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A Framework for Interference Mitigation in Multi-Cell 802.11 Wireless LANs

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Abstract

Despite being robust and efficient within the same Basic Service Set (BSS) of a Wireless LAN (WLAN), the CSMA/CA fails to satisfy the QoS requirements for many users in a dense WLAN due to the interference problem. This paper proposes a framework for interference mitigation in multi-BSS infrastructure 802.11 WLANs. Our interference mitigation approach is based on Access Point (AP) Coordination. With this approach, interfering APs negotiate and switch from the 802.11 CSMA/CA to a time slotted mechanism whenever users' QoS is observed to be degraded and diagnoses conclude that the cause is high interference. Unlike previous work published in this area, the proposed approach is in alignment with the ongoing discussions within the standarization bodies in the sense that system operation is driven by measurements of interference conditions rather than fixed models which may not apply to all scenarios. We utilize the wireless bandwidth and improve the fairness among WLAN users. We present results of detailed simulation experiments as well as real implementation.

Contents

Chapter 1

Introduction

Due to the diminishing costs of wireless devices, Wireless Local Area Networks (WLANs) [1] have been massively deployed in public places such as: university campuses, offices, apartments, airports and hotels. Nowadays, more and more devices are equipped with WLAN access capability and WLAN is becoming the preferred access technology for an increasing number of users. In alignment with the growth of WLANs, users demands are also increasing and their satisfaction becomes a challenging task for both network designers and administrators.

In multi-BSS infrastructure WLANs, each access point (AP) is usually assigned a fixed channel. As in all communication systems, the 802.11 spectrum is a scarce resource. The number of supported channels by any IEEE 802.11 standard is limited and among all channels, only few of them do not overlap. WLAN administrators try to improve users' connectivity with their APs by deploying a high density of APs. However, the dense deployment of APs can introduce additional mutual interference unless the network is carefully planned and tuned.

In current 802.11 WLANs, channel access is governed by the CSMA/CA mechanism. Despite that this mechanism is robust within a single BSS, it fails to provide acceptable service for many WLAN users in multi-BSS deployments when the traffic load gets high. As the traffic load increases, interference among neighboring BSSs increases, leading to collisions and retransmissions, which in turn add to the load and consequently to more collisions.

In this work, we propose a framework to combat interference in infrastructure 802.11 WLANs. Our interference mitigation approach is based on AP Coordination. With this approach, APs of interferring BSSs negotiate and employ a time slotted channel access mechanism if QoS is observed to be degraded and diagnoses reveal that the cause is interference. When interference conditions improve, APs negotiate and switch back to the CSMA/CA modus.

1.1 Relevant Work and Background

1.1.1 A brief overview of 802.11 MAC

The 802.11 MAC DCF protocol is based on CSMA/CA. The CSMA/CA works as follows: A node wishing to transmit a data packet first has to sense the medium, and, if no activity is detected, the node waits a randomly selected additional period of time before it transmits if the medium is still free. If the receiving node receives the packet intact, it issues an ACK frame to confirm the reception of a data packet. The ACK frame completes the process if successfully received by the sender. The sender assumes a collision to have occurred if the ACK frame is not successfully received. In this case, the data packet is transmitted again after deferring another random amount of time.

1.1.2 The Notion of Interference and its Impact on WLAN Performance

In this work we constrain ourselves to the case of non-overlapping channels. Interference will denote hereafter a phenomenon where signals transmitted from one BSS spread to a neighboring BSS that operate over the same channel. An interference region is the area around a sending node where its signals are powerful enough to affect the ability of other nodes to decode other signals from third party over the same channel.

Unfortunately, in infrastructure WLANs, the CSMA/CA is robust and works efficiently within a single BSS but not sufficient to alleviate the interference problem in an Extended Service Set (ESS) environment of high density of deployed APs and at high traffic load. Signals from neighboring BSSs on the same channel can prevent local nodes from transmitting their frames, even if intended receivers might not be within an interference region of the intended receiver (This is known as the *Exposed Node Problem*). Similarly, while a node in a BSS is receiving a frame, a coincident in time signal from a neighboring BSS may corrupt the frame under reception if the interfering signal has comparable strength relative to the signal strength of the frame being received. This is known as the *Hidden Node Problem.* It leads to collisions and errors which will cause discards and retransmissions. Generally, collisions among nodes (STAs and APs) influence and degrade the performance of all nodes since the average time required to transmit a frame successfully by any node increases gradually as the number of collisions in the BSS increases.

