 802.11 operation). This assumption arises since we use a constant threshold T_{RSSI} in our system. However, this is not necessary because we can include the transmission power into the transmitted packet and therefore the threshold T_{RSSI} can be adapted accordingly. Furthermore, we claim that the received information is accurate in case that the mean *RSSI* value of the transmitted signal is higher than the predefined T_{RSSI}. In particular, *RSSI* helps us estimating how far the STAs/APs that transmit are and T_{RSSI} gives us the ability to receive accurate information from the STAs/APs that are close (and therefore it is possible that they face the same channel conditions). In our experiments (simulation environment) we have seen that the higher T_{RSSI} values we obtain, the more accurate this information is. T_{RSSI} depends on the conditions of each system. Therefore, the system manager must adjust the threshold value according to the operational conditions (indoor or outdoor environment).

We must mention here that it is difficult to predict the radio propagation especially in indoor environments, due to propagation effects (scattering, diffraction, reflection, etc.) and the variability of the environment [24]. Consequently, the accuracy of the *RSSI*-based distance estimation may vary in these environments. In our framework we have

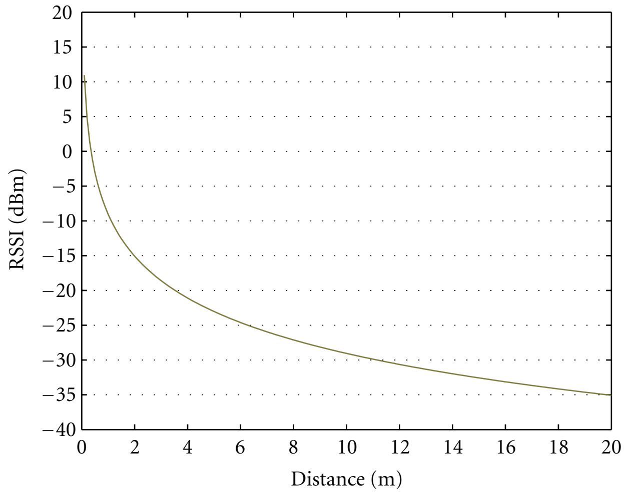


Figure 5: RSSI versus distance (free propagation).

used the simple approach based on the received signal, in order to provide a baseline of the framework. Since we do not focus on the way we will choose the criteria for the approximation of the nodes "locality", the simple algorithm of using *RSSI* provide a lightweight system solution. Handoff is a time-critical procedure and therefore, it must be executed seamlessly and avoiding the effects of additional delays. The accuracy of the *RSSI*-based distance estimator can be improved in case that we use more sophisticated techniques [25, 26].

The communication between the APs is totally "orthogonal" to the communication between the STAs. In particular, in multicell WLANs the APs communicate through their wired connections and in wireless mesh networks the APs use the wireless backhaul to communicate. Especially in wireless mesh networks the APs can be equipped with a second interface for the backhaul communication (based on the network architecture) or use separate channels. Therefore, we can claim that the cooperative information sharing between the APs is performed independently and in parallel with the ad-hoc cooperative information sharing during the measurement periods.

The main part of our framework is the cooperative handoff mechanism that uses the information obtained from the previous procedures and provides seamless handoffs in the network. The flow diagram in Figure 6 depicts the basic steps that are executed during a cooperative handoff procedure. We describe in detail the main steps of this mechanism.

3.2.4. Cooperative Handoff

Step 1. STA realizes that it must find a new AP (based on the underlying association/handoff decision protocol) and initiates a handoff procedure. So, it sends a *neighbor report request* to the AP (old AP) that is currently associated with. The *neighbor report request* can be imported to the *probe request* frame that the STA sends in order to probe an AP and receive useful information (in 802.11-based scanning procedure).

Step 2. Old AP sends back a *merged neighbor report* to the STA. The *merged neighbor report* contains information about its neighboring APs, which has been obtained during the last measurement period. In particular, the *merged neighbor report* use several information fields that are part of the *Optional Subelements* super field (Figure 3) and carry information for each neighboring AP. The *merged neighbor report* can be incorporated into the *probe response* frame that the AP sends back to the STA during the 802.11-based scanning process. *Neighbor report* contains similar information to *beacon report*. The main difference here is that the *neighbor report* contains additional information about "objective" characteristics of the new APs (that the STA receives through the old AP).

Step 3. STA comes up with a handoff decision based on the underlying association/handoff decision protocol that is applied in the network using (a) the information obtained during the Step 2, and (b) the information for the neighboring APs that the STA has obtained through the ad-hoc cooperative information sharing procedure, that was executed during the last measurement period. We must make clear here that in our framework every STA that initiates a handoff procedure uses both types of information (a) and (b) to come up with a handoff decision.

An important observation here is that our cooperative handoff mechanism gathers handoff information during a *probe request* (the *neighbor report request* is incorporated into the *probe request*) and a *probe response* (the *merged neighbor report* is incorporated into the *probe response*) exchange between the STA and the AP. The traditional 802.11-based scanning process wastes approximately the same time in scanning just one channel, since each STA must keep listening to a channel for a constant time in order to hear all the beacons that are transmitted by the neighboring APs and then scan the next channel. Therefore, our mechanism is much faster in gathering the information that the STAs need and the added overhead is quite small (less than an 802.11-based one-channel scanning). In addition, the communication between the APs can be independently executed (during the measurement periods) from a handoff procedure. In this way the information from the neighboring APs (to the old AP) will be immediately available to the STA, when a cooperative handoff procedure is executed.

