An Inter-Access Point Coordination Protocol for Dynamic Channel Selection in IEEE802.11 Wireless LANs

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***Abstract*—This paper presents and evaluates an Inter-Access Point Coordination protocol for dynamic channel selection in IEEE 802.11 WLANs. It addresses an open issue for the implementation of many distributed and centralized dynamic channel selection policies proposed to mitigate interference problems in Wireless LANs (WLANs). The presented protocol provides services to a wide range of policies that require different levels of coordination among APs by enabling them to actively communicate and exchange information. An Intra-Cell protocol that enables interaction between the AP and its accommodated stations to handle channel switching within the same cell is also presented.**

I. Introduction

Over the last years wireless local area networks (WLANs)[1] WLANs have become the preferred technology of access in homes, offices, and hot-spot areas (like airports and meeting rooms). Although originally several solutions for WLANs have been competing, today virtually all WLANs are based on the IEEE 802.11 standard.

This has lead to the situation that more and more APs have been installed in relatively small geographical areas. Often one can observe that AP scanning generates a list of more than 20 APs in the same location. However, the number of available channels by any IEEE 802.11 standard is limited and among them only a few do not overlap. Therefore, coverage areas of APs are likely to "collide" at least partially, causing mutual co-channel interference. This current trend creates challenging problems for network planners, protocol and policy designers.

We believe that channel selection is one of the most efficient solutions to alleviate the impact of co-channel interference problems. Although frequency planning helps to reduce this kind of interference, it is not efficient enough due to the dynamic changes in the wireless environment and the stochastic characteristics of user traffic and users distributions. Thus, we believe that this allocation has to be done in a dynamic way. This calls for three aspects:

- Policies (centralized or distributed ones) that determine when to use which channel.
- Protocols that support the exchange of information between APs and the agreement on the next channel assignment (Inter-AP or Inter-Cell Protocols).
- Protocols that support a synchronous switch of the channel by all STAs within the cell (Intra-AP or Intra-Cell Coordination Protocols).

While a lot of research has been devoted to the first issue (policies), to the best of our knowledge a protocol that enables neighboring APs to actively talk to each other and agree on the operational channels in their cells does not exist yet. This paper proposes and discusses such a protocol. Thus, we discuss here a key requirement for autonomic network control. The proposed protocol supports different levels of coordination between WLAN APs. It enables them to exchange the relevant information required for channel selection policies that not only try to put neighboring APs on different channels but also benefit from information sharing to bring down the negative influence of channel switching on active users and effectively decide on new operational channels. We show by means of simulation that even a simple channel selection policy built on top of our protocol can significantly improve network performance and provide users better QoS in comparison to uncoordinated channel selection by APs.

The remainder of this paper is organized as follows: Section II presents a literature survey and discusses requirements for channel selection. We present our proposed Inter-Cell and Intra-Cell channel selection protocols in Section III. In Section IV, we evaluate the performance of the proposed protocols before we conclude our paper in Section V.

II. Aspects of Channel Selection

A. State of the Art

Generally, channel selection policies are either implemented as distributed and centralized schemes. With distributed ones each AP locally assesses the quality of its operational channel and decides individually by some criterion to move to a new channel found to be better than the current one. This criterion is often based on the local observation of the AP as well as the measurement reports received from its associated stations (STAs). The measurements and the exchange of reports between an AP and its STAs have been standardized in 802.11k [2]. An Intra-Cell protocol like IEEE 802.11h [3] can be used to announce the new channel to the cell's STAs.

Distributed policies often lead to suboptimal solutions. They can be found for example in [4], [5], [6], and [7]. In [4] APs share load information which is modeled as the number of associated stations. Each AP uses the shared load information and tries to maximize its local channel throughput for the different potential channels based on a cost function. In [5] each AP locally measures the interference level it experiences and tries to avoid selecting an interfering channel used in its neighborhood. The interference information as well as the new selected channel is broadcasted to neighboring APs. In [6] each AP locally estimates the number of active stations that use the channel in the neighborhood and selects the channel that is less overloaded by actively monitoring channel utilization. A rather simple algorithm has been proposed in [7] where each AP periodically assesses channel quality and hops to a new channel randomly selected based on past experience if the current channel quality is not acceptable. Mishra et al. [8] have shown that local monitoring of a channel by AP fails to capture all types of interference that can exist in a network as it does not involve station's feedback. Therefore, the authors have also incorporated the number of stations experiencing conflicts as a metric in a coloring-based decentralized approach. The recent paper of [9] presents a new distributed channel selection approach that achieves good fairness among APs.