1.1.3 Interference Mitigation

The 802.11 standard provides the Request to Send/Clear to Send (RTS/CTS) mechanism to reduce interference. However, this mechanism is not efficient enough due to the following shortcomings:

- RTS/CTS may not work across multiple BSSs. The main design assumption with RTS/CTS is that all nodes within sender and receiver vicinity will hear the RTS or CTS packets and set their NAV accordingly. However, this assumption may not necessarily hold in multiple BSS deployments, whereby a node(s) may be busy receiving a frame generated within its BSS and therefore will not get the RTS or CTS sent by a neighboring BSS.
- RTS/CTS introduces considerable overhead and may unnecessarily decrease the communication efficiency (see [3]).

References [4, 5] propose coordination-based channel assignment policies to mitigate interference in WLANs. APs cooperate through sharing of interference information via the backhaul and agree on the channel assignment that each one has to use. In [6], we developed an inter-AP protocol for dynamic channel selection in IEEE 802.11 WLANs. The protocol facilitates the implementation of numerous centralized channel selection policies by enabling a cluster of interferring BSSs to negotiate and agree on the channel to be used within each BSS for the sake of interference reduction. Although these references show some improvement in system performance through novel channel assignment policies, this improvement is unfortunately limited especially under high load. The reason is the lack of nonoverlapping channels the 802.11 standard supports, which requires the assignment of same channel to mutually interferring BSSs. Thus, solutions addressing exclusively channel selection have a limited improvement potential, and additional coordination among multiple BSSs using a single channel is essential. The usage of partially overlapping channels (not considered in depth in this report) increases the system capacity but does not resolve the potential of interference.

1.1.4 Coordinated Channel Access

The IEEE 802.11e standard (enhanced to support QoS with multimedia) coordinates channel access within a BSS. Nevertheless, the standard does not address the problem of overlapping BSSs/cells that use the same channel. There is no mechanism beyond CSMA/CA to coordinate the channel access across BSSs, thereby there is no guarantee that during the transmission of a frame by some STA in a time slot other STAs belong to neighboring BSSs will remain silent. This is due to the fact that BSSs operate asynchronously and independently.

The authors of [7] and [8] address time slotted access schemes with 802.11. Nonetheless, their work focuses on solving implementation challenges of a time slotted approach with 802.11 adaptors in small testbeds of two nodes. Hence, the interference mitigation problem was not directly addressed.

The work of Bejerano et. al. [9] presents a managed WiFi system to support QoS in 802.11 WLANs with multiple BSSs. It uses Inter-AP coordination to allow overlapping BSSs coordinate their operation during up-link transmissions of the PCF modus so as to improve fairness among STAs. The presented solution proposes to assign disjoint time slots to BSSs that interfere with each other, whereby during a time slot assigned to one BSS other interfering BSSs should remain silent (i.e Blocked). The length of the time slot that each BSS gets depends on the number of users the AP accommodates. Although the solution has shown improvement, still it has some drawbacks: First, the authors assume a circular channel model which is not the case in practice due to fading. Second, the PCF modus is not supported by most IEEE 802.11-compliant products. Third, the authors consider only uplink transmissions while in many cases most of the traffic is downlink and the collision rate due to hidden APs is quite high. One example is Internet type traffic in which the uplink traffic volume is relatively light and most of the traffic is downlink coming from Internet. Fourth, the BSS-based scheduling does not efficiently utilize the wireless bandwidth since it does not exploit exposed nodes within interfering BSSs which can simultaneously send their packets.

Recently, there has been a significant amount of research activities in the area of wireless mesh and sensor networking, aiming for network performance enhancement through channel access coordination [10, 11, 12, 13, 14]. While we are following the same general ideas of scheduling transmissions, our work differs from the foregoing efforts in that we are aiming at development of a holistic framework for interference mitigation, covering interference estimation and switching between a CSMA/CA and a time slotted access schemes depending on interference conditions. We also consider a different approach for solving the scheduling problem.