The ad-hoc cooperative information sharing plays an important role in our framework since there are situations where the old AP cannot be aware of the operational conditions of all the candidate APs for association. In a mesh environment the APs communicate over a wireless backhaul network and a candidate AP could be placed out of the transmission range of the old AP. Besides, in multicell environments a candidate AP could lose connection with the old AP or it could belong to another subnetwork where the communication with the old AP is impossible. For example in Figure 7 we assume that STA3 is currently associated with AP1 and it

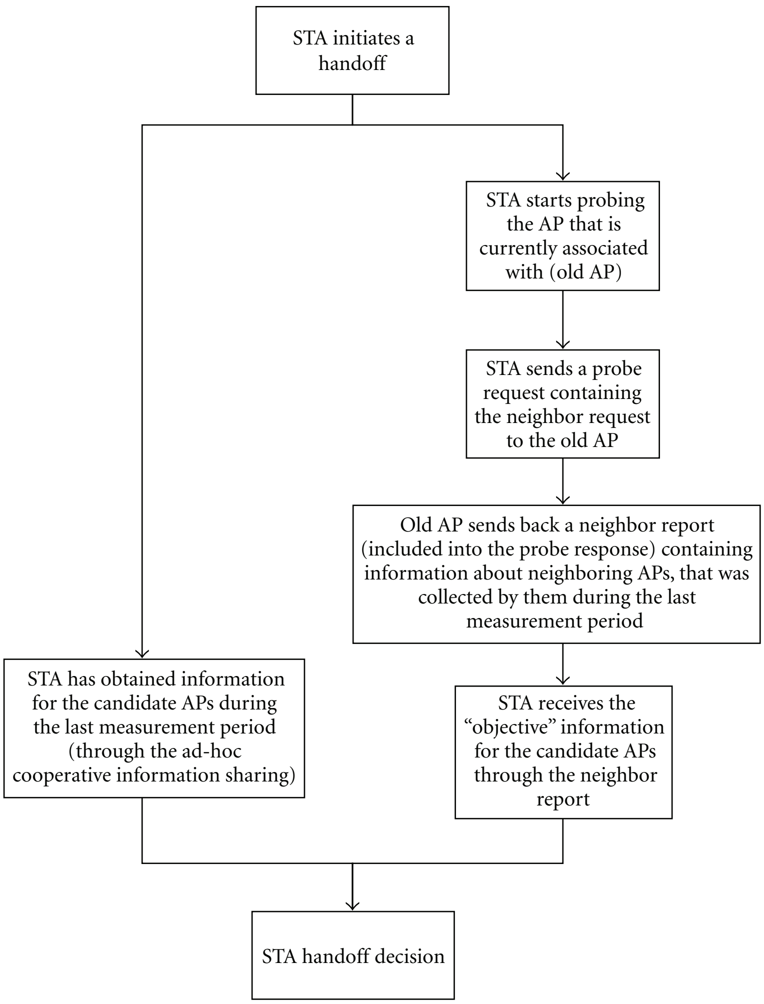


Figure 6: Cooperative handoff procedure.

initiates a handoff process. AP1 (old AP) cannot be aware of the operational conditions of AP2 (using the neighbor report mechanism) because AP2 is located out of the transmission range of AP1. In this case the STA3 receives this information from STA4 and STA5, through the ad-hoc cooperative procedures. Furthermore, we use ad-hoc cooperation in order to obtain "subjective" information (uplink channel conditions, etc.). This information cannot be obtained using inter-AP cooperation (neighbor report) because the APs are not aware of these operational parameters.

If the STA decides that the "subjective" information is accurate, then it has all the information it needs to proceed with the handoff decision. In the opposite situation, since the STA considers the "subjective" information as inaccurate, it has to find a way to figure out the channel conditions between itself and the active APs in the neighborhood. In the existing approach, the STA could start scanning the available channels and get measurements about the neighboring APs. In our scheme the STA is aware of the available APs and the channels they currently use, by exploiting the "objective" information it has obtained. Thus, instead of scanning all the available channels, it directly "jumps" to the active channels, saving in this way significant time and decreasing the scanning delay.

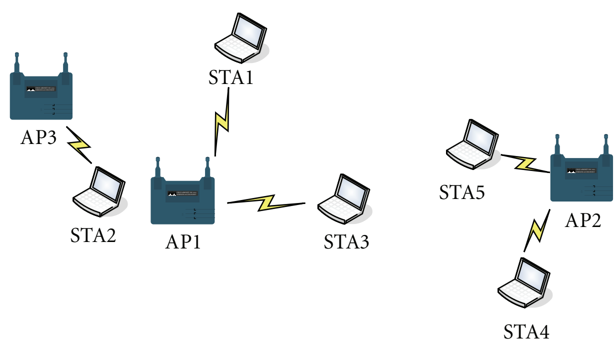


Figure 7: Special case: cooperative handoff.