On the other hand, with centralized channel selection schemes, a global control instance is employed. It is responsible for collecting status information from all WLAN APs, computing by some criterion new channel assignments and distributing this information afterwards to all APs. Centralized solutions can achieve the global optimum at the cost of higher computational requirements and a higher control overhead. For example, in [8] and [10], an extensive study of the channel assignment problem is presented, investigating the performance of a centralized algorithm. This algorithm requires stations to convey the interference level they experience to a central instance which is responsible for assigning channels to APs in a way that minimizes interference between stations.

In fact most of the schemes try to minimize the interference using different approaches and require different levels of coordination between APs. However, the means that handle coordination are not specified but are just assumed to be there.

Apart from these studies on policies, a few management protocols for WLAN already exist. The Inter-Access Point Protocol (IAPP) [11] enables some coordination among APs. However, it has been specifically devoted to coordinate two APs to support seamless roaming of mobile users. Hence, it does not fulfill the requirements of channel selection whereby other new information elements have to be conveyed between a group of neighboring APs to support services called by channel selection. In [12], a recent study by Garcia et. al. proposes layer 2 and layer 3 mechanisms for Inter-AP communication. The authors assume multi wireless interface APs. APs broadcast status information over a second wireless interface.

The IEEE 802.11h [3] amendment has proposed a mechanism for Intra-Cell channel switching. The requirement for that mechanism stems from the main goal of the standard which is the necessity of channel vacation whenever the channel owner (so called "Primary User") starts using his channel. The standard aims at enabling the usage of the 802.11a-based WLANs in Europe. Currently, this mechanism is also under discussion within the IEEE 802.11v Task Group.

B. Channel Selection Requirements

In fact the objective of a dynamic channel selection scheme should go beyond the assignment of best channels to APs. It should also consider the impact of channel change on the STAs which are required to switch their operational channels as well as the feasibility of approach implementation. We think that the following issues should be considered:

- Firstly, centralized schemes perform well theoretically, but impose a high overhead. We believe that semi-centralized solutions would be helpful in reducing this overhead. By this, a cluster of APs, or even two ones, could cooperate in the channel selection process. Such solutions apply to managed WLANs in many organizational deployments such as hotels, airports, and centrally managed hotspots.
- Secondly, any policy requires coordination regarding the timing of channel selection. For example, even with a good distributed policy there is the chance that two interfering cells simultaneously trigger the policy. Although they might be lucky enough to find a new less interfering channel, channel selection will change nothing if the same new channel is selected by both. However, an active dialogue between APs would enable them to coordinate channel selection decisions.
- Thirdly, some STAs in a cell might miss the switch command and consequently lose their connection with the current AP. One way to reduce this negative impact is to announce multiple channel switch commands [3]. Furthermore, a selection policy could include the number of associated stations in a cell into its decisions. Notice in this context that just channel switching and resynchronization might consume up to 19 ms [13].
- Fourthly, within a cell, some STAs may not be willing to follow the current AP over to a new channel, for example, because of interference reasons. A protocol supporting channel selection could help such stations handing off to other APs without service degradation.

C. Paper Contribution

The above discussion on the different aspects of dynamic channel selection policies motivates the requirement of protocols to support them. In this work, we propose and discuss two protocols, namely an Intra-Cell and Inter-Cell protocol. The former assures a synchronous and smooth transition of the AP and its accommodated STAs within a single cell from one channel to another. The latter facilitates interaction between a group of neighboring APs for information exchange. Furthermore, it supports the implementation of a wide range of channel selection policies proposed for WLAN management. We believe that the protocols could be incorporated to the IEEE 802.11v emerging standard.

III. Coordination Protocols for Dynamic Channel Selection

A. Inter-Cell Protocol

A policy running on each AP might decide that a new channel selection is required based on local interference information as well as the measurement reports received by STAs. The Inter-Cell protocol provides services to such a policy. It enables two or more neighboring APs to coordinate their channel selections. Among the set of the APs, one distinct AP takes the role of the ***Initiator*** while the other AP(s) respond. The initiator first solicits channel status information from the other APs. After receiving this information, a channel assignment proposal is generated by the initiator and distributed to the other APs. These can then locally decide to accept the proposal. Then, the initiator either asks the APs to implement the proposal (only on the set of APs which agree to the proposal) or it can come up with an alternative proposal. Finally the protocol falls back to an idle state enabling other APs to become an initiator.

Inter-Cell Communication Channel*:* A fundamental issue in AP coordination is the channel over which a cluster of APs exchange the coordination messages. Potentially, APs could directly communicate over the wireless channel if they are within the communication range of each other. However, as APs operate on different channels, switching of the operational channel might be needed which harms associated STAs quite a lot. In [12], the authors have used a second radio to broadcast cell information as a solution to this problem. One could also utilize the network backbone (Distribution System) that connects all APs to convey coordination messages. While this provides a reliable medium, it limits the coordination to APs that belong to one administrative domain unless IP communication is employed. In addition, an AP could use *Forwarders*, which are STAs that lie in the overlapping areas of APs. Nevertheless, this influences the forwarding STAs. In this work we focus on the last two mechanisms.