1.2 Report Contribution

This report proposes a framework to combat interference in infrastructure 802.11 WLANs based on AP Coordination. With the proposed approach, WLAN APs that operate in a CSMA/CA modus over the same channel observe the QoS in their BSSs. If QoS is observed to be degraded and measurement-based diagnoses reveal that the cause is interference; APs negotiate, agree on disjoint time slots to access the wireless channel, and change to a time slotted operation modus. When interference conditions improve, APs negotiate and switch back to the CSMA/CA modus. By combining the CSMA/CA and a time slotted access scheme, we try to preserve the best features of both schemes. Our main goal is to improve the WLAN bandwidth utilization and the fairness among stations (STAs). In alignment with the ongoing discussions of upcoming standards and the recent results of [2] which advocate measurements based approaches, both switching principles and discovery of interference relations, and thus the identification of links which have to be time decoupled is based on measurements.

1.3 Report Structure

The rest of this report is organized as follow: In Chapter two, we present our interference mitigation framework. Chapter three discusses various models for identification of interference relations among wireless links. Slot assignment algorithms are described in Chapter four. A brief description of signalling protocols is provided in Chapter five. Chapter six evaluates the performance of the proposed framework via detailed simulation and real experiments and Chapter seven concludes this report.

Chapter 2

A Framework for Interference Mitigation

This chapter presents the framework for interference mitigation in IEEE 802.11 multi-BSS infrastructure based WLANs. The assumed system model is first described. Then we give an overview of system operation and describe its blocks.

2.1 System Model

We consider an ESS 802.11 WLAN (see figure 2.1) composed of $\boldsymbol{N}$ APs and $\boldsymbol{M}$ stationary STAs, ($\boldsymbol{M} \geq \boldsymbol{N}$). APs are assumed to operate on non-overlapping channels. Nonetheless, extensions to the case of partially overlapping channels is easily possible in the framework. Some APs are assigned the same channel. APs are connected to a single distribution system (DS). APs provide communication services to the $\boldsymbol{M}$ STAs that reside within their coverage area, which is as shown in figure 2.1 assumed to be irregular due to fading. At any time instant, a STA is associated to a single AP. The coverage areas of APs are assumed to overlap. Neither the location of an AP nor its operational channel is known to the other APs.

2.2 Solution Idea

We exploit the efficiency of a temporal separation approach to mitigate interference in multi-BSS 802.11 WLANs. As pointed out previously, the 802.11 CSMA/CA channel access scheme provides best effort service. It is easy to implement, does not need synchronization among contending nodes, and works well at low traffic load. At increased traffic levels, frequent collisions and retransmissions due to interference occur, degrading the QoS the wireless users experience. On the other hand, a collision-free channel access scheme, such as a time slotted access scheme, is appealing and performs better than the CSMA/CA at high traffic loads despite the signalling overhead it adds [9, 30].

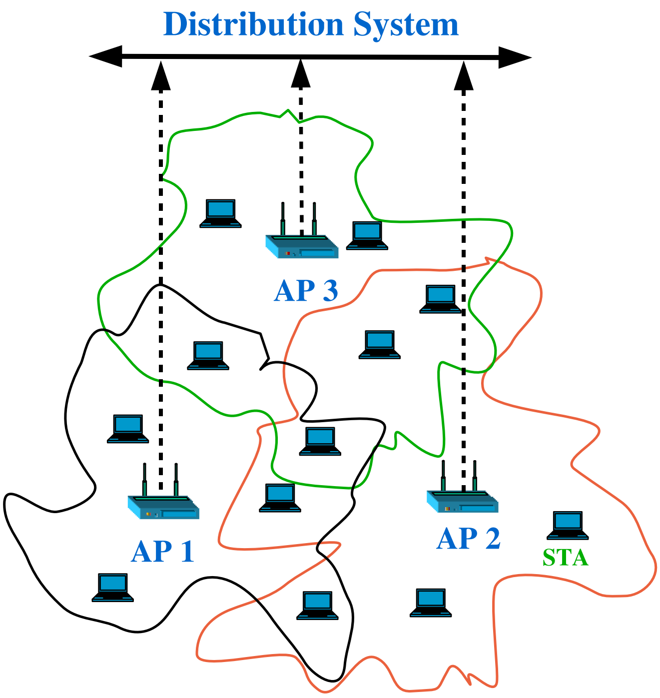

Figure 2.1: Network Model

Our results (provided in section 6.2.3) have shown that, there is a threshold beyond which a time slotted access scheme starts to degrade system performance. We combine the CSMA/CA and a time slotted channel access scheme. To preserve the features of current 802.11 MAC, interfering BSSs switch from the CSMA/CA access mechanism to the time slotted mechanism only if high interference is detected. A switch-back to the CSMA/CA operating modus takes place when interference conditions are observed to improve.

