TKN Telecommunication Networks Group

Technical University Berlin

Telecommunication Networks Group

Inter-AP Coordination Protocols

Murad Abusubaih, James Gross

abusubaih@tkn.tu-berlin.de

Berlin, July 2006

TKN Technical Report TKN-06-005

TKN Technical Reports Series

Editor: Prof. Dr.-Ing. Adam Wolisz

Abstract

IEEE 802.11 based WLANs are becoming increasingly widely deployed. Although network planning helps in solving some problems in WLANs, still exist many issues that stem from the static behavior of WLAN's networking elements required to be solved. More effort is needed toward a dynamic reconfigurable WLAN that adapts its parameters according to the dynamical changes in the RF environment and traffic load characteristics.

A promising solution for many problems exist in todays WLANs is the Inter-AP coordination, whereby APs exchange some information that could intelligently be used to alter transmission parameters. In spite of the fact that the Inter-Access Point Protocol (IAPP) implies some coordination among APs, this protocol just aims at supporting user's mobility among APs. Hence, new Inter-AP Coordination protocols that enables manufactureres and policy designers to develop algorithms that improve and optimize the usage of the WLANs Radio Resources are required.

This report presents some Inter-AP coordination protocols toward dynamic, intelligent and optimized WLANs. The report proposes and discusses three coordination protocols that would support three important services, namely are: Dynamic Channel Switching, Capacity Sharing, and Dynamic Adjustment of Transmission Power.

Contents

Chapter 1

Introduction

IEEE802.11 WLANs have been extensively deployed in many different locations like homes, university campuses, airports etc. to serve users as they roam. As the cost of access points (AP) is continuously decreasing and in order to achieve a high coverage for roaming users, more and more APs have been installed in relatively small geographical areas. However, the number of supported channels by any IEEE802.11 standard is limited and among the supported channels only few of them do not overlap. Therefore, coverage areas of APs are likely to overlap. Potentially, this can lead to high co-channel interference within several neighboring WLANs and can create challenging problems for network planners, protocol and policy designers. As a result of this trend, the main objective for the future is to dynamically and intelligently manage and optimize radio resources between several WLAN APs, which will provide users high quality of service (QoS).

Many problems in WLANs stem from the fact that APs have been designed to be used in a stand-alone manner rather than coordinated manner. Therefore, we propose to refine the design of APs and add coordination services which are required to:

- Minimize interference between APs and STAs operating in the same channel but within different cells.
- Maintain high SNIR to assure high data rate for all users.
- Share the capacity of AP among neighboring APs if possible.
- Minimize handoff latency.
- Optimally and dynamically adjust the transmission power among interfering APs.
- Optimally and dynamically select working channels for different cells.
- Enable efficient channel usage scheduling.
- Enable efficient admission control solutions.

1.1 The IEEE802.11k Standard

Within IEEE802.11, the only measured value available to APs and STAs is the Received Signal Strength Indication (RSSI) which is related to the power level measured during packet reception. Therefore, and in order to better manage and utilize radio resources, the IEEE has formed a task group, referred to as 802.11k, for Radio Resource Measurements (RRM). The task group has defined a set of measurements and reports to be exchanged between STAs and their APs to enable policy designers to refine the WLAN operational protocols in a standardized fashion. The way in which those reports could be used for radio resource management has not been specified.

In the 802.11k standard, a STA can do measurements and report the results to the AP or another STA upon request. A STA can request another STA to perform measurements on its behalf. The procedures that handle the exchange of reports have been defined in the standard. In most cases, APs requests STAs to report measurement reports, but in some cases STAs might request some data from the APs. The set of supported reports include:

- **The Beacon Report:**

  The AP can request a STA(s) to monitor the RF environment and respond with a summarized information about the detected beacons from a BSS(s) that uses some channel(s) specified in the request. The response is standarized in a report called the beacon report. It includes information regarding the services that observed APs support as well as the connection qualities to those APs.

- **Frame Report:**

  This report is requested by APs. It includes information about all the frames a STA has received from other STAs during the measurement period. The information includes the average received power as well as the number of frames received from each address.

- **Channel Load Report:**

  The channel load report is built by STAs and requested by APs. It mainly includes the fraction of time a specified channel has been sensed to be busy during the measurement period.

- **Noise Histogram Report:**

  This report is requested by APs. It includes all non 802.11 energy received on the channel when CCA indicates that no 802.11 signal is present.

- **Hidden Station Report:**

The hidden station report is generated by a STA and requested by APs. It includes the number of fames and the address of the hidden STA. The measuring STA tracks a hidden STA if it receives initial transmissions (Not retransmissions) of frames that must be acknowledged but does not receive the corresponding acknowledgments (ACKs).

- **Medium Sensing Time Histogram Report:**

  This report is generated by STAs and provides the AP with a statistical distribution of the medium idle and busy duration during the measurement interval as observed by the STA.

- **STA Statistics report:**

  Through this report a STA informs the AP about its connection quality and network performance during the measurement period.

- **Neighbor report:**

  This report is requested by STAs and might be used to optimize the aspects of roaming across WLAN cells. The report includes an ordered list of APs that the STAs may use as candidates for BSS roaming. APs can generate the neighbor report utilizing the information received in the beacon reports from all STAs. It enables the AP to collect load characteristics information from the neighboring BSSs.

To acquire some measurements, a STA might need to switch to other channel(s) for some time period. This will result in service disruption during this period and consequently affect active applications. More detailed information on IEEE802.11k can be found in [1].

1.2 The IEEE802.11f standard

Some AP coordination protocols have been defined in the Inter-AP Protocol (IAPP) to support users roaming across the various cells. The IEEE802.11f [4] has standardized a set of messages to be communicated over the Distribution System (DS) to support mobility among APs from different vendors. The purpose of these messages is to:

- Enable the new AP and the old AP to exchange STA context information such as security information that speeds up the reauthentication procedure of a STA on reassociation.

- Cause layer 2 devices to update any forwarding information they may hold regarding the roaming STA so that frames destined for it are delivered to a point in the DS where the new AP can forward those frames to this STA.

1.3 The IEEE802.11v standard (Wireless Network Management)

Currently WLAN network control is limited to the APs. Network administrators have little control over the WLAN STAs. The IEEE 802.11v standard aims at providing (efficient) mechanisms that simplify WLAN deployment and management. The standard provides functionalities to control the STA's Management Information Base (MIB) over the air. Specifically, the Task Group wants to define the procedures to:

- Enable AP to automatically inform the STA which network it should connect to without the need to manually set the Service Set Identifier (SSID).
- Enable AP to control the STA's parameters like the operational channel and data rate.
- Allow an AP to request a STA to connect to another AP to facilitate efficient load balancing solutions.

The work on this standard began in 2005 and the IEEE expects to finalize it in 2008.

1.4 Related Work

Despite the fact that there are some active IEEE802.11 task groups aiming at providing standarized protocols for Radio Resource Measurements (RRM) and Wireless Network Management [1, **?**], we did not find a complete framework for Inter-AP Coordination protocols. Indeed there are some schemes proposed for improving WLAN performance which assume some kind of coordination between APs. For example, in [7], a set of coloring based channel assignment algorithms for WLAN channel management have been proposed. The paper of [7] investigates the performance of coordinated versus uncoordinated algorithms. It focuses on specific algorithms that involve special coordination for scheduling purposes rather than generalized protocol infrastructure which might support different solutions. In [9], a fast handoff algorithm has been suggested for centralized IEEE802.11 WLANs where the STA's context information is handled by an inter-AP coordination protocol and transferred via a central switch that connects the APs. A cooperative scheme for admission control and load distribution has been elaborated in [5] where APs indirectly cooperate via a central admission controller that decides where STAs should associate if they are able to hear more than one AP. A similar scheme that assumes different physical bit rate STAs can be found in [6]. In [8], the authors propose an agent-based load distribution scheme. Agents running on APs exchange load information to cooeratively balance the load among APs by forcing a handover of some STA(s) from one cell to another. The drawback of this approach is that it is not aware of the STA(s) that are commanded to dis-associate, i.e it does not guide a STA where to go. Hence a STA may lose network connection if it is not lucky enough to find a new serving AP after the legacy scanning procedure.

Actually, our work differs from the previously discussed activities in the sense that it focuses mainly on protocol issues rather than policies. Specifically, we aim at designing reliable Inter-AP protocols that enable efficient resource management policies which lead to better QoS.

1.5 Contribution and Report Contents

Although 802.11f includes some mechanisms for coordination between APs in order to achieve seamless handover, these mechanisms do not suffice to handle many problems which still exist regarding coordination of AP (as a result of AP's static behavior). Therefore new coordination protocols that enable APs actively talking to each other and targeting at a more sophisticated and improved WLAN resource management are required.

Specifically, this work contributes in designing a set of AP coordination protocols that fulfill the following services:

- **Coordinated Dynamic Channel Switching:**

  Aims at enabling a dynamic and efficient channel selection criterion to mitigate interference problems between neighboring APs.

- **Coordinated Dynamic Adjustment of Transmission Power:**

  Aims at enabling active negotiation and agreement between interfering APs on the level of the emitted power.

- **Coordinated Capacity Sharing among APs:**

  Aims at enabling improved load sharing solutions by facilitating coordinated and planned STA assignments rather than random assignments which often prevent an even load distribution between APs.

The design of these protocols involves the following key aspects:

- Mechanisms by which APs discover each other.
- Mechanisms for Inter-AP Communication.
- Detailed design of the coordination protocols and the corresponding signaling messages.

- Reliability issues.
- Performance evaluation.

We base our comparison between coordinated and uncoordinated protocols on the common metrics usually used in WLAN performance evaluation, whcih are namely throughput and round trip delay for delay sensitive application.

The remainder of this technical report is organized as follows: We start with Chapter 2 presenting the potential alternatives for exchanging information between coordinated elements. In Chapter 3, we present the design, explanation, and discussion of our AP Coordination Protocols. Then we present simulation results to demonstrate the efficiency of AP Coordination Protocols for better WLAN resource utilization and user's QoS enhancements in Chapter 4 before we conclude our report in Chapter 5.