Protocol Service Primitives*:* The protocol comprises a set of primitives defined as stream messages that enable APs to interact and reliably exchange coordination information. These primitives support:

1) **Neighbor Channel Change Request:** Enables any AP to request one neighboring AP to switch it's operational channel for a limited or unlimited time period.
2) **Group Channel Change Request:** Enables any AP to request a cluster of neighboring APs for a semi-centralized channel selection.
3) **New Channel Assignment Distribution and Confirmation:** Enables the Initiator to distribute and confirm new channel assignment to its neighbors.
4) **Synchronous APs' Channel Switching:** Assures synchronous switching in a cluster of neighboring APs from old to new channels.
5) **Conflict Resolution:** Allows for negotiation, deterring, and orderly management of concurrent channel selection demands that could be issued by multiple APs.

The Inter-Cell protocol service primitives are listed in Table I.

Primitive	Function
CellStatus.Request	Enables an AP to initiate the protocol. The request can be sent to one particular AP or a cluster of neighboring APs derived from the current neighboring list.
CellStatus.Indication	Signals the reception of a cell status request.
CellStatus.Response	Allows any AP to respond to a cell status request.
CellStatus.Confirm	Signals the reception of a cell status response.
ChannelSet.Request	Enables the initiator to distribute the new channel assignment.
ChannelSet.Indication	Signals the reception of Channel Set Request.
ChannelSet.Response	Confirms the reception of Channel Set Request.
ChannelSet.Confirm	Signals the reception of a Channel Set Response.
ChannelSetNotify. Response	Invoked to allow any AP to notify the initiator its readiness for executing the switching command or declination of the suggested settings.
ChannelSetNotify. Indication	Signal the reception of a notification message.
ChannelSetCommit. Request	Invoked to allow the initiator to commit the distributed channel allocation vector.
ChannelSetCommit. Indication	Signals the reception of a channel set commit message.
ChannelSetCommit. Response	Allows an AP to inform the initiator that it has received the commit message.
ChannelSetCommit. Confirm	Signals the reception of a response to a channel set commit message.

TABLE I
Inter-Cell Protocol Service Primitives

Inter-Cell Protocol Specification*:* Here we describe the procedures that shall be followed during the assorted phases of the protocol operation. Definitions of the structures of messages are provided in subsection III-D.

- Any AP that receives the ***CellStatus.Request*** message shall reply with a ***CellStatus.Response*** message. If this AP has already triggered the protocol (Initiator), it shall indicate that to the requesting AP in the response message. The latter might exclude it, delay, or cancel it's own procedure.
- If some APs do not respond to the ***CellStatus.Request*** message, either some APs are "re-polled" or the initiator goes on without having a response from every AP.
- For some time period, any AP shall not send a ***CellStatus.Request*** message if it has already replied to another one sent by another Initiator AP. If a ***CellStatus.Request*** arrives while pending with another previous request, the AP shall respond to the new request indicating that it is currently pending with another initiator.
- After receiving the ***CellStatus.Response*** message(s), the policy shall determine which AP(s) should use which channel(s). The new channel assignment vector shall be sent to the involved APs in a message ***ChannelSet.Request***. Upon reception of this message, a ***ChannelSet.Response*** message shall be sent to the initiator.
- After sending channel set response, an AP shall check the possibility of accepting new channel settings or not. The decision shall be included and sent to the initiator AP in a message ***ChannelSetNotify.Response***. The initiator

AP shall poll any particular involved AP from which a notification message has not been received within some time interval.
- After it has received the notifications from all involved APs and if they agree on the new settings, the initiator shall send a message to confirm the new channel assignment ***ChannelSetCommit.Request***. If negative notification has been received from some neighbors, a new proposal is suggested for more *COUNT* times. The commit message shall be sent multiple times and include a decrementing timer of the exact instance at which the physical switch shall take place. Receiving APs shall send a ***ChannelSetCommit.Response*** message.
- If an AP has sent the notification message and does not receive the commit message within a time period, it shall re-send the notification until it receives the commit or a counter limit is reached after which it assumes the whole procedure to be canceled.

The protocol finite state machine is shown in Figure 1.