In general one could argue that the transmission in time slots and consequently blocking some communication in neighboring BSSs would waste the WLAN capacity. On the one hand, this might be true, but on the other the reduction of overall collisions and consequently the reduction of the time span a MAC protocol needs to hold a packet until it is successfully transmitted would probably compensate this capacity reduction. Despite the importance of aggregate throughput of all users, the portion that each user gets is very important. One should also try to maximize the number of users that are happy with the offered service.

2.3 Solution Description

An architectural block diagram for AP operation is shown in Figure 2.2. The system works are follows: While providing services to the associated users, WLAN APs observe the QoS (i.e latency, how easy they can deliver packets to associated users ?, estimate of collision rate, interference level) in their BSSs. Based on interference conditions and access mode switch rule set, the BSSs switch between a CSMA/CA and a time slotted operation modes. The basic system blocks are: **Interference Conditions Estimator, Channel Access Scheme Selector, a Slot Assigner/Scheduler, and a Coordination Protocol.** In this section and the following ones, we elaborate our design principles of the various system components.

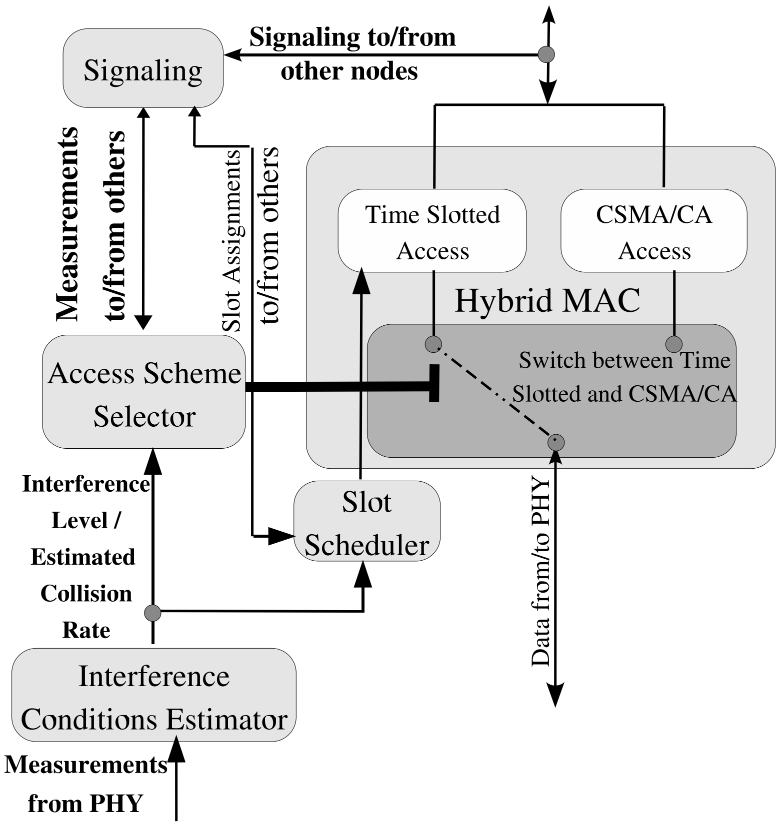

Figure 2.2: Architectural Block Diagram

2.3.1 Interference Conditions Estimator

The Interference Conditions Estimator resides at each AP. It processes AP's local ("own") observations and interference measurement information reported by STAs and produces an estimate of the interference in the BSS. The measurement information from any STA includes an estimate of interference at the STA side and the identity of each interferer. The estimate of interference conditions will then be used as input to the access scheme selector as well as the slot scheduler as will be described in the following subsections. Potential metrics that characterize interference conditions and therefore influence the decision on the channel access scheme could be:

- The interference level in the BSSs as reported by STAs.
- The amount of latency being added to packets.
- Retransmission rate.
- Diagnoses of frame error causes.