Chapter 2

Inter-AP Communication Possibilities

This chapter describes the various possible ways by which APs might communicate and exchange coordination information messages required to improve the WLAN performance.

2.1 Assumed Network Architecture

We assume an infrastructure network that consists of a groups of APs as shown in Figure 2.1. A Basic Service Set (BSS) comprises of one AP and at least one station STA. The set of infrastructure BSSs interconnected via a backbone is referred to as Extended Service Set (ESS).

2.2 Backbone

APs might communicate coordination information via the wired network. This option has the advantage that no wireless STA is involved in the communication process and wireless bandwidth is saved. However, the backbone network might impose some delay specially when the coordinating APs belong to different networks which implies that a layer three communication is required.

2.3 Direct AP-AP Wireless Communication

If coordinating APs are within the range of each other, they could directly communicate and exchange coordination messages (if they operate on the same channel). Although this has the advantage of a smaller delay, it is costly if coordinating APs originally operate on different channels (which requires them to switch to a common channel

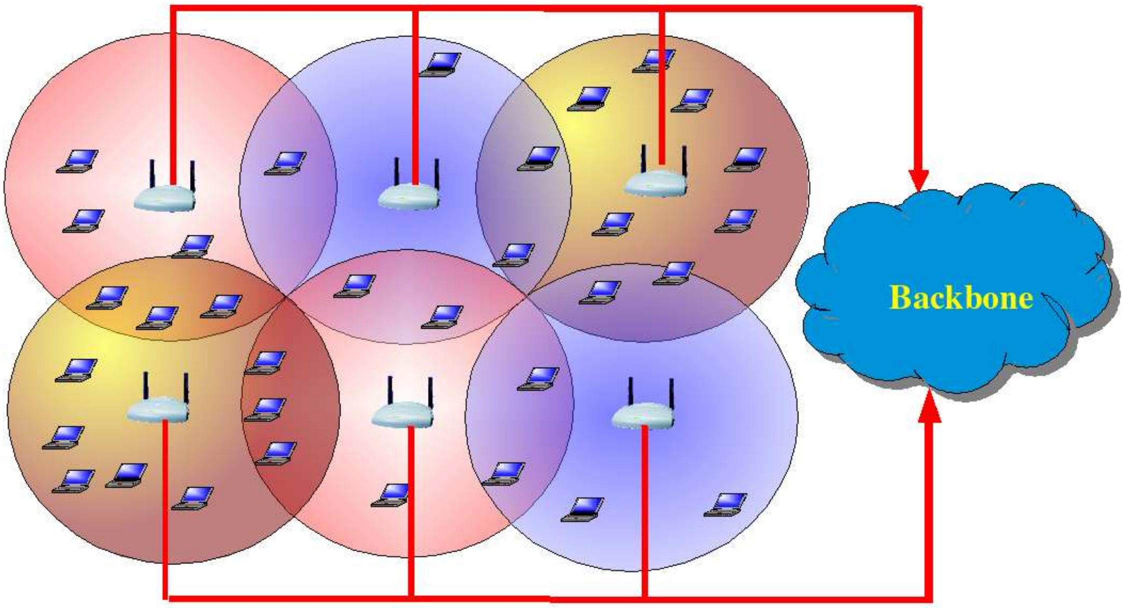

Figure 2.1: A Typical 802.11b WLAN

to exchange coordination information). In fact a high activity per cell is a trigger to perform AP coordination, thus, the channel switching will most likely harm many STAs (as the AP is not available for some time span while it switches to another channel and tries to communicate with other APs)..

2.4 Forwarders

Another possible AP communication alternative is to utilize coordination message forwarders. When APs are deployed, overlapping regions are usually planned so as to have continuous coverage in the area of interest and to facilitate users roaming across the various APs. Potentially, STAs that are located in overlapping regions are able to hear more than one AP. Those STAs are good candidates to forward coordination messages between APs. The AP could build the forwarders list from the neighboring information provided by STAs through some alternative schemes which are described in Section 3.1.

2.4.1 Selecting the Best Forwarder

The AP might have multiple candidate forwarders to the same neighboring AP. It is the AP duty to select the best forwarder since possibly those candidates have different connection qualities with the neighboring APs. On one hand, the AP needs a forwarder that most likely will deliver the coordination messages and forward them to the destined neighboring AP, on the other hand active applications on the forwarder should not be harmed if the forwarder is required to switch its operating channel. This would highly influence the forwarder selection criterion at the AP. Hence, an AP should make a trade-off between STAs connection qualities with neighboring APs and their activities in the current cell.

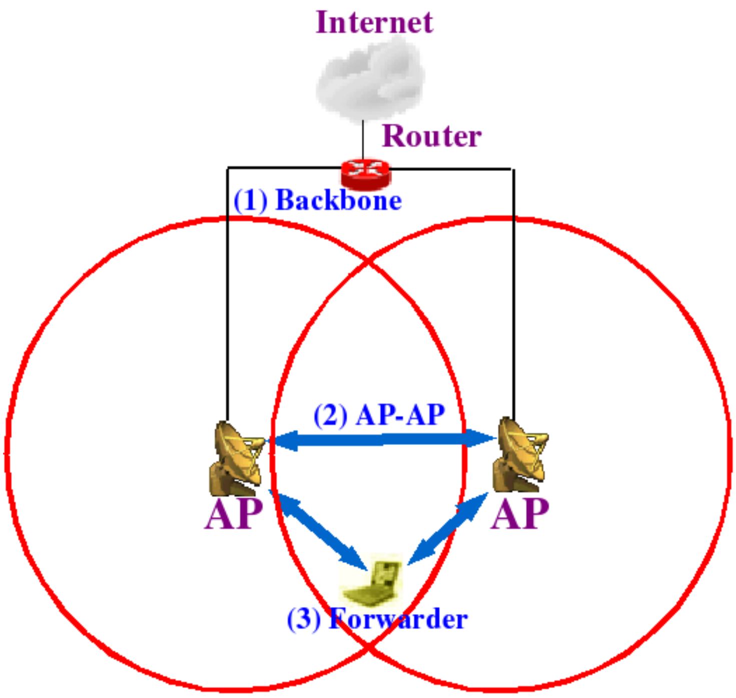

Figure 2.2: Inter-AP Communication Possibilities

Chapter 3

AP-Coordination Protocols

In this chapter, a set of AP coordination protocols are presented. The first issue in coordination protocols is the construction of the group of coordinating elements (APs). Therefore, we start by describing some mechanisms by which APs could discover themselves.

3.1 Neighbor Discovery

APs are continuously transmitting beacon frames every 10ms or 100ms. The beacon frames are broadcast frames that can be received by every station which lies in the AP vicinity. After being powered up, a STA should have to scan the supported channels either actively by sending probe request frames or passively by listening to beacons transmitted by APs. After some time, a STA will have a list of APs from which it selects the best one based on the received power level.

In WLANs, some STAs might roam from one cell covered by an AP to another cell covered by a different AP. The protocol that handles STA's roaming among APs is the Inter-Access Point Protocol (IAPP) which requires some signaling between the old and new APs. The signaling is done via the backbone network.

Moreover, within the 802.11k framework, STAs can be requested to monitor and perform some measurements and report that to their APs. The measurement requires a STA to switch to the requested channel set and monitor the RF environment.

This information base available at STAs would be very usefull for enabling APs discover themselves. In summary, APs could build the neighbor list as follows:

- APs initially configured to operate on the same channel might directly hear each other.

- The association request frame might include a list of APs from which a STA has received beacons or probe responses.
- APs can learn about their neighbors from STAs that roam across multiple cells.
- STAs might be polled periodically to submit measurement reports like the 802.11k Beacon and Medium Sensing Time Histogram reports.
- During their idle times (which might be in the night or during low activity periods), APs might perform some kind of scanning and discover their close neighbors.
- An AP might broadcast a special message called **WHO IS MY NEIGHBOR**. All APs that receive this message shall reply to it.

3.2 Coordinated Dynamic Channel Switching

3.2.1 Service Definition

It might happen that STAs in a cell experience high interference from some nearby AP. This occurs mainly when neighboring APs were initially configured to operate on the same channel and one of them (or both) are heavily loaded. One possible protocol that supports solutions to the co-channel interference problem proposed within the 802.11v standard is switching the "own" current operating channel and use a (hopefully) less interfered one. This protocol is firstly introduced within the IEEE802.11h standard to facilitate the use of the 5GHz band in Europe. Briefly, when a 5 GHz WLAN channel is detected to be occupied by some primary system (in this case radar systems), 802.11 devices should dynamically vacate the occupied channel and switch to another one.

We believe that dynamic channel switching could be better done in a coordinated manner. Such a coordination protocol for channel switching would reduce the cost associated with channel switching and would enable the design of optimal channel selection strategies. By enabling an active dialogue between interfering APs, an AP could request a neighboring AP (from which some interference power stems) to change its frequency for a limited or unlimited time period. By this, we could have flexible WLANs that better support specific user's demands. Moreover we aim at better supporting WLANs users by enabling a user-triggered channel switching. By this (under certain conditions) a STA might request its AP to move to some different or even specific channel for some time period.

In the next sections we describe the uncoordinated channel switching protocol and determine its weaknesses and then present a coordinated protocol that tries to overcome those weaknesses.

3.2.2 Uncoordinated Channel Switching Protocols

An uncoordinated channel switching protocol procedure would be:

- AP uses interference measurement information reported by its STAs (802.11k beacon and medium sensing histogram reports).
- An AP intends to switch to a new channel shall announce that to all currently associated STAs.
- STAs shall send confirmation messages specifying whether they are going to switch their channels or not.
- After receiving the confirmation messages (and if the AP decides to switch the operating channel), an AP shall send a notification message informing the STAs about the exact time the physical switch will happen. The time is expressed in terms of the number of beacons that should be received before the physical channel switching takes place.