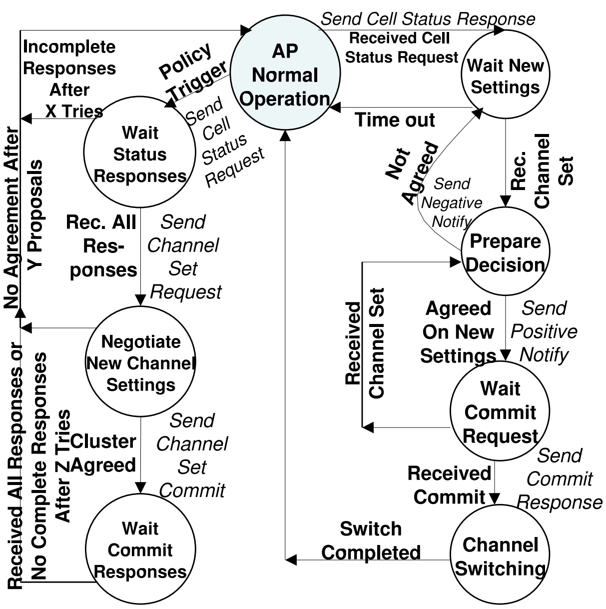

Fig. 1. Inter-Cell Protocol Finite State Machine

B. Intra-Cell Protocol

Any AP that accepts a new channel setting might simply switch its channel upon commitment reception. However, STAs inside the cell will experience service disruption and start legacy scanning which also negatively affects load balancing policies. Alternatively, an AP could negotiate new channel settings with its STAs and make a final decision based on this local voting results and a local cost value. The intra-cell protocol facilitates such interaction between the AP and its STAs within a cell towards transparent channel change.

***Protocol Service Primitives**:* Here we describe the Intra-Cell Protocol service primitives which support:

1) **Channel Change Request:** Enables a STA to request it's AP to move to another channel for some time period.
2) **Reliable Interaction between an AP and STA:** Assures reliable delivery of Intra-Cell coordination messages.
3) **Message Forwarding:** Enables message forwarding between neighboring APs.
4) **Synchronous and Transparent Channel Switching:** Assures synchronous and smooth STAs transition from the old to the new channel.

The service primitives are listed in Table II.

Primitive	Function
STAChannelSwitch. Request	Invoked to allow a STA to issue a channel change request.
STAChannelSwitch. Indication	Signals the reception of a channel switch request from a STA.
STAChannelSwitch. Announce	Allows an AP to announce channel switch intention within its cell.
STAChannelSwitch. Response	Invoked to allow a STA to form and send its response to a channel change request.
STAChannelSwitch. Confirm	Signals the reception of a response to the announcement message.
STAChannelSwitch. Commit	Allows an AP to confirm a previously sent channel switch announcement.
STAMessageForward. Request	Allows an AP to request a STA to convey a message to a neighboring AP.
STAMessageForward. Indication	Signals the reception of a message forward request.

TABLE II
INTRA-CELL PROTOCOL SERVICE PRIMITIVES

C. Intra-Cell Protocol Triggering Time

The protocol is triggered by the AP whenever it intends to switch the current operational channel.

***Protocol Specification**:*

- STAs shall be able to request their APs to move to another channel by sending a ***STAChannelSwitch.Request***.
- Any AP that intends to switch its channel shall announce that to its STAs via ***STAChannelSwitch.Announce*** message and ensure delivery of the message to each STA. The announcement shall include the new channel allocation in the neighborhood.
- STAs in the cell shall reply to the announcement message by sending a local message ***STAChannelSwitch.Response***. The message shall include whether a STA will switch to the new channel or not and the new AP it wishes to join in case it won't follow over to the announced channel.
- An AP should transfer the context of all STAs that won't follow and their corresponding traffic to the APs they intend to join.
- If any AP decides to switch to a new channel, it should send a commit command via a ***STAChannelSwitch.Commit***. The commit message shall include the exact time the physical switch will take place. This information could be appended in the beacon frames with a decrementing timer as proposed in [3].

An important question is: How could STAs identify the cell (AP) from which (some) interference is experienced? This could be based on measurements. In hot-spot areas, APs are densely deployed and their coverage areas overlap. Therefore, STAs in a cell would be able to decode the received packets from the surrounding cells. The IEEE 802.11k standard [2] introduces a report called the frame report which can be utilized for this purpose after a slight modification. Basically, in IEEE 802.11k standard and in response to a frame request, a STA shall reply with a report frame containing one or more frame report elements. Among some other fields, each element contains the number of frames transmitted by each address. This basic request could be modified to be more flexible by including a **FLAG** field in this frame structure. By setting this **FLAG** field, an AP could instruct its STAs to submit the frame report regarding the frames transmitted by or transmitted to neighboring APs. If the **FLAG** field is NULL then STAs should perform measurements and submit a legacy report.

D. Structure of Protocol Messages

In this subsection we specify some of the information elements of the main messages we have used in our proposed protocol.