Another issue that arises in our cooperative handoff framework is the possible greedy behavior of the STAs that share information about the active APs in the network. In other words, one or more STAs can misbehave in the system and send fake information to their neighboring STAs. In this

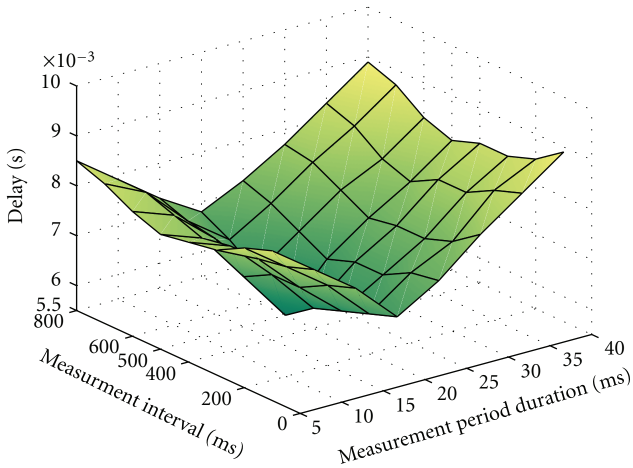


Figure 8: Optimal interval values for the measurement periods (STAs and APs follow these intervals).

way our cooperative handoff framework does not perform effectively since it does not have the correct information. Our scheme assumes that a trusted information exchange has been established in the network. The issue of the trustworthy among the stations is out of the scope of this paper and it can be achieved using authentication techniques.

Before ending this section we must note that in our cooperative framework we use a separate control channel for information exchange. An interesting approach would be to equip the STAs with a second communication interface for information exchange. In other words, we could keep the first interface for data communication and the second for channel scanning and control information sharing. This approach would gain in performance since we would avoid control channel switching delays. However, this is not a realistic scenario while most end user devices are not equipped today with a second interface (cost reasons, etc.). This is the main reason that leads us to choose control channel communication in our framework. Nevertheless, this could be an additional option in our framework.

4. System Evaluation

We have implemented our cooperative handoff framework using OPNET [27]. Our mechanisms were built on top of the IEEE 802.11 standard in order to achieve backward compatibility. We have modified the main control frames (beacon, probe frames) in order to simulate the basic measurement mechanisms that are introduced by 802.11k and incorporate the appropriate information in them. The light modifications that we have introduced in the basic functionality of the IEEE 802.11 standard do not affect the performance of the network. In our simulation study we compare our framework to the scheme proposed in [13] and to 802.11. The work in [13] proposes a selective scanning algorithm and a caching mechanism in order to reduce the delay introduced by the scanning phase.

As far as the overhead and the communication cost are concerned, it is true that our cooperative mechanisms introduce an overhead in the performance of the network since now the STAs/APs have to switch to the control channel (in a periodic basis) in order to gather handoff information from the neighbors. Besides, several control frames must be transmitted during the periodic 802.11k-based measurement periods in the network. However, our framework does not introduce higher overheads and communication costs as compared to 802.11k. As we have mentioned, our scheme is built on top of the main mechanisms determined by the 802.11k standard and it is fully compliant with it. More information about the performance of the 802.11k standard can be obtained in [28]. Our simulation study takes into account the communication costs and the extra delays that are present in our framework, during the execution of our mechanisms. The simulation results declare that our cooperative handoff framework gains in performance as compared to other schemes. The main reason for this improvement is that in our framework we avoid unavailing channel scanning. Besides, the information sharing that is introduced between the STAs/APs during the measurement periods provide seamless handoffs in the network, avoiding in this way large delays and traffic interruptions. In more detail, the overhead that our mechanisms add is approximately similar to the overhead added by the one channel scanning procedure which is significantly smaller than the original overhead (in 802.11-based handoff procedure), which is equal to this time multiplied by the number of the channels that are scanned (more details will be given later in this section). Therefore, the main outcome of this work is that the number of the scanned channels is significantly reduced (compared to 802.11 channel scanning).

As described before, 802.11k introduces mechanisms for information exchange during a period called measurement period. In our scheme STAs use these mechanisms in order to collect information related to the available APs in their neighborhood. The duration of the measurement period as well as how frequent the period is initiated is not defined by the standard. In order to study how the measurement period affects the performance of our mechanism and the overhead that is introduced, we run several experiments on a multicell wireless network of 5 partially overlapped cells and 65 STAs (we give more details about the simulation environment in the following subsection). Figure 8 depicts the average transmission delay (average delay of all transmissions in the system) in the system as the measurement period (x axis) and the measurement intervals (y axis) change. As we can see in this figure the more often the measurements are taken place, the more accurate is the information that is exchanged. However, the overhead increases due to frequent information exchange in the network and the average transmission delay is getting higher. The average transmission delay is increased too, when the frequency of the measurements is increased (measurement interval). Our system is not able to obtain "up to date" information during a cooperative handoff procedure and therefore the performance of the handoff mechanism decreases. Additionally, large measurement periods increase significantly the overhead too. On the other hand, when