A closer look at the implications of the uncoordinated channel switching solutions reveals many issues:

- Interfering APs might decide simultaneously to switch their channels. Although they might be "lucky enough" to find new less interfering channels, channel switching will change nothing if they select the same new channel.
- In many cases, it might be less costly if some neighboring AP switches its operating interfered channel as it might have a less interfered candidate channel than the own alternative channels.
- An AP might wish to request its neighboring AP to switch its channel for some time period which is not possible with uncoordinated protocols.
- What will happen to STA's traffic currently conveyed by some AP? Potentially, APs do not know which STAs will also switch to the new channel. However, STA's traffic still arrives at the AP.
- Some STAs might have not been able to hear the channel switching command or able to receive every beacon frame so as to synchronize the switching with the AP. Therefore, channel switch announcement messages shall be sent several times to ensure that all STAs receive it. That means the signaling overhead associated with uncoordinated protocols and the possibility that a STA misses the switch message highly depend on the number of STAs and their activity levels in the cell.

3.2.3 A Coordinated Channel Switching Protocol

With coordinated channel switching protocols, potentially some issues listed in the previous section would become easier to be solved. The idea is to view the network at a broader range beyond one AP.

Here an AP shall be able to request its neighboring AP to switch to other channel if possible. It might happen (even likely) that one of them will find a less interfered alternative channel to use. The two loaded APs shall actively talk to each other and one of them shall switch to a new channel.

Through coordination information (e.g. AP load, number of STAs, least interference level from candidate channels), APs might decide which one of them shall switch its channel.

This coordination will be effective in:

1. **Reducing the messaging overhead (Network cost):**

   As stated before, and in order to insure delivery of announcement messages, those messages should be transmitted many times over the wireless link. Through few coordination messages which could be transmitted over the backhaul, the overhead associated with announcement messages can be significantly reduced.

2. **Reducing the negative influence on switched STAs:**

   By considering the traffic characteristics of STAs in the interfering cells, efficient solutions based on coordination could reduce the impact of channel switching on active applications. Hence, higher QoS is ensured.

3. **Minimizing the number of STAs that have not been able to hear the beacons and channel switch announcement messages:**

   In simple words, the higher the number of STAs in a cell, the higher the number of collisions which leads to a higher probability that some STAs could miss the messages associated with channel switching.

4. **Eliminating random channel switching in the cells:**

   The messages communicated among APs would cause some neighboring interfering APs to cancel channel switching decisions as well as preventing simultaneous hopping on the same channel which implies that interfering APs will initiate the switching protocol later on.

A dynamic coordinated channel switching protocol would be:

- An AP sends a Channel Switch Request Message ***ChannelSwitch.Request*** to a neighboring AP. The message shall include the amount of measured interference on the current channel, the amount of interference measured on the best potential candidate channel for switching, the number of STAs the AP accommodates, and the AP load information.
- Upon reception of the Channel Switch Request Message, the AP shall check the possibility of switching its own channel and reply with a message including the answer ***ChannelSwitch.Response***.
- After receiving the ***ChannelSwitch.Response*** message, an AP knows whether the requested AP agrees on channel switching or not. If the request has been denied, the AP can decide to switch its own channel.
- An AP which intends to switch the channel shall announce the new channel to its STAs as well as to its neighbor APs through an announcement message ***ChannelSwitch.Announce***. This message shall include the new channel the AP intends to switch to.
- STAs in the BSS shall confirm channel switching announcement message by sending a local message ***ChannelSwitch.Confirm***. The message shall include whether a STA will also switch to the new channel or not.
- If the AP finally decides to switch to a new channel, it should send a notification message ***ChannelSwitch.Notify*** to its STAs and other neighboring APs. The notification message shall include the exact time the physical switch will take place.

Figure 3.1 depicts the Channel Switching Protocol procedure.

Notes:

1. An AP could either start by sending channel switch request to a neighboring AP or by sending channel switch announcement in response to STA(s) request. The details of switching policies is beyond the scope of this document.
2. The channel switch announcement message is sent to the other APs so as to inform them that some AP is planning to switch its operating channel. This will reduce the probability that neighboring APs issue random channel switch requests.
3. As it is obligatory for all STAs to respond to the switch announcemet message, there should be some way to ensure that the responses have been delivered by

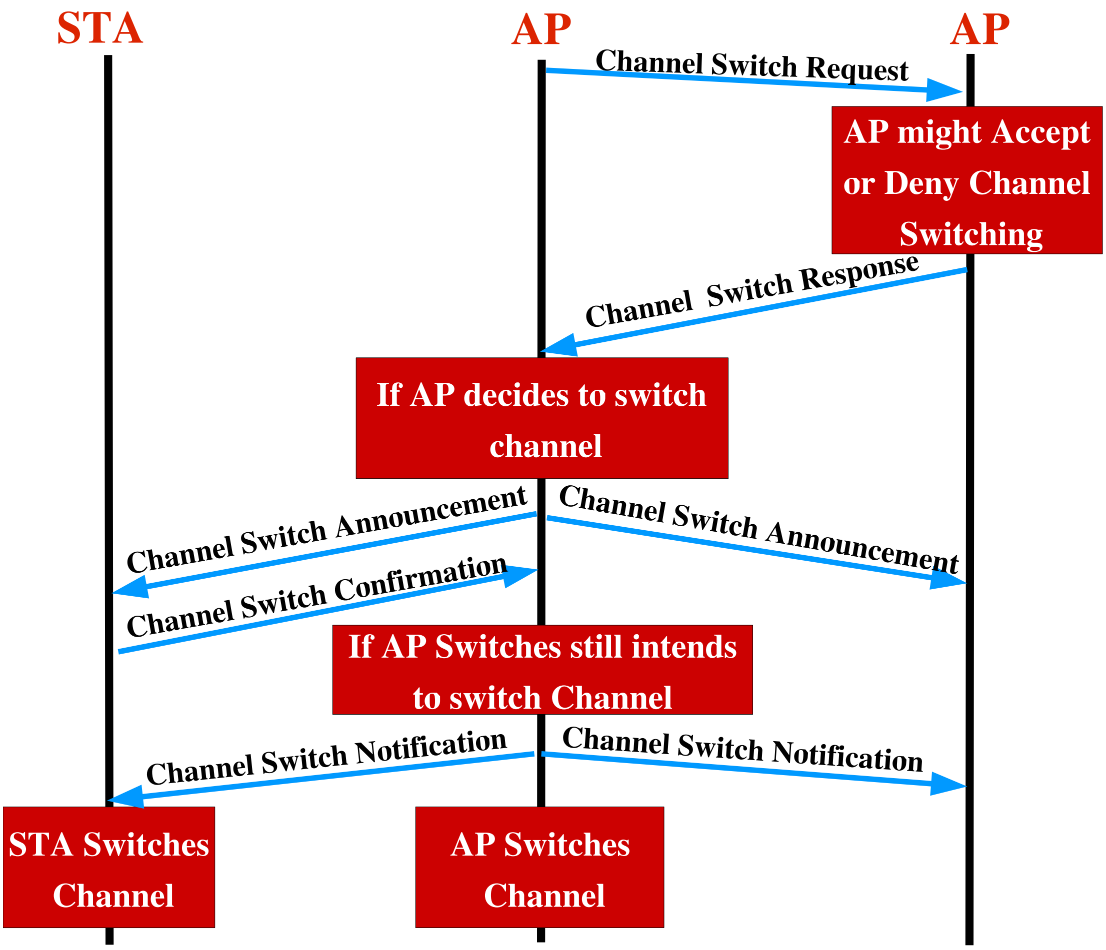

Figure 3.1: Channel Switching Procedure

the AP. The probability that any response message won't be correctly received by the AP increases as a function of the number of STAs in the cell since all STAs that were "lucky" to easily receive the switch announcement will try immediately to respond to that message and therefore the collision propability will be high. Therefore, we recommend that STAs shall not immediately respond to announcement messages but rather randomly select a time instance within the period [0, Physical Switch Time - $\triangle$].

4. An important question is: How could an AP identify the cell (AP) from which interference is comming: A first approach is to utilize the load information and to share it between neighboring APs. One could argue that the source of high interference is most likely a loaded neighboring AP operating on the same channel. Another approach could be based on measurement reports. In hot-spot areas

like offices, campuses, hospitals, and airports, APs are densly deployed and their coverage areas are overlapped. Therefore, STAs in a cell that experience high interference on the operating channel would be able to decode the received packets from the surrounding interferers that belong to a neighboring cell. As described in Chapter 1, the 802.11k standard introduces a report called the frame report which can be utilized for this purpose after a slight modification. Basically, in 802.11k standard and in response to a frame request, a STA shall reply with a frame report frame containing one or more frame report elements. Each element includes the number of frames, BSSID, Received Channel Power Indicator (RCPI), and the Transmit Address.
The structure of the frame request is shown in Figure 3.1. The Channel Number

Channel Number	Regulatory Class	Randomization Interval	Measurement Duration

Table 3.1: Frame report Request

filed specifies the channel for which the requested measurement report applies, the Regulatory Class indicates the frequency band for which the requested measuremet report applies, the Randomization Interval specifies an upper bound of the random delay after which the measurement should be started, and finally the measurement duration indicates the time duration the measurement should be carried out. This basic request could be modified to be more flexible. If we include an **Address** field in this frame structure, then the AP could request its STAs to submit the frame report regarding the frames tranmitted by or transmitted to a specific address which actually could be an address of a neighboring AP operating over the same channel. If the Address field is NULL then STAs should perform measurements and submit a legacy report.

3.2.4 Protocol Triggering Time

This protocol is triggered whenever:

1. The measured (and reported) interference over the operating channel exceeds a threshold for a certain time span.
2. The AP has received local channel switch requests from many STAs in the cell.
3. The AP has accepted a channel switch request from some STA.

3.2.5 Frame Structure

This section presents a preliminary frame structure for all frames involved in the Coordinated Dynamic Switching Protocol.