- ***CellStatus.Request*** Message: This message includes a field that indicates whether the message is sent to a cluster or just to one neighbor, the number of currently associated STAs, the AP **Load** (as defined in [2]), and the **Interference map** that specifies the amount of interference measured over the supported channel set. Each value corresponds to the average value of the interference measured by all STAs accommodated by the AP on a channel. A STA shall compute the interference level I as follows:
$$I = \frac{\overline{P_{\rm rx}} T_{\rm on}}{T_{\rm on} + T_{\rm off}} \tag{1}$$
where $\overline{P_{\rm rx}}$ is the average measured power over the corresponding channel during the measurement period. $T_{\rm on}$ and $T_{\rm off}$ denote the time span during which the medium has been sensed to be busy or idle respectively. These time variables are introduced to account for the fact that interference depends on the traffic characteristics of interfering cells. An AP shall be able to derive estimates for $T_{\rm on}$ and $T_{\rm off}$ from the IEEE 802.11k Medium Sensing Time Histogram Report [2].
- ***CellStatus.Response*** Message: This message specifies whether the responding AP agrees on new channel settings or not and the reason if not. For example, the reason could be: Not willing to participate, pending with another request, or already an Initiator. The response message shall also include status information elements as in the CellStatus.Request message.
- ***ChannelSet.Request*** Message: Specifies the new channel allocation for all involved APs.

IV. Performance Evaluation

In this section we first evaluate analytically the performance of the Inter-Cell coordination protocol in terms of delay if running on top of the distribution systems as well as the wireless interface with forwarders. Then we present simulation results regarding the network performance if the Inter-Cell protocol is used to coordinate the channel assignments. In these experiments, the Intra-Cell protocol has been fully implemented while a first simple version of the Inter-Cell protocol has been implemented. The first version of the protocol enables APs to exchange the set of messages we proposed in the protocol description and agree on operational channels in their cells. However, reliability and concurrent requests resolution issues are not implemented yet. The dynamic channel selection policy used has been proposed in [8]. It tries to operate APs that accommodate large number of STAs on different channels. To implement this scheme, we utilize the interference map and the number of STAs in the cell included in cell status messages. The goal of the experiment is to investigate the performance gain of coordinated channel selection and switching and how the proposed protocol facilitates its implementation.

A. Evaluation of the Inter-Cell Protocol Delay

We consider a WLAN that comprised of N APs. APs are connected via a full duplex 802.3 Ethernet Switch with 100Mbps cables. Each AP dynamically coordinates the selection of a channel with its neighbors. We consider two possible channels for inter-AP communication: Firstly, the wired backbone through the switched Ethernet and secondly the forwarding solution with stations acting as relay over the wireless channel. The performance metric of interest is the time delay caused by the exchange of coordination messages between a cluster of neighboring APs. Note that the frequency of coordination depends on the users' activity inside the WLAN and the protocol triggering policy at APs. We do not include the delay required for the computation of new allocations as it depends on the utilized policy. We denote the message length as L Bytes, the number of participating APs as M, the frame error probability due to frame errors as P_e, the probability of error due to collisions as P_c, and the line bandwidth as B Mbps.

1) The Wired Backbone: We start with the formula for the average time required to transmit a frame of length L successfully in Ethernet, as derived in [14]:
$$T_{\rm suc} = T_{\rm f} + \frac{P_{\rm fail}}{1 - P_{\rm fail}} T_{\rm fail} \tag{2}$$
where $T_{\rm f}$ is time of a frame transmission. $P_{\rm fail}$ and $T_{\rm fail}$ are the probability of a failed transmission and its time span respectively. $T_{\rm f}$ can be written as:
$$T_{\rm f} = 8L/B + T_{\rm buff} \tag{3}$$
where $T_{\rm buff}$ is the latency in the switch buffer which could reach in the worst case 10^{-3} second or even less in todays switching technologies. In fact the transmission can fail due to frame errors or collisions which are independent events. Therefore:
$$P_{\rm fail} = P_e + P_c - P_e P_c \tag{4}$$
$T_{\rm fail}$ is given as:
$$T_{\rm fail} = T_{\rm f} + T_{\rm wait} \tag{5}$$

where T_{wait} captures retransmissions timer's time out and back-off time in case of collisions. Putting things together, we could write T_{suc} as:

$$T_{\text{suc}} = \frac{8L + BP_{\text{fail}}(T_{\text{wait}} + T_{\text{buff}})}{1 - BP_{\text{fail}}} + T_{\text{buff}} \qquad (6)$$

Thus, the total delay due to transmitting and receiving the protocol messages experienced by the initiator AP in a cluster of size M is $D = (4M+3)T_{\text{suc}}$. The $(4M+3)$ is the total number of messages the initiator AP transmits and receives in a successful one-time run of the protocol. However, the delay D is not contiguous, the longer contiguous slot could be $(M+1)T_{\text{suc}}$ during the reception of cell status responses from neighbors.