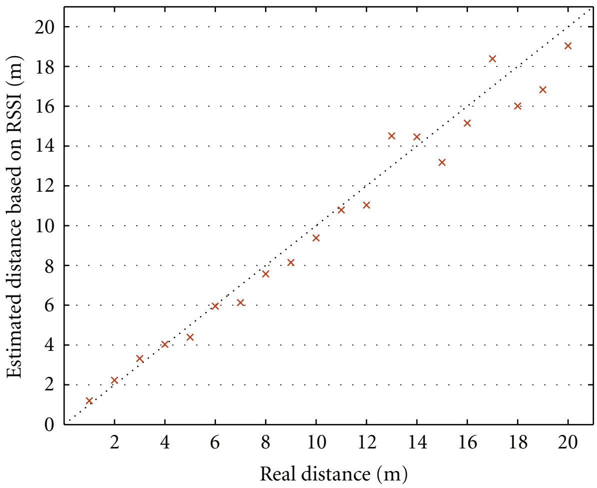


Figure 9: RSSI based distance estimation accuracy.

we use very small measurement periods, our mechanism does not "have the time" to take into account the "up to date" information that is carried in the control frames. Consequently, the average transmission delay increases. In Figure 8 we can observe that the optimal system operation (minimum transmission delay) is achieved when the measurement period lasts for 20 ms and it is initiated every 500 ms (we use these values in our simulation study). We must mention here that the aforementioned values resulted from our simulation study. The duration of the measurement period and its periodicity is a system designer decision. Therefore, the system designer must adapt the measurement period to the properties of the system.

Figure 9 depicts the accuracy of the RSSI based distance estimation used in our system. We observe that the estimated distance is close enough to the real distance of STAs/APs that transmit.

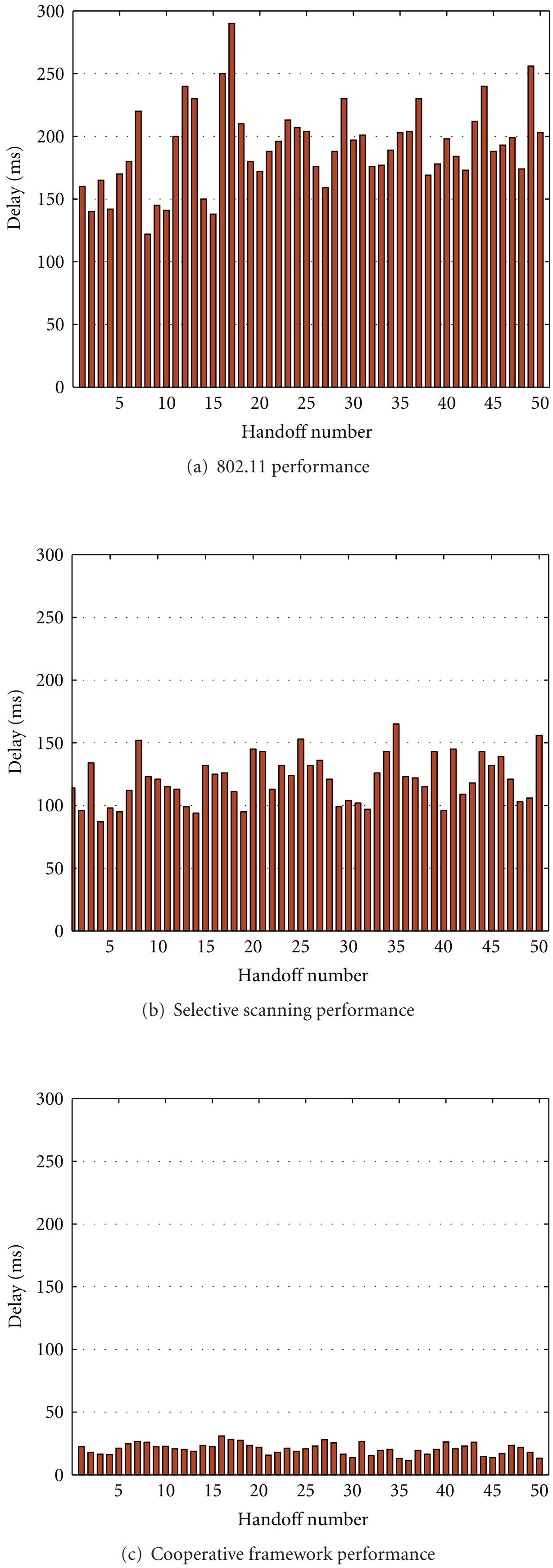
4.1. The Multicell Scenario. We first study a multicell 802.11g network that consists of five partially overlapping cells. In such simple topologies we can control the parameters of our system and therefore we can have a clear view of the performance of the proposed protocols. The STAs are uniformly distributed (at random) in the network and their data frames are transmitted at 1024 kbps (we consider CBR traffic). We vary the number of source/destination pairs in order to vary the overall load. The source and destination nodes are chosen randomly among the nodes in the network. We compare the performance of the basic 802.11-based handoff mechanism to the performance of our 802.11k compliant cooperative handoff framework as the communication interference changes during the network operation. In order to effectively evaluate the performance of our framework we consider two cases: (a) the communication load is represented by the number of STAs that are associated with an AP, and (b) the communication load is represented by the airtime metric introduced in our previous work [6] (the measured communication load in (a) and (b) is used as described in our cooperative procedures). In particular, the airtime cost of STA $i \in U_a$, where U_a is the set of STAs associated with AP a, is