1- Channel Switch Request Frame (*ChannelSwitch.Request)*

Msg. Number	Interference Level	Load	Count	Least Interference Level	Duration

Table 3.2: Channel Switch Request Frame

Msg. Number:
This field is an counter that distinguishs between the different channel switch request messages.
Interference Level:
This field specifies the amount of interference measured over the interfered channel. This value corresponds to the average value of the interference measured by all STAs accommodated by the AP and shall be computed by each STA as follows:

$$InterferenceLevel = \frac{\overline{P_{rx}} T_{on}}{T_{on} + T_{off}} \tag{3.1}$$

where $\overline{P_{rx}}$ is the average measured power over the operating channel during the measurement period. T_{on} and T_{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 interferece depends on the traffic characteristics of intefering cells. An AP shall be able to derive estimates for T_{on} and T_{off} from the IEEE802.11k Medium Sensing Time Histogram Report.
Load:
This filed indicates the current load on AP requesting channel switching which corresponds to the fraction of time the operational channel has been sensed to be busy during a measurement interval as defined in [1].
Count:
This field specifies the current number of STAs accommodated by the AP.
Least Interference Level:
The least amount of interference measured on some other channel.
Duration:
The time period the channel switch is requested.
(Some codes could be defined to request the channel switch for unlimited time period.)

2- Channel Switch Response Frame (*ChannelSwitch.Response)*

Msg. Number	Accept/Reject	Switch Timer

Table 3.3: Channel Switch Response Frame

Msg. Number:
This field specifies the corresponding message number of the channel switch request message to which the AP is going to respond.
Accept/Reject:
This field Specifies whether the responding AP agrees on channel switching or not.
Switch Timer:
Indicates the time period after which the physical switch will take place if the switch request has been accepted **OR** the time period after which the AP might be able to accept new requests if the current request has been rejected.

3- Channel Switch Announcement Frame (*ChannelSwitch.Announce)*

Msg. Number	Channel	Duration	Switch Timer

Table 3.4: Channel Switch Announcement Frame

Msg. Number:
This field is an up counter that distinguish between the different channel switch announcement messages.
Channel:
Specifies the new channel the AP is going to switch to.
Duration:
Indicates the time period the AP will use the new channel.
(Some codes could be defined to indicate that the new channel will be used for unlimited time period.)
Switch Timer:
Indicates the exact time period after which the physical switch will take place.

4- Channel Switch Confirmation Frame (*ChannelSwitch.Confirm)*

Msg. Number	Accept/Reject	AP

Table 3.5: Channel Switch Confirmation Frame

Msg. Number:
This field specifies the corresponding message number of the channel switch confirmation message that the STA confirms.
Accept/Reject:
Specifies whether the STA is going to follow over the new channel or not.
AP:
If the STAs does not accept the switch command, the AP field specifies the AP the STA intends to join.

5- Channel Switch Notification Frame (*ChannelSwitch.Notify)*

Msg. Number	Channel	Switch Timer	Duration

Table 3.6: Channel Switch Notification Frame

Msg. Number:
This field specifies the corresponding message number of the channel switch notification message.
Channel:
Specifies the new channel the AP is going to switch to.
Switch Timer:
Indicates the exact time period after which the physical switch will take place.
Duration:
Indicates the time period the AP will use the new channel.
(Some codes could be defined to indicate that the new channel will be used for unlimited time period.)

3.3 Coordinated Adaptation of Transmission Power Across Multiple APs

3.3.1 Service Definition

Transmission power control in WLANs has received a great attention from manufacurers and policy designers. The main objective is to set the emitted power of both APs and STAs to an optimal value so as to reduce co-channel interference between cells operating over the same channel as well as improving network capacity via better spatial reuse of the available WLAN channels. This is actually twofold. Firstly, APs should be able to optimally adjust their own "downlink" transmission power. Secondly, controlling the transmitted power of STAs (Uplink) from the infrastructure should be possible. When lower power levels are used within a BSS, the probability that some STA won't be able to hear the transmission on the channel will become higher. This would mean an increase in the number of hidden nodes which is a major and important concern of all transmission power control schemes.

The IEEE 802.11h includes a transmission power control feature but proposed to satisfy the regulatory domain requirements rather than controling the cell range for interference mitigation. Moreover, there is no method by which an AP individually controls the STA's power level.

We believe that more features should be added to power control protocols towards optimal and fair solutions. Through a couple of coordination messages that could be negotiated between APs themselves as well as APs and STAs. As a consequence, better schemes could be designed on top of those protocols.

Basically, a coordinated transmission power control protocol shall enable an AP to request its neighboring AP(s) to adjust the transmission power level in its cell for some time period. Adjustment could mean increase for load balancing purposes or coverage extension, otherwise decrease for interference mitigation. An AP shall be able to adjust its own transmission power and/or ask its associated STAs to do so. Moreover, a coordinated transmission power adjustment protocol shall support the development of power adjustment solutions at a broader scale which might involve all interfering APs.

3.3.2 Coordinated Transmission Power Adjustment Protocol Specification

- An AP could request transmission power adjustment by sending a transmission power adjustment request message ***TransmissionPowerAdjustment.Request*** to one /all APs from which high interference is being measured for example. The request could be a local request asking the requested AP to adjust the emitted power in its cell or globally asking for power adjustment across all interfering APs.

- Upon reception of the transmission power adjustment request message, the receiving AP shall reply with a message ***TransmissionPowerAdjustment.Response***, the content of this message depends on the request type (local or global). If the request is local then the message just includes whether the power level could be adjusted or not, otherwise it shall include some cardinal relevant information (possibly path loss).
- With global power adjustment request and upon reception of the response message, the new power allocation vector shall be distributed to APs in combination with a message called ***TransmissionPowerAdjustment.Adjust***.
- APs shall confirm the reception of the power adjustment message with a message ***TransmissionPowerAdjustment.Confirm***.
- If an AP has decided to command its STAs to adjust their power level it shall send them the message ***TransmissionPowerAdjustment.Adjust***.

Figure (3.2) illustrates the coordinated transmission power adjustment procedures.

3.3.3 Protocol Triggering Time

The AP triggers this protocols if the accommodated STAs report high interference over the operating channel from neighboring cells.

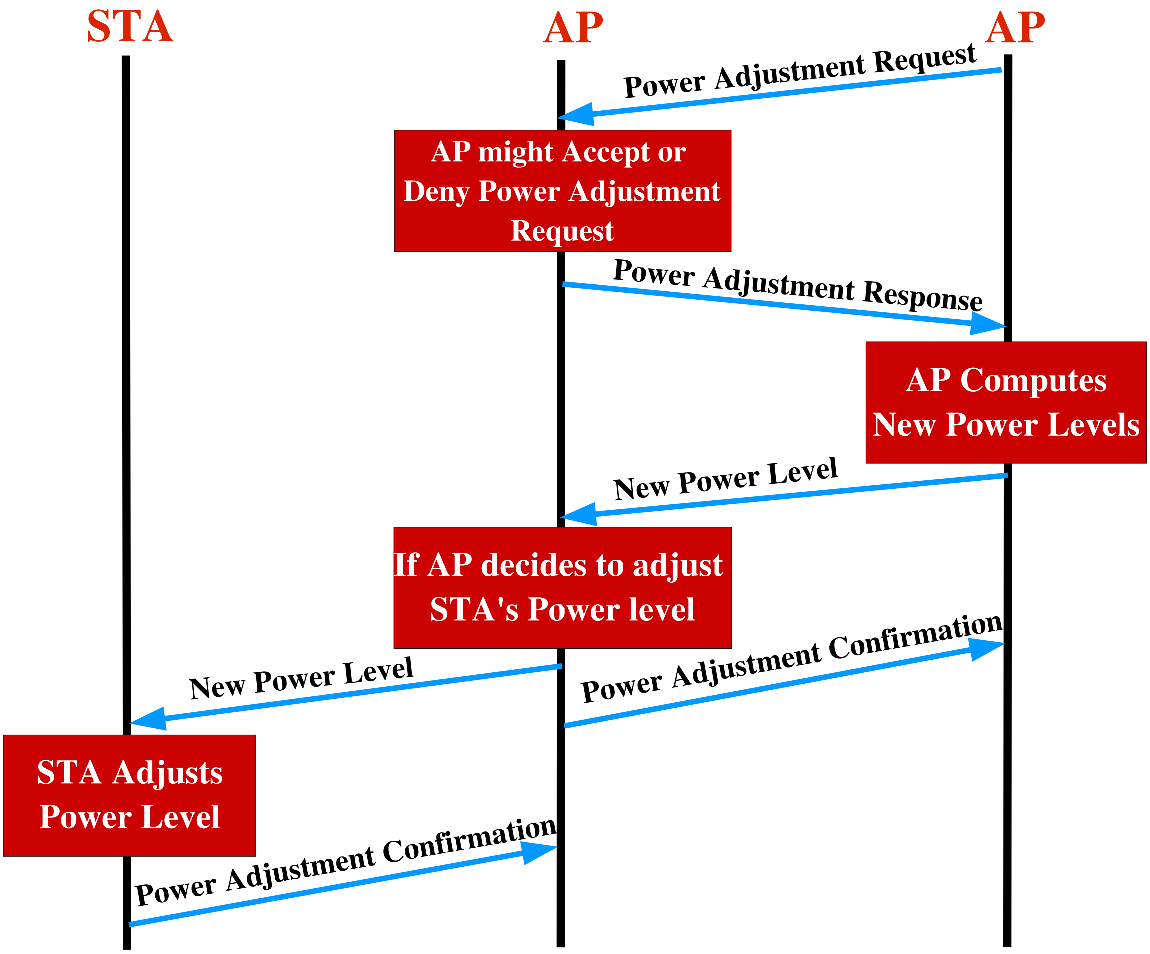

Figure 3.2: Transmission Power Adjustment Protocol Procedure

Notes:

1. To minimize the amount of information to be exchanged between cooperative APs, one might consider only the clients with least Signal to Interference and Noise Ratio (SINR).