2) Forwarders: In this case the initiator AP uses an intermediate STA to relay coordination messages based on the IEEE802.11 DCF channel access mechanism. Following the analysis in [15], a node successfully transmits a frame after j consecutive unsuccessful transmissions within a time period of $T(j)$, given by:

$$T(j) = T_{\text{P}} + T_{\text{H}} + T_{\text{DIFS}} + \frac{L}{R} + T_{\text{SIFS}} + T_{\text{ack}} + T_{\text{backoff}}(j) \qquad (7)$$

T_{P} and T_{H} represent the time duration of the physical layer preamble and header. T_{DIFS} is the Distributed Coordination Function Inter-frame Space and T_{SIFS} is the Short Inter Frame Spacing, $L = (28 + L_{\text{MSDU}}) \cdot 8$ is the length of the MAC packet in bits (where L_{MSDU} is the MAC Service Data Unit length and the 28 bytes stem from the MAC header), $T_{\text{ack}} = (T_{\text{P}} + T_{\text{H}} + \frac{112}{R})$ is the duration of the ACK frame, and $T_{\text{backoff}}(j)$ is the average back-off interval after j consecutive unsuccessful transmission attempts given as:

$$T_{\text{backoff}}(j) = \begin{cases} \frac{2^j(T_{\text{CWmin}}+1)-1}{2} \cdot T_{\text{Slot}} & 0 \le j < 6 \\ \frac{T_{\text{CWmax}}}{2} \cdot T_{\text{Slot}} & \text{j} \ge 6 \end{cases} \qquad (8)$$

where T_{Slot} is the basic slot duration, T_{CWmin} and T_{CWmax} are the minimum and maximum contention window sizes respectively.

However, $T(j)$ is only the *raw* average transmission time of a frame. The frame is still subject to frame errors, which requires one or several retransmissions. The average time span that a STA requires to transmit a single frame *correctly* is [15]:

$$T_{\text{suc}} = T(0) + \sum_{j=1}^{\infty}(1 - P_{\text{fail}})P_{\text{fail}}^{j}\left[\sum_{m=0}^{j-1} t(m) + T(j)\right] \qquad (9)$$

where $t(m) = T_{\text{P}} + T_{\text{H}} + T_{\text{DIFS}} + T_{\text{backoff}}(m) + \frac{L}{R} + T_{\text{SIFS}} + T_{\text{ack}} + T_{\text{Slot}}$ is the time between two consecutive transmissions if the frame transmission fails.

Additionally, a forwarding STA might need to switch its operating channel to relay coordination messages to an AP that operate over a different frequency. This switching and re-synchronization time delay T_s is vendor dependent but might reach 19ms in some WLAN cards. In this case the total delay is $D = 2\left[(4M+3)T_{\text{suc}} + T_s\right]$.

Figures 3 and 4 plot the maximum contiguous delay experienced by the protocol initiator versus packet error probability for different number of coordinating APs. In Figure 3 the Inter-AP communication goes through the wired backbone while in Figure 4 the forwarding STAs are assumed to convey coordination messages between APs. The results show that a central management of large groups cause longer delays specially with the forwarders and high error probabilities. Thus, the idea of semi-central management would be very much helpful in reducing this delay. Additionally, the delay can be further reduced if the initiator AP serially polls its neighbors one by one and collect status information. The values of the constant parameters are set as in [16].

B. Network Performance Simulation

1) Simulation Scenario: In the simulation study, we consider firstly five 802.11b APs that operate on IEEE 802.11b channels as shown in figure 2. The APs are placed 250m apart from each other. As the number of non-overlapped channels supported by IEEE802.11b is three, two pair of APs will interfere with each other. 40 FTP stationary users appear at different time instances and at different places. FTP sessions terminate at the wired part of the network at a single server. The latency for packets between APs and the server was set to 10μs.

Every FTP user either downloads or uploads a file, whereby its size is indefinitely large. All TCP users utilize greedy TCP with packet length of 1000 bytes. The TCP traffic was generated with Jugis Traffic Generator (jtg)[17].

As the throughput of the whole network should be maximized, every AP and STA measures the throughput every second in up- as well as downlink directions. APs and STAs throughput and the behavior of the throughput during and after channel switching is our metric.

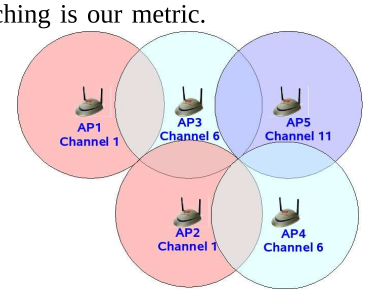

Fig. 2. AP Positioning and Channel assignment

2) Interference Measurement: In order to judge the cell interference over each channel we use the average received power by all accommodated STAs during the measurement interval in the simulation, as obtained by Equation 1.