$$C_a^i = \left[O_{ca} + O_p + \frac{B_t}{r^i}\right]\frac{1}{1 - e_{pt}^i}, \tag{2}$$

where O_{ca} is the channel access overhead, O_p is the protocol overhead and B_t is the number of bits in the test frame. Some representative values (in 802.11 g networks) for these constants are $O_{ca} = 335\,\mu$s, $O_p = 364\,\mu$s and $B_t = 8224$ bits. The input parameters r^i and e_{pt} are the bit rate in Mbs, and the frame error rate for the test frame size B_t, respectively. More information about this metric and the underlying association/handoff decision mechanism can be obtained in [6]. It is clear that in the second case we take into account channel quality information (error rate and transmission rate), which are qualitative measurements, contrary to the first case where we just take into account the number of the associated STAs.

In the first simulation scenario we support 65 STAs (uniformly distributed at random) in the multicell network. We measure the handoff delays in the system when our cooperative mechanism is applied in comparison to the selective scanning algorithm proposed in [13] and to 802.11. In particular, we measure the delay of each handoff that is present in our system (x axis represents the handoff number) and we calculate the average handoff delay values. In order to evaluate the performance of our mechanisms we consider both stationary STAs and mobile STAs. We use random waypoint mobility model, where the velocity is chosen randomly between 1 and 20 m/s. Figures 10(a), 10(b), and 10(c) depict the handoff delays during the pure 802.11-based handoff mechanism execution, the selective scanning algorithm application and our scheme. In this scenario the STAs are stationary. In order to vary the channel conditions we add interference generating *jammers* that are periodically active in our system. When *jammers* are active, they continuously transmit jamming packets that cause interference. In this way we force the stationary STAs to handoff to a new AP, where interference is limited. Selective scanning improves the performance of the 802.11-based handoff mechanism using a channel mask, scanning in this way a small subset of the available channels. It is clear that our system achieves lower handoff delays due to the fact that prehandoff information is obtained rapidly (without scanning). In Figures 11(a), 11(c) and 11(b) we observe the handoff delays in a network that supports random STA mobility. The outcome is similar to the previous experiment. The proposed framework achieve quite lower handoff delays. Table 1 compares the average handoff delays between 802.11, the selective scanning algorithm, and our cooperative framework. An important outcome is that our mechanisms improve the 802.11-based handoff delay by approximately 89% when we have stationary STAs and 92% when we support mobile STAs in our system. We allegate that this significant delay improvement will play an important role in the improvement of the end-to-end network performance. More details about this claim will be provided in the remaining section.

During our second simulation scenario the number of the associated STAs in the network increases from 5 to 65