2. Reliability issues are an important part of power adjustment protocols but will be discussed in future work.

3.3.4 Frame Structure

This section presents a preliminary frame structure for all frames involved in the Coordinated Dynamic Transmission Power Adjustment Protocol.

1- Transmission Power Adjustment Request Frame (*TrasmissionPowerAdjustment.Request*)

Msg. Number	Local/Global	Duration	Increase/Decrease

Table 3.7: Transmission Power Adjustment Request Frame

Msg. Number:
This field specifies the corresponding message number of the Transmission Power Adjustment Request Message.
Local / Global:
This field specifies whether the request is local or global.
Local: AP requests a neighboring AP to adjust its transmission power if possible.
Global: AP asks for global power adjustment among all interfering APs, where a specific algorithm shall be used to assign new power levels for all interfering APs. With the Global option, the responding AP shall include path loss information.
Duration:
Specifies the time period the new power level should apply.
Increase / Decrease:
An indicator flag that specifies whether the requesting AP asks for power increase/decrease.

2- Transmission Power Adjustment Response Frame (*TrasmissionPowerAdjustment.Response*)

Msg. Number	Accept/Reject	Path loss

Table 3.8: Transmission Power Adjustment Response Frame

Msg. Number: This field specifies the corresponding message number of the Transmission Power Adjustment Response Message.
Accept/Reject:
Specifies whether the request has been accepted or rejected.
Path Loss:
Path loss information required for Global Power Adjustment . **(To be specified later)**.

3-Transmission Power Adjustment Frame (*TrasmissionPowerAdjustment.Adjust)*

Msg. Number	AP/STA	New Power Level

Table 3.9: Transmission Power Adjustment Frame

Msg. Number: This field specifies the corresponding message number of the Transmission Power Adjustment Message.
AP/STA:
Specifies the BSS or the STA that shall use this new power level.
New Power Level:
Specifies the new power level that shall be used by an AP or a STA.

3.4 Capacity Sharing

3.4.1 Service Definition

It might happen that within an ESS some APs are highly loaded while others are only slightly loaded or even idle. In this case APs might negotiate about the load balance and some clients might be hosted by the lightly loaded AP(s) if several STAs can associate to multiple APs.[1]

3.4.2 Uncoordinated Capacity Sharing

Many schmes have been proposed for load distribution among APs. Most of them aim at balancing the load between APs based on some statistical results available at APs. The main metrics that have been used so far are:

1. The number of associated users.
2. The number of transmitted and received frames through the AP in the uplink as well as the downlink in a time period.
3. The fraction of time the channel was busy in a time period.

So far, load balancing policies are mainly based on the following approaches:

[1]We name this protocol mechanism "Capacity Sharing" as a lightly loaded AP shares capacity with a heavily loaded AP.

- APs just provide some guidance information to new STAs via beacons. Decision algorithms reside at the STA side.
- APs might prevent a new STA from joining a cell if capacity rules are going to be violated after STA's association.
- APs might enforce some already associated STA(s) to terminate their sessions and perform a new legacy scan to acquire new other APs.
- APs could switch to some channels other than the operational one and broadcast a couple of advertising beacons supplemented by load information. STAs might capture some beacons and decide to handover to other cells.

In spite of the fact that the previously listed approaches involve some AP-STA cooperation, some drawbacks are associated with these mechanisms:

- The cooperation is not enough and geared to support specific solutions.
- Service disruption and performance degradation to all active STAs during AP hopping on the various channels for status advertisement purposes.
- Service disruption occurrs when STAs switch channels and perform new scanning.
- Although some guidance information might be passed to the STA to help it in selecting a new potential AP, there is no guarantee that this new proposed AP is willing to accept new connections. This implies longer service disruption time due to scanning and some additional signaling frames for the reassociation process.
- Any load balancing goal among APs is harder to be achieved if several STAs decide to handoff to other cells simultaneously (potentially to the same cell). The reason behind that is actually the uncooperated, random, and potentially concurrent individual decision at APs and/or STAs.

A fundamental question is which APs should be involved in load balancing One possible scheme toward load distribution in infrastructure WLANs is to dedicate a load manager which could reside in a WLAN switch responsible for collecting information from all network's APs and deciding which to roam where. Definitely, this might lead to optimal solutions as the central manager has a global view of the whole network. However, such solution implies high unnecessary signaling overhead since most likely STAs will be able to join an AP in their neighborhood and not anywhere. Therefore, a better (less costly) or even most likely optimal decisions could be made at the AP, the AP just needs to command some station(s) to handoff to a specific AP in the STA's vicinity. Relevant neighboring information is anyway available at the AP (via 802.11k) with all STAs connectivity information to their neighbors.

To this end, coordination protocols are promising in minimizing the cost associated with the capacity sharing procedures and achieving load balancing goals. In the next section we describe a coordination protocol toward load sharing between AP. It introduces some new messages as well as new information elements that could be used as base for optimized load balancing policies.

3.4.3 A Coordinated Capacity Sharing Protocol Specification

A coordinated capacity sharing protocol would be:

- A loaded AP shall be able to send a Capacity Sharing Request Message to a neighboring AP ***CapacitySharing.Request***, requesting the sharing of capacity. The message shall contain the amount of capacity needed, the AP load, and the sharing duration.
- The neighboring AP shall be able to reject or accept this request. The answer shall be specified in a new response message called ***CapacitySharing.Response***.
- If the request has been rejected, the requesting AP may select another AP and send a new capacity sharing request message to it. Otherwise, the AP should send a confirmation message ***CapacitySharing.Confirm*** to the hosting AP confirming its previously sent sharing request. This message enables the hosting AP to know whether to reserve the granted capacity or not so as to be able to better deal with other requests that might arrive from other neighbors.
- The requesting AP shall send a join request message ***JoinAccessPoint.Request*** to the intended STAs supplemented with the new AP cardinal information.
- Upon receipt of this message, a STA shall respond with a join response message ***JoinAccessPoint.Response*** indicating whether it accepts the join request or not.
- The ***JointAccessPoint.Response*** message triggers a transparent forwarding protocol, whereby all the traffic designated for the moved station(s) should be buffered and transferred to their new APs. This will drastically reduce losses and a seamless channel capacity sharing is achieved.

Actually, the ***CapacitySharing.Request*** and ***CapacitySharing.Response*** messages provide more control on capacity sharing. They help in achieving stability by preventing uncoordinated and potentially concurrent random joining of STAs among APs, which make load balancing hard to be achieved.
Figure (3.3) depicts the Capacity Sharing Protocol procedure:

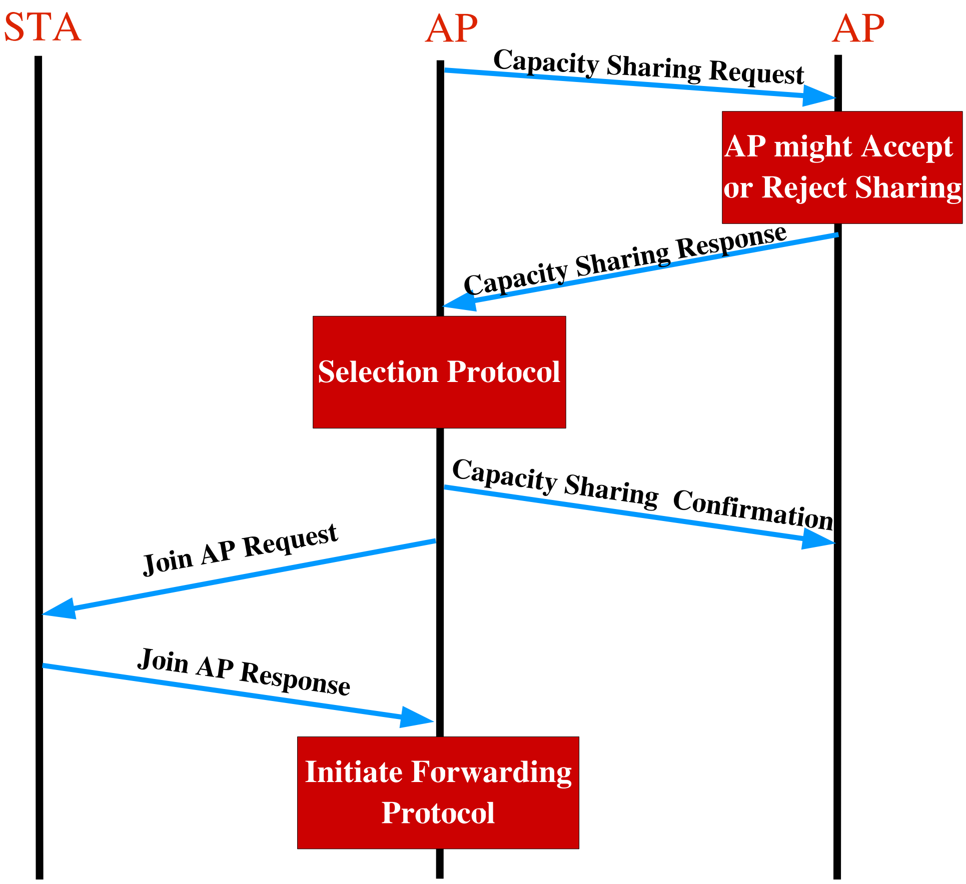

Figure 3.3: Capacity Sharing Protocol Procedure

3.4.4 Protocol Triggering Time

The AP shall trigger this protocol if its load is above a predefined threshold for a period of time and it knows that some neighbor is slightly loaded.

3.4.5 Frame Structure

This section presents a preliminary frame structure for all frames involved in the Capacity Sharing Protocol.