3) Simulation Results: Figure 5 shows the behavior of the aggregate throughput of two interfering APs (AP 1 and AP 2) for the first 120 seconds. The figure illustrates the effect of simple channel switching whereby AP 1 did not inform its STAs about its intention of changing the operational channel.

As the STAs are required to execute legacy scanning and association procedures, a connection disruption has occurred and AP 1 aggregate throughput is highly degraded during this period which lasts approximately between 1 and 3 seconds (around second 65). However, after channel switching, the aggregate throughput of both APs has been doubled. Figure 6 shows that the connectivity disruption problem has been resolved through the Intra-Cell protocol where STAs are informed about the exact time the physical switch will occur.

Figure 7 depicts the aggregate throughput of two interfering APs (AP 1 and AP 2) after they have simultaneously switched to the same channel. The switching occurred around second 62 where a peak in the throughput at that time can be noticed. Clearly, as the two APs have selected the same new channel, no gain in the aggregate throughput has been achieved after channel switching. Figure 8 shows the influence of channel switching on throughput of a STA that has missed the switch command. A disruption has occurred and lasts about 2.5 seconds necessary for legacy scanning and association procedures.

Finally and most importantly and in order to explore the performance of the proposed protocol in a larger network, we consider a WLAN of 10 APs and 60 STAs. The channels were initially set based on legacy (optimal) frequency planning methodology. Figure 9 compares between centralized, two neighbors coordination, and uncoordinated dynamic channel selection approaches. We have implemented the allocation mechanism presented in [8] on top of the Inter-Cell protocol of this paper. An interference based mechanism has been used with the two neighbors coordination channel selection approach where the least interfered channel is selected as a new channel.

With centralized coordinated channel selection, the Inter-Cell protocol was used to collect interference information from neighboring APs and the mechanism of [8] has been used to compute the new channel allocation. After switching to the new channels distributed by Initiator APs, the aggregate WLAN throughput is substantially improved as shown in Figure 9. However, a performance loss can be observed due to the protocol and policy overhead during channel selection and switching (around Second 150). Also, a good improvement in the throughput performance has been achieved with the two neighbors coordination mechanism with negligible overhead. Apart from that, Figure 9 shows that a small improvement has been gained when APs decentrally and individually assessed the channels and switched to new less interfered ones. Two results can be drawn from this last experiment:

1) The Inter-Cell protocol has facilitated the implementation of the centralized criterion.
2) Even the cooperation of two neighboring APs can significantly improve the QoS at very low cost in certain cases.

V. Conclusions

This paper proposes an Inter-AP coordination protocol for dynamic channel selection and switching in IEEE 802.11 WLANs. It supports interactive communication between a group of APs and can cope with either central or distributed channel selection policies. We show by means of simulation that the QoS improvements gained from a simple coordinated channel selection scheme, implemented on top of the proposed protocol, are already significant. The protocol overhead is high with forwarding stations but is rather acceptable with the wired backbone solution.

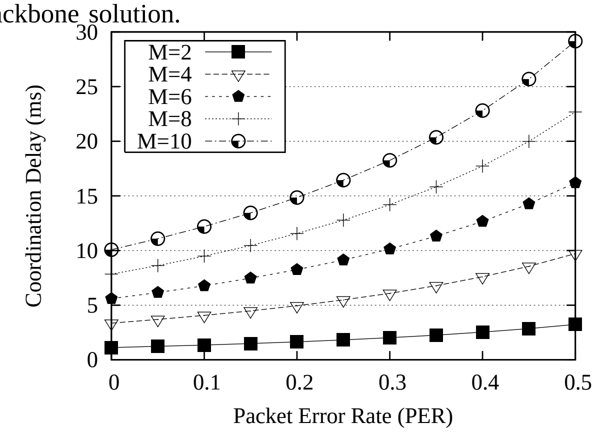

Fig. 3. Coordination delay at the Initiator AP for different cluster sizes using the wired backbone

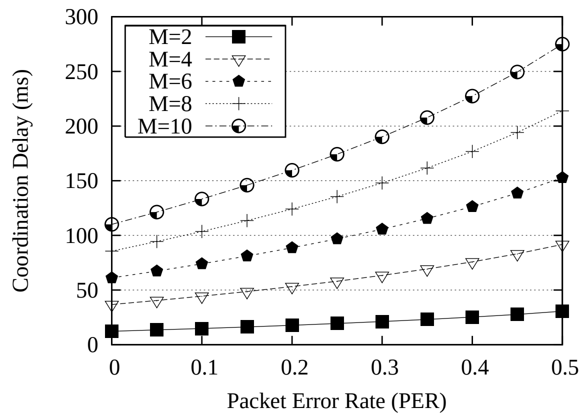

Fig. 4. Coordination delay at the Initiator AP for different cluster sizes using forwarders