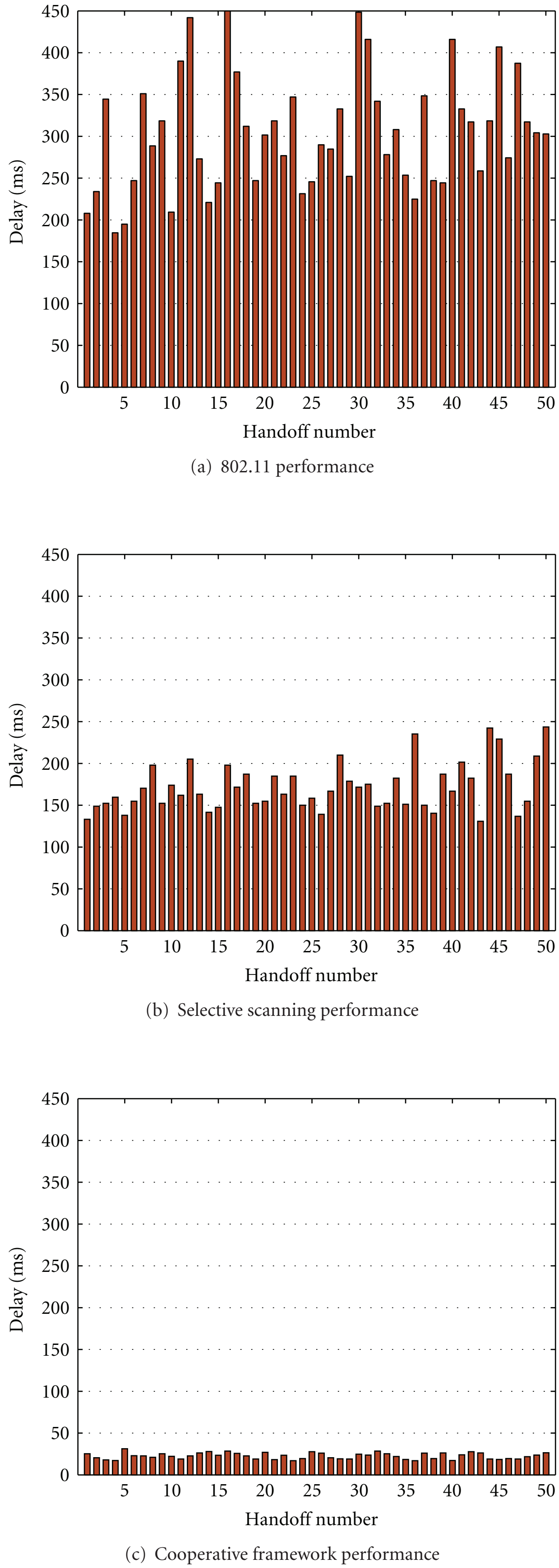


(a) 802.11 performance

(b) Selective scanning performance

(c) Cooperative framework performance

Figure 10: Handoff delays with stationary STAs.

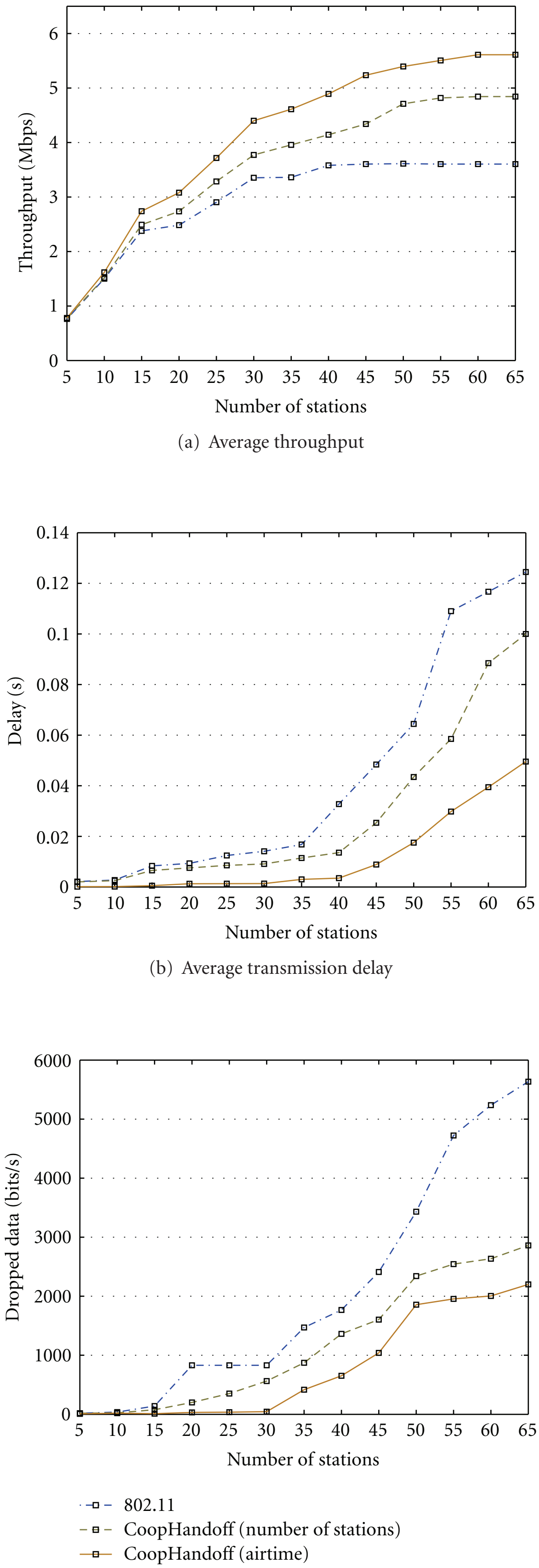


(a) 802.11 performance

(b) Selective scanning performance

(c) Cooperative framework performance

Figure 11: Handoff delays with mobile STAs.



(a) Average throughput

(b) Average transmission delay

(c) Average dropped data

Figure 12: Simulation results for the multicell scenario.