1- Capacity Sharing Request Frame (*CapacitySharing.Request*)

Msg. Number	Capacity Needed	Load	Rate Index	Sharing Duration

Table 3.10: Capacity Sharing Request Frame

Msg. Number:
This field specifies the corresponding message number of the Capacity Sharing Request Message.
Capacity Needed:
This field indicates the amount of capacity required.
Load:
Specifies the current load on an AP as defined in Section 3.2.5.
Rate Index:
This field reflects the characteristics of the physical rates of the frames transmitted and received by the AP during a time period T. The Rate Index could guide load sharing schemes in determining the best cell to be assigned to STAs for load distribution purposes. The idea behind this information element stems from the fact that, in IEEE 802.11, low physical rate STAs will drastically pull down the throughput of high physical rate STAs if they share the same medium. The rate index shall be computed as follows:

$$RateIndex(RI) = \sum_{i=R_{min}}^{R_{max}} R_i * T_i/(R_{max} \times T) \tag{3.2}$$

where R_{min} and R_{max} are the minimum and maximum supported physical rates respectively. R_i is the physical rate i, T_i is fraction of time the AP spent transmitting and receiving frames at physical rate R_i, and finally T is the total observation time period. In IEEE802.11b, for example, $R_i \in \{1, 2, 5.5, 11\}$Mbps.
Sharing Duration:
The time duration the requesting AP needs the requested capacity.

2- Capacity Sharing Response Frame (*CapacitySharing.Response*)

Msg. Number	Accept/Reject	Cardinal Rules	Capacity	Load
Rate Index	—-	—-	—-	—-

Table 3.11: Capacity Sharing Response Frame

Msg. Number:
This field specifies the corresponding message number of the Capacity Sharing Response Message.
Accept/Reject:
This is a one bit field set to indicate whether the responding AP accepts or denies the request.
Cardinal Rules:
Any Specific Rules the hosting AP insists.
Capacity:
This field represents the amount of capacity a hosting AP is willing to share.
Load:
Specifies the current load on an AP as defined in Section 3.2.5.
Rate Index:
Reflects the characteristics of the physical rates of the frames transmitted and received by the responding AP. Rate Index has been specified previously. It guides the requesting AP in deciding on the STAs to be commanded to join the neighboring cell so as not to degrade the performance of its already joined STAs.
Retry Time:
This field includes the time after which the AP might have some capacity to be shared if it denies sharing requests temporarily. This guides a loaded AP which receives reject responses in determining which AP it might ask later on.

3- Capacity Sharing Confirmation Frame (*CapacitySharing.Confirm*)

Msg. Number:
This field specifies the corresponding message number of the Capacity Sharing Confirmation Message.
Confirm:
This flag indicates whether the requesting AP is going to move some STA(s) to the hosting AP or not.

Msg. Number	Confirm	Capacity	——-

Table 3.12: Capacity Sharing Confirmation Frame

Capacity:
This field denotes the load of the STA(s) which are going to join the hosting AP if the AP does know this value at this stage.

4- Join AP Request Frame (*JoinAP.Request)*

Msg. Number	Channel	Cardinal Rules	Session Termination Time

Table 3.13: Joint AP Request Frame

Msg. Number:
This field specifies the corresponding message number of the Join AP Request Message.
Channel:
This field specifies the channel the receiving STA shall switch to.
Cardinal Information:
Any specific important rules insisted by the hosting AP.
Session Termination Time:
The time span that will elapse after a response message has been received and before the current connection with the AP will be terminated.

5- Join AP Response Frame (*JoinAP.Response)*

Msg. Number	Accept/Reject

Table 3.14: Joint AP Response Frame

Msg. Number:

This field specifies the corresponding message number of the Join AP Response Message.

Accept/Reject:

This filed specifies whether the STA will handoff to the new proposed AP or not.

Notes:

1. **Status Advertisement:**
   With Coordinated Capacity Sharing Protocols, a lightly loaded AP could send an advertising message to the STAs in neighboring cells via their APs. Therefore, APs do not need to hop over other channels to invite STAs to their cells. The Capacity Sharing Response frame *CapacitySharing.Response* could be used for this purpose.

2. **Selecting a hosting AP:**
   As the AP has a broader view of the network, efficient or even optimal decisions might be achieved. Otherwise, STAs will rely on their information base and perform local selection decisions. The procedure by which a hosting AP is selected from a list of neighboring APs is policy specific. Among many other schemes, the following schemes might be used:

   - The simplest choice is the selection of the less loaded AP.
   - The decision could be based not only on APs load but also on the connectivity of the candidate STA(s) to the AP which they will join.
   - The Cell Rate Index and the potential rate a candidate STA will use in the new cell.
   - A policy that uses a combination of the relevant parameters.

3. The purpose of the selection protocol in Figure 3.3 is to select some STA(s) that are to be commanded to associate to another AP. The policy by which such STA(s) is selected is beyond the scope of this report.

4. The objective of the Forwording protocol in Figure 3.3 is to handle the incoming traffic destined to the STA commanded to roam to a neighboring STA.

5. **Question: Could a STA reject a Join Access Point message?**

Chapter 4

Simulation Setup and Preliminary Results

This chapter presents preliminary performance evaluation results of the proposed AP-Coordination protocols in previous chapters for IEEE802.11b based WLANs. The performance results are obtained by means of simulation using the NCTUns simulator.

4.1 Dynamic Channel Switching

4.1.1 Scenario

The real-world case, which serves as a basis for this work, consists of a large area like a departure hall in an airport. Due to the large area as well as a potentially high number of users, five 802.11b APs that operate on different IEEE 802.11b channels are placed within this hall. As the number of non-overlapped channels supported by IEEE802.11b is three, two pair of APs will interfere with each other. The channels were assigned as shown in figure 4.1. Users appear in this hall at different points in time and at different places. They have nomadic mobility degree, i.e., users start their devices and stay at a constant position during their active session. Two different user types may be present: either FTP or VoIP clients.
We investigate the real-world case with two scenarios. Firstly, we consider only 40 FTP users, while secondly only 30 VoIP users are present within the WLAN area. FTP as well as VoIP 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. The cables connecting the APs to the server (via an 802.3 switch) have a 100 Mbit/s bandwidth.

4.1.2 Performance Evaluation Metrics

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. AP's

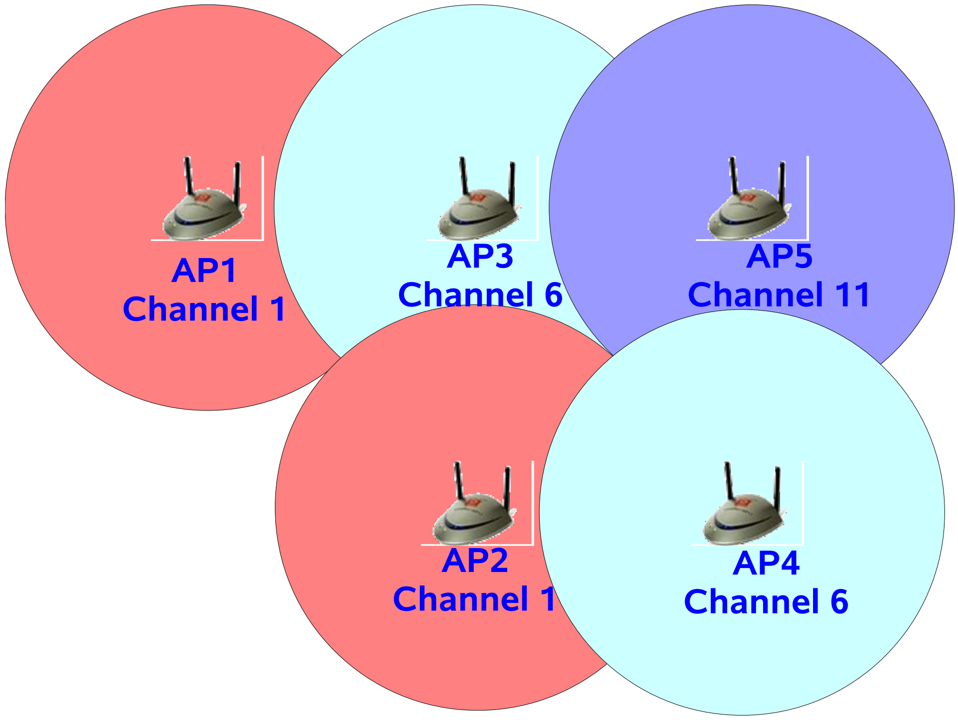

Figure 4.1: AP Positioning and Channel assignment

and STA's throughput and the behavior of the throughput during and after channel switching is the first metric. Despite packet loss, the end-to-end delay is the most critical component for VoIP. In simulations investigating VoIP, the average round-trip time is measured additionally. The average round-trip time averaged over all STAs is a second metric. We base our comparision between coordinated and uncoordinated channel switching on those metrics.

4.1.3 Traffic Models

Every FTP user downloads 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)[3]. Each VoIP call is modeled by a bi-directional, isochronous audio flow. With ITU-T's G729 codec (which is widely used in 802.11 devices) and an audio frame length of 10ms, this results in an audio packet size of 10 bytes. The VoIP traffic was generated using the RTP/UDP traffic generator which comes with NCTUns simulator[2].

4.1.4 Results

FTP Scenario:

Figure (4.2) 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 the 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 been 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 (4.3) shows that the connectivity disruption problem has been resolved through the channel switch notification message which informs STAs about the exact time the physical switch will occur.

Figure (4.4) depicts the aggregate throughput of two interfering APs after they have simultaneously switched to the same channel. The switching has been occurred around second 62 where a peak in the throughput at that time can be noticed. As the two APs have selected the same new channel, no gain in the aggregate throughput has been achieved after channel switching. On the other hand figure (4.5) shows that AP 2 throughput has considerably degraded. This is due to the fact that many STAs were not able to receive the switch command and consequently they needed to perform legacy scanning.