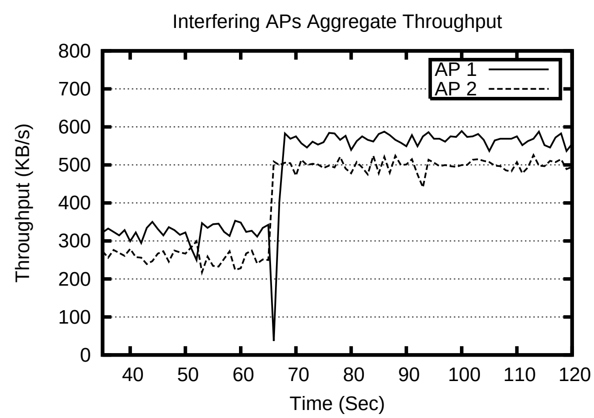

Fig. 5. Channel Switching without STA-AP coordination

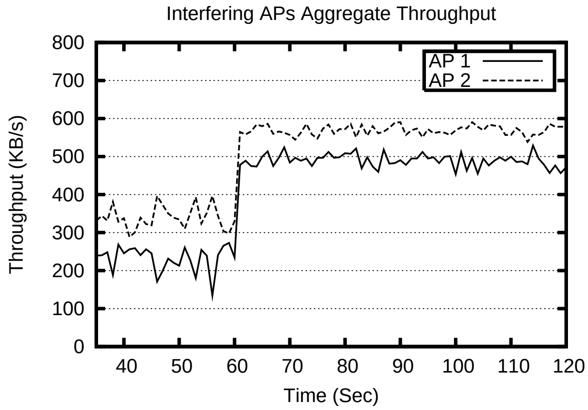

Fig. 6. STA-AP Coordinated Channel Switching

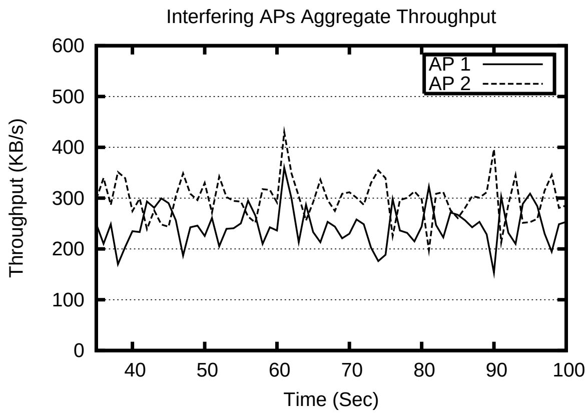

Fig. 7. Simultaneous uncoordinated Channel Selection

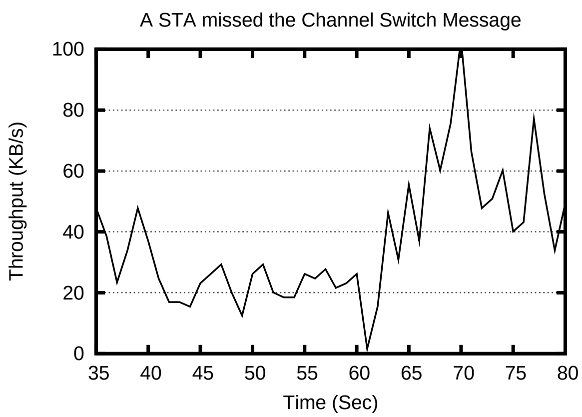

Fig. 8. Throughput of a STA that missed Switch Command

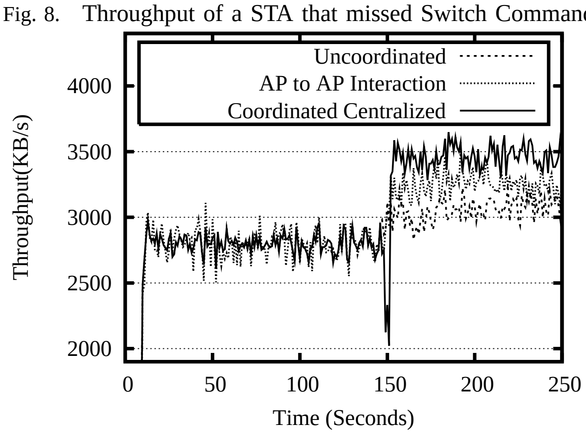

Fig. 9. Centralized, Two Neighbors Coordination, and Uncoordinated Dynamic Channel Selection

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