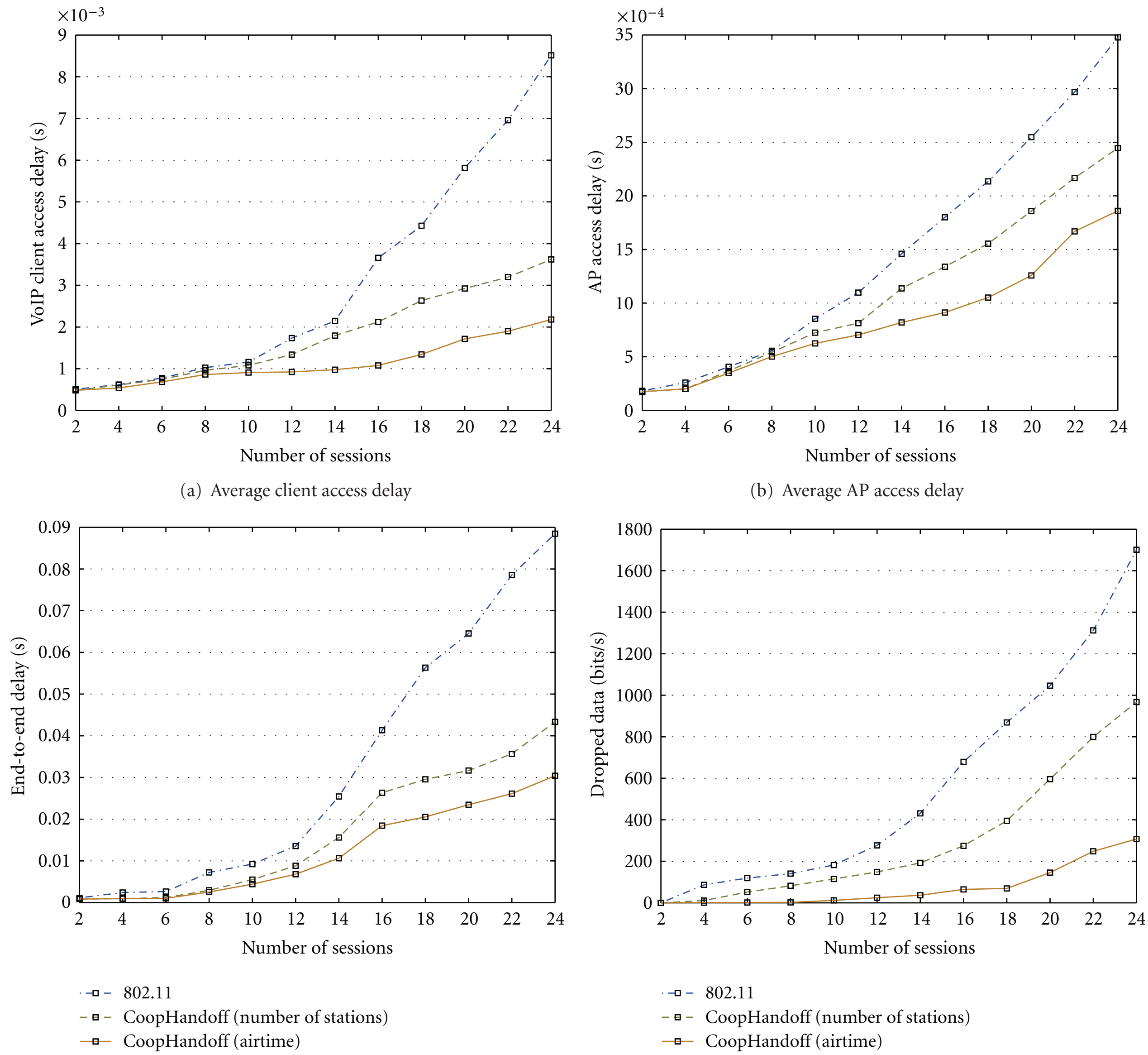
Table 1: Average Handoff delays.

	Stationary STAs	Mobile STAs
802.11	191 ms	303.39 ms
Selective scanning	120.96 ms	171.6 ms
CoopHandoff	20.73 ms	22.69 ms
Selective scanning improvement	36.67%	43.44%
CoopHandoff improvement	89.14%	92.52%

(STAs are uniformly placed in the network). We measure the network throughput, the average transmission delay, and the data dropping. These measurements are representative and reflect the system performance under different operational conditions. In order to effectively evaluate the performance of our cooperative framework we consider two cases. The underline association decision mechanisms use: (a) the number of STAs as the load metric and (b) the airtime cost as the load metric. In particular, the association decision mechanisms avoid overloaded APs using these metrics (where the number of the associated STAs is large in the first case, and in the second case where the cumulative airtime cost in the cell is high).

Figure 12(a) depicts the network throughput as the number of the associated STAs in the network increases. We compare the throughput values that are achieved during the execution of the basic 802.11-based handoff scheme and our cooperative framework. It is clear that the highest throughput values are achieved when we apply our cooperative handoff mechanisms since they speed up the handoff procedure. Airtime mechanism achieves the best performance because it takes into account channel quality information for both uplink and downlink communication and so it uses a more representative load metric than in the case we consider the number of STAs. In low load conditions, we observe a quite small throughput improvement when we use the proposed mechanisms. In high load conditions, throughput increase is higher. The maximum throughput improvement that is achieved by our cooperative handoff mechanism is approximately 55% (when we have 65 associated STAs). It is important to notice that the 802.11 network throughput is stabilized when we have 45 associated STAs in the network. This means that after this point the provided QoS in the network is getting worse as the number of the STAs in the network increases. On the other hand, our cooperative framework expands the network capabilities and maximizes the network throughput in presence of 65 associated STAs in the network.

In Figure 12(b) we observe the average transmission delay in the network. It is clear that in low load network operation, the average transmission delay of 802.11 is quite small and close to the average delay that is achieved by our cooperative mechanisms. When the number of the associated STAs increases over 35 the average delay of 802.11 is getting extremely high. In contrary, our cooperative mechanisms provide an additional performance improvement to the airtime mechanism and keep the transmission delay in low level. The 802.11-based handoff policy is quite static and



(a) Average client access delay
(b) Average AP access delay
(c) Average end-to-end delay
(d) Average dropped data

Figure 13: Average delays and dropped data in VoIP.

that causes some cells to be overloaded while the number of the associated STAs increases. Our approach provides fast dynamic reassociations/handoffs in order to keep a balanced network operation. The high 802.11 scanning delays are avoided as our cooperative mechanism “grants” the appropriate information to the STAs that are trying to reassociate with new APs.