Figure (4.6) 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, figure (4.7) compares between coordinated and uncoordinated channel switching. These results can be better explained referring to figure 4.1. AP2 measures high interference on its primary channel 1. It has decided locally and individually to switch to another less interfered channel which was found to be channel 11 (Uncoordinated Channel Switching). We have found that around 6.08kbps per user throughput improvement has been gained after channel switching (the dashed line of figure 4.7). However with coordinated channel switching, AP2 has requested its neighboring AP (AP1) to switch its channel to a new one, AP1 has also found channel 11 to be the best candidate channel to switch to. In this case and after channel switching, we have noticed that the per user throughput has been improved by around 73.52kbps. This big difference can be simply explained as follows: Firstly, the amount of interference does not only depend on the location of the APs and the amount of overlapp between them but also on the spacial distribution of STAs in the interfering cells. Secondly, the aggregate throughput after channel switching is highly related to amount of interference the switched devices (AP and its STAs) constitute on other neighboring cells operating originally over the new selected channel. Actually, this observation should influence WLAN dynamic channel switching policies.

VoIP Scenario:

Figures (4.8) and (4.9) show the behavior of the aggregate throughput of the VoIP users with coordinated and uncoordinated dynamic channel switching. Figure (4.8) depicts the throughput of the VoIP users for coordinated and uncoordinated channel switching. It is clear that a degradation in performance has occurred when AP 2 (Referring to figure 4.1) decides individually to move to another channel. This degradation in the throughput is due to the fact that the switched STAs accommodated by AP 2 have started to highly interfere with the STAs originally operating over the new selected channel in the neighboring cell. Figure (4.9) shows that the degradation in the aggregate throughput of VoIP STAs during the switching interval. Higher loss in the throughput has been measured in the case when AP 2 has locally and individually decided to switch its channel. Additionally the average round trip propagation delay of the STAs have been measured to be 26.2ms when AP 1 switches its channel compared to 52.81 ms when AP 2 switches its channel.

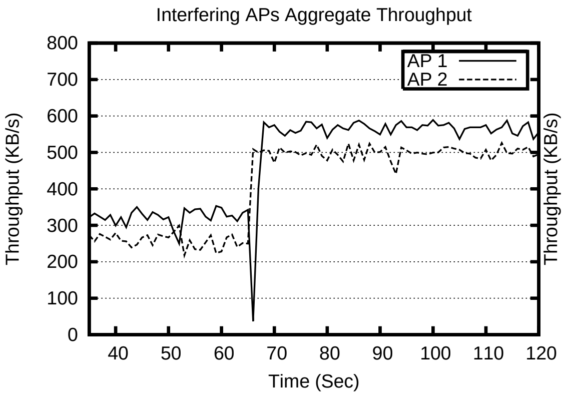

Figure 4.2: Uncoordinated Channel Switching - FTP Scenario

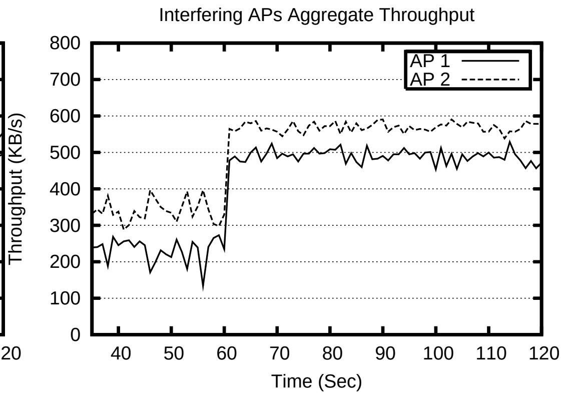

Figure 4.3: Coordinated Channel Switching - FTP Scenario

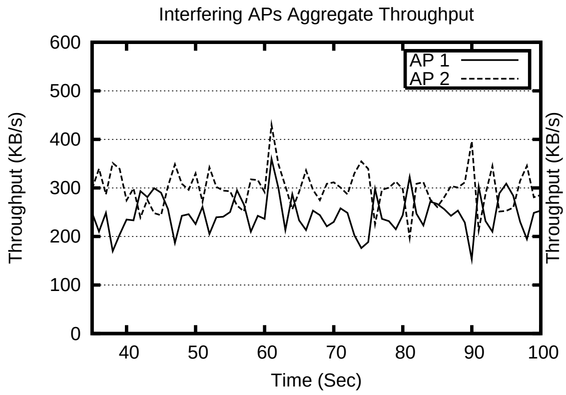

Figure 4.4: Simultaneous uncoordinated Channel Switching- FTP Scenario

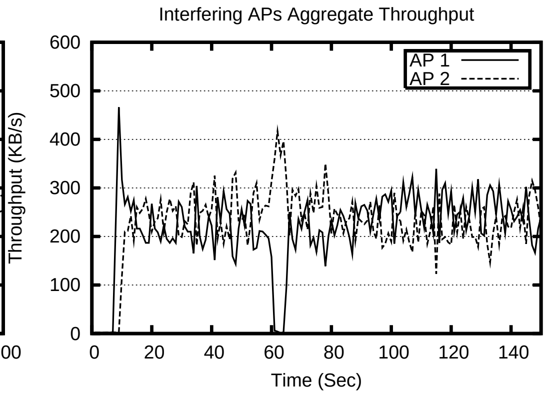

Figure 4.5: Simultaneous uncoordinated Channel Switching- FTP Scenario

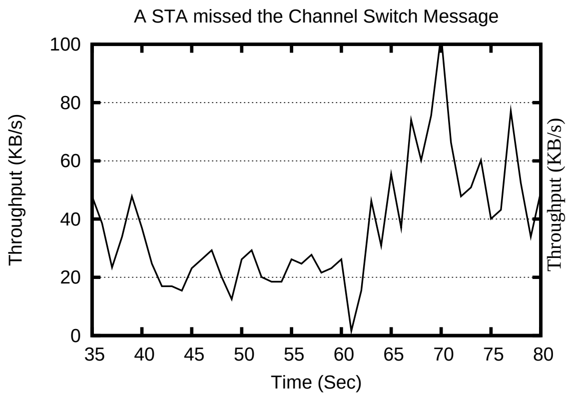

Figure 4.6: Throughput of a STA missed Switch Command- FTP Scenario

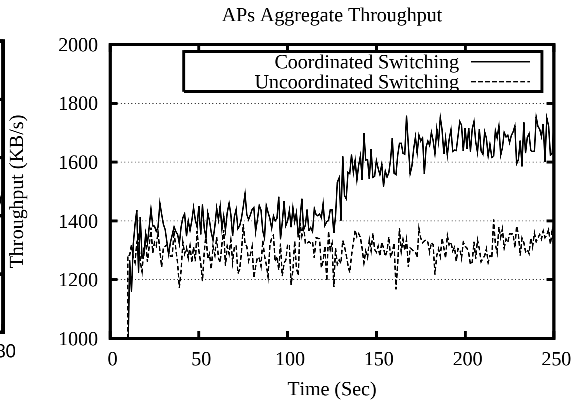

Figure 4.7: Coordinated and Uncoordinated channel switching- FTP Scenario

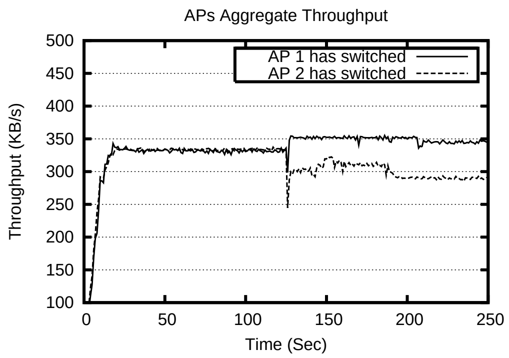

Figure 4.8: Channel Switching - VoIP

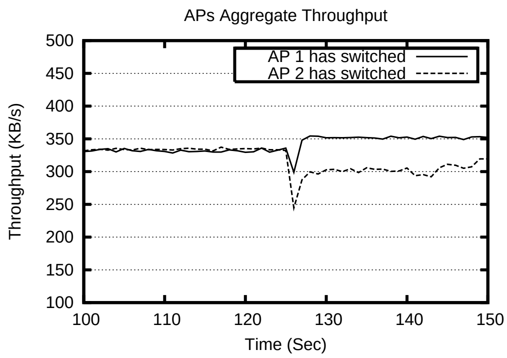

Figure 4.9: Channel Switching - VoIP

4.2 Dynamic Power Control

4.2.1 Scenario

We investigate the dynamic power adjustment protocols based on the same scenario described in the previous section with the architecture shown in figure 4.1. However, we consider here only FTP users.

4.2.2 Performance Evaluation Metrics

Our performance metric is the same as for the dynamic channel switching namely: Aggregate WLAN Throughput which is computed every 1 second. We show the effect of power adjustment on APs throughput through simple coordinated and uncoordinated power adjustment criterions.

4.2.3 Traffic Models

Also here every FTP user downloads a very large file. All TCP users utilize greedy TCP with packet length of 1000 bytes. The TCP traffic was generated with Jugis Traffic Generator (jtg)[3].

4.2.4 Results

Figure (4.10) presents a comparison between the aggregate throughput of all STAs before and after dynamic power adjustment (around second 100). The figure also shows that the throughput is higher when both APs and STAs have adjusted their transmission power level. The used criterion is a simple synchronous power adjustment policy whereby the power level was reduced from its original value 100mw to 50mw. Figure (4.11) shows the behavior of the aggregate throughput of all STAs before and after tranmission power adjustment. On the other hand, figures (4.12 and (4.13)) show the behavior of each interfering AP pair (AP 1,AP 2) and (AP 3,AP 6) before and after adjusting the emitted power level to 50mw. One can deduce that Cell 2 and Cell 6 suffer more from interference, hence, their throughput is lower. The figures also show the throughput improvement after transmission power level adjustment.

Figures (4.14 and 4.15) depict the results of another simple synchronous power adjustment policy where an AP just tries to maintain a received power level at the farthest STA but also not exceeding a minimum and maximum levels which we have assumed to be 50mw and 100mw respectively. From those figures, it is clear that throughput of the APs is about the same after transmission power adjustment which means some kind of fairness has been achieved. Finally, in (4.16 through 4.18), we show the effect of uncoordinated power adjustment policies. Figure 4.16 shows the throughput of AP 1 while figure 4.17 depicts the throughput of AP 2, (AP 1 and AP 2 use the same channel as shown in figure 4.1). Each AP starts with a power level of 50mW and individually adjust its power level simply if its STAs report an increase in the power level from the interfering AP. As a results of this independent (asynchronous) power adjustment, each AP will increase its power level whenever its neighbor has increased its power. Therefore both APs will end up with the maximum allowed power level, hence nothing has been gained. This scenario highly proves that power adjustment policies should be based on active negotiation and agreement between APs.

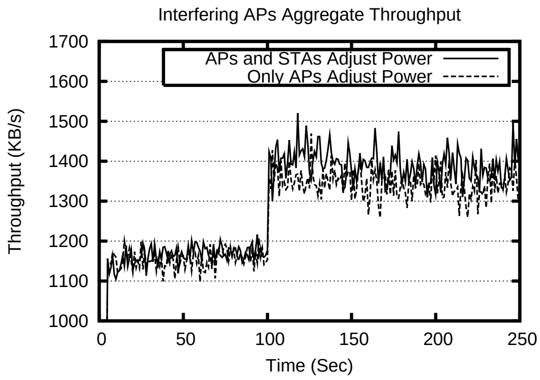

Figure 4.10: Synch. Tx. Power Adjustment

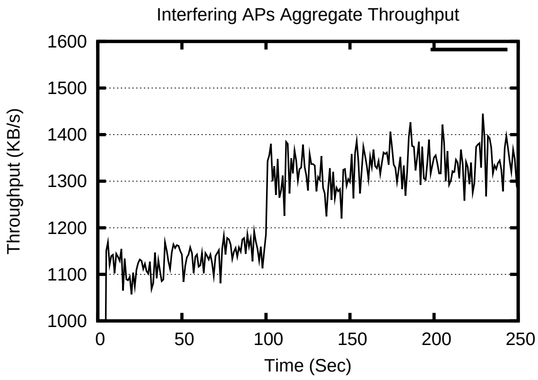

Figure 4.11: Synch. Tx. Power Adjustment

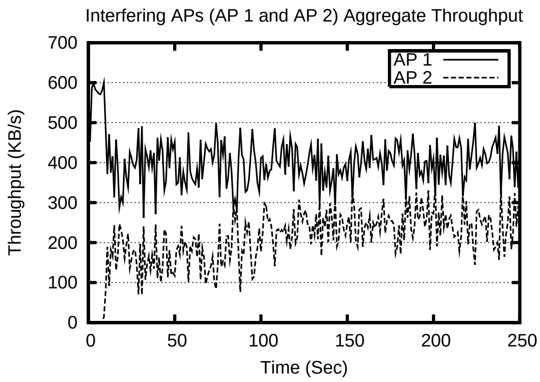

Figure 4.12: Synch. Tx. Power Adjustment

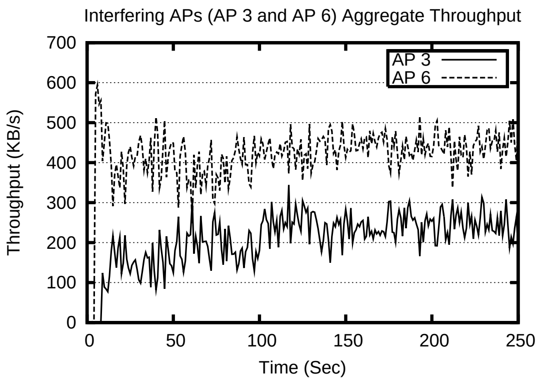

Figure 4.13: Synch. Tx. Power Adjustment

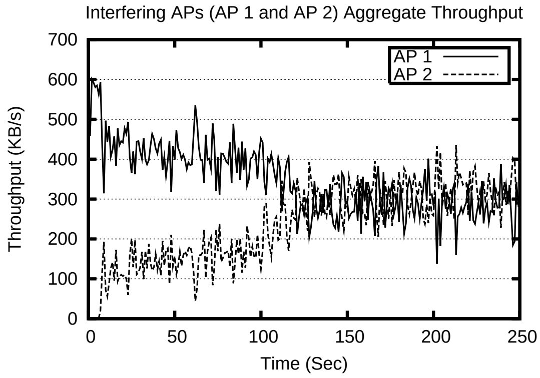

Figure 4.14: Synch. Tx. Power Adjustment

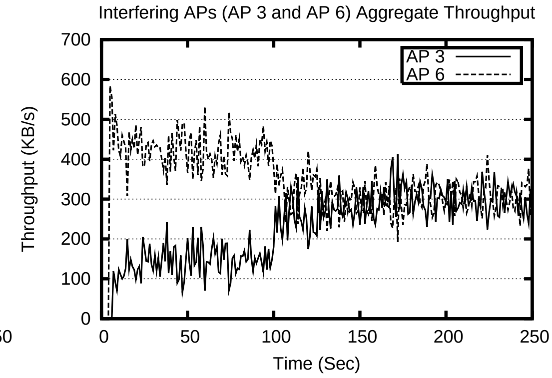

Figure 4.15: Synch. Tx. Power Adjustment

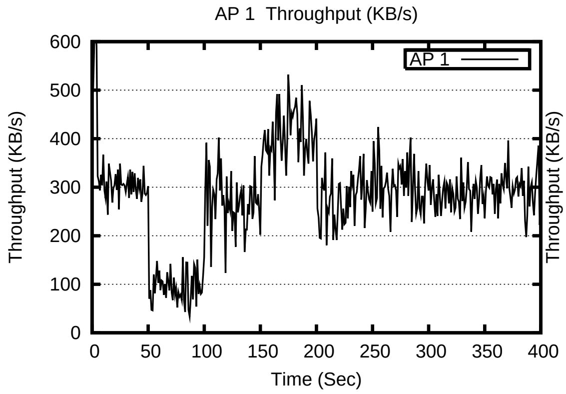

Figure 4.16: Uncoordinated Asynch. Tx Power Adjustment

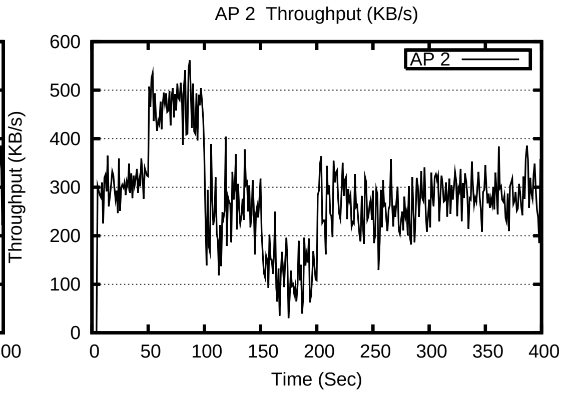

Figure 4.17: Uncoordinated Asynch. Tx Power Adjustment

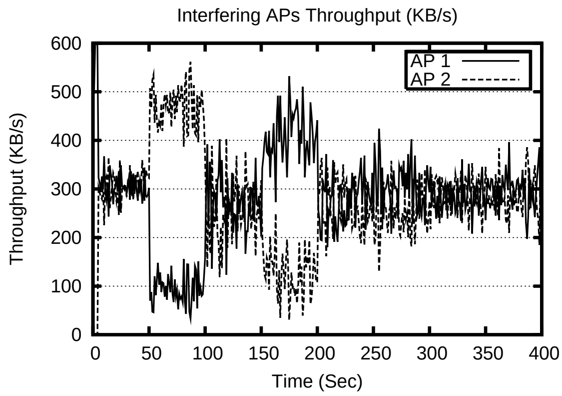

Figure 4.18: Uncoordinated Asynch. Tx Power Adjustment

Chapter 5

Conclusions and Future Work

In this report we have attempted to present a framework for a cognitive WLAN via a set of Inter-AP coordination protocols. We focus on protocols that support three important services: Dynamic Channel Switching, Dynamic Transmission Power Adjustment and Capacity sharing. While Dynamic Channel Switching and Dynamic Transmission Power Adjustment have been proposed to mitigate interference, Capacity Sharing aims to distribute the WLAN capacity evenly among APs. An extensive study and detailed design including reliability issues as well as signaling overhead still remain to be investigated. Dynamic Power Adjustment and Dynamic Channel Switching are both candidate solutions for interference problems. It seems to be interesting to compare the efficiency of both solutions in terms of complexity, performance, signaling and overhead. Moreover, we will evaluate the performance and efficiency of our coordination protocol designed to support capacity sharing and load balancing policies by conducting more simulation studies. In fact, it is our goal to conduct all these issues in the near future.

Bibliography

[1] *IEEE 802.11k*, Radio Resource Measurement, IEEE Draft 2.0. February 2005.

[2] http://nsl.csie.nctu.edu.tw/nctuns.html.

[3] http://www.cs.helsinki.fi/u/jmanner/software/.

[4] *IEEE802.11F*, IEEE Recommended Practice for Multi-Vendor Access Point Interoperability via an Inter-Access Point Protocol Across Distribution Systems Supporting.

[5] A. Balachandran P. bahl and G. Voelker. Hot Spot Congestion Relief in Public-area Wireless Networks. In *IEEE Workshop on Mobile Computing Systems and Applications,Callicoon, NY*, June 2002.

[6] G. Fanglu and C. Tzi-cker. Scalable and Robut WLAN Connectivity Using Access Aoint Array. In *Proc. of the 2005 International Conference on Dependable Systems and Networks (DNS'05) Vehicular Technology Conference 2004-Fall (VTC2004-Fall)*, 2005.

[7] A. Mishra V. Brik S. Banerjee A. Srinivasan and W. Arbaugh. Efficient Strategies for Channel Management in Wireless LANs. Technical report, June, 2005.

[8] H. Velayos and G. Karlson. Load Balancing in Overlapping wireless LAN cells. In *IEEE ICC 2004, Paris, France*, June 2005.

[9] J. Wang and L. Bao. Mobile Context Handoff in Distributed IEEE802.11 Systems. In *International Conference on Wireless Networks, Communication and Mobile Computing, ,Vol. 1, pp.680-685*, 2005.