Figure 12(c) depicts the amount of packets dropped due to channel errors and collisions in the communication. As we can see, our mechanisms achieve lower number of dropped packets. The sophisticated channel quality based association policies that are introduced by the airtime mechanism and our fast cooperative reassociation procedures provide a balanced network operation. STAs that face poor channel conditions and high number of dropped packets, perform fast handoffs in order to improve the network efficiency while the underling airtime association mechanism optimizes the STAs handoff decision.

4.2. The Mesh Network Scenario. In order to measure the end-to-end network performance, we study the application of the proposed mechanisms in an 802.11-based wireless mesh network. We simulated a wireless mesh network in the OPNET simulation environment. The wireless routers that are provided by the OPNET wireless module are part of the backhaul network. The peripheral routers serve as APs as well. In our simulation we use 6 peripheral routers (mesh APs) and 4 backhaul routers (mesh Points). We implemented RM-AODV that is introduced by 802.11s [29] standard and we applied this routing protocol at the mesh backhaul (we can apply any QoS-aware routing protocol at the mesh backhaul in order to evaluate our framework). The STAs are uniformly distributed (at random) in the wireless mesh network. For the communication between the wireless routers in the backhaul network, we use the physical model of IEEE 802.11a OFDM physical layer. The supported physical rate is 12 Mbps. The STAs are associated with the available peripheral APs. We simulated a VoIP application in the 802.11-based wireless mesh network, which is a QoS sensitive application. In our simulations we uniformly placed several VoIP clients in the network. We run different simulation scenarios where we varied the number of the VoIP sessions that are supported in parallel.

First of all we measured the average local client access delay in the network. In practice, this delay reflects the time that the packet is generated until it leaves the client interface. The number of the sessions that are supported in parallel increases from 2 to 24. Figure 13(a) depicts the average VoIP client access delay. Our cooperative mechanism (with the airtime metric) achieves lower client access delays in the network. Consequently, our cooperative framework provides fast handoff procedures and keeps the client access delay in low level. The traditional 802.11 operation overloads the network and therefore increases significantly the access delay of the clients. In high load conditions, the delay improvement that is introduced by our mechanism is very high.

Figure 13(b) depicts the average local AP access delay in the network. This delay is the time passed from the arrival of a VoIP packet at the AP until the moment that it is either successfully transmitted over the wireless mesh network or dropped. As we see we get similar results to those of the client access delay. In pure 802.11 the overloaded APs (in high load conditions) have a lot of traffic to forward to the mesh backhaul network. The main consequence is that the VoIP packets have to wait for a long time to be transmitted by the APs, introducing in this way high AP access delays.

In Figure 13(c) we observe the average end-to-end delay in the VoIP packet transmission. The end-to-end delay is affected by the previous two kinds of delays that we have described and the routing delay that is introduced in the backhaul network. In our cooperative framework we achieve low end-to-end delays in the network. Especially in the airtime mechanism operation the delay improvement is very high. This improvement is true due to the fast VoIP clients/APs access in the network and the fast handoff that is provided. We allegate that the most interesting result is depicted in Figure 13(c), where the pure 802.11 operation can support at most 14 sessions in parallel while our cooperative framework supports 24 sessions. Therefore, we have a network performance improvement of approximately 66%.

The last figure (Figure 13(d)) depicts the dropped packets during the operation of the mesh network. Channel errors and packet collisions are the main reasons for this packet dropping. In 802.11 the number of dropped packets is high. Our proposed mechanisms decrease this number and manage to keep it low even in high load conditions.

Concluding this section we summarize the key achievements of our cooperative framework that are highlighted in our evaluation study:

(i) adaptability of the measurement mechanisms defined in 802.11k

(ii) lower handoff delays, compared to 802.11 and to selective scanning approach

(iii) seamless mobility management in the network

(iv) efficient scalability and network performance in wireless multicell environments

(v) support of QoS-sensitive applications in dynamic wireless mesh environments.

5. Conclusions

In this paper we propose a new handoff framework that introduces cooperation between STAs/APs. Our cooperative framework is compliant to 802.11k and it utilizes information exchange and measurement mechanisms that are specified in the standard in order to eliminate the scanning/probe delays in the handoff process. The proposed mechanisms work independently of the underling association/handoff procedures and therefore they can be applied in combination to any association/handoff protocol. Besides, the proposed mechanisms in this framework can be applied to 802.11-based WLANs and wireless mesh networks. Our main contributions in the current research field are

(i) an 802.11k compliant cooperative handoff framework for wireless networks

(ii) two cooperative schemes that take full advantage of the mechanisms that 802.11k provides

(iii) extensive simulation experiments where we support QoS sensitive applications. We evaluate the performance of our framework by applying different underlying handoff decision protocols and we measure the performance improvement that is achieved.

Our future directions include the implementation of these mechanisms using Linux open source drivers and the evaluation of our system in real conditions.

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