Actually, increased latency or retransmission rate does not always indicate high interference. This is due to the fact that these parameters depend also on wireless channel conditions. Bad channel conditions (e.g weak signal) may also increase retransmission rate and consequently the amount of latency packets may experience. Therefore, the selection of the access scheme has to be jointly based on observation of APs' measurements (e.g latency) and interference level estimations reported by STAs to their respective APs. For the sake of organization, methods for interference estimation are separately detailed in chapter 3.

2.3.2 Access Scheme Selector

The access scheme selector is responsible for selecting the proper access scheme to be employed within a set of cooperating BSSs. The decision is based on:

1. Access Mode Switch Rules.
2. Observations and diagnosis of the QoS degradation reported by local interference conditions estimator and measurements signalled from other APs.

In principle, the rules for switching the channel access mode shall be based on the amount of channel time nodes spend sending retransmissions due to interference (i.e the difficulty of delivering packets to their intended receivers). This retransmission time will cause other frames coming from upper layers to be blocked or delayed from being transmitted, degrading the network performance. Nonetheless, precise rules and thresholds for the selection of the channel access mode are still under development. In our simulation experiment, we used the following rule: A switch to the time slotted modus takes place if the average packet delay (estimated by each AP as the time from sending a packet until the reception of the corresponding ACK) due to interference (observed through increased collision rates as reported by STAs) exceeds some threshold D_{th}. Nonetheless, the precise threshold value that generally works for any network topology is to be estimated.

2.3.3 Slot Scheduler

Basically, slot scheduler is an algorithm for assigning channel access rights. Specifically, the function of the algorithm is to allocate orthogonal or disjoint time slots for all links within the set of coordinating BSSs. Interference relations among links are the input to the assignment algorithm. The scheduling algorithm should find out the set of transmissions/links that can go in parallel without collision. This becomes extremely important as the number of STAs and cooperating APs increases. In this case, the sequential assignment of time slots (i.e. the assignment of one long time slot to each participating AP as done in [9]) becomes not possible since other BSSs cannot be blocked (wait) for long time. Chapter 4 elaborates on slot assignment algorithms.

2.3.4 Coordination Protocol

The protocol enables neighboring interfering APs to exchange interference information and negotiate on switching between the two channel access mechanisms. If a change to the time slotted modus is decided by the access scheme selector, the coordination protocol is used for announcement of the new operation mode to all coordinating BSSs as well as the distribution of slot assignments. Chapter 5 elaborates more on coordination protocol.

Chapter 3

Interference Measurement

In this chapter we first discuss the methods for determination of interference relations among network nodes. Then, we provide a passive measurement approach for determining and estimating interference in dense multi-BSS 802.11 WLANs.

3.1 Methods for Determining Interference Relations

Finding interference relations among different nodes is a challenging problem unique to wireless networks. Studies in the literature follow two different approaches to incorporate interference while modeling wireless communication systems:

- Assuming a model for the interference.
- Performing active interference measurements.

Though the measurement of interference is more realistic, most of studies in the literature however follow the first approach. Two models are being widely used:

- **The Simple Interference Model:** This model was first proposed in [19]. The authors call it the protocol model. With this model, and if nodes employ same transmit power level, a receiver j is assumed to successfully receive a frame from a transmitter i (i.e. interference free) , if no other node within a certain interference radius from j is simultaneously transmitting.
- **The Physical Interference Model:** This model [19] predicts that a transmission can be successful if the signal to interference ratio SINR exceeds some threshold. Specifically, a sender i transmits a frame successfully to receiver j, iff: (Power received from i) / (total power received from other potential simultaneous senders + noise power level) is above a threshold value $SINR_{TH}$, where this threshold value is necessary for a successful decoding of i's transmission.

Obviously, the physical interference model is less restrictive than the simple model. With the physical model, it may happen that a packet is successfully received by a receiver, even if there is another node located within the interference radius of this receiver is simultaneously transmitting. Additionally, it considers other attenuation sources like fading other than the path loss.

The core of active interference measurement approaches is the measurement of throughput or signal strength [23, 24, 25, 26, 27]. With the throughput-based approach, two links i and j are assumed to interfere iff the throughput of one degrades when the other is active. This is referred to as pairwise interference. The determination of interfering links takes place in the dedicated configuration phase and the start of network operation. With the signal strength based approach, each node sends in turn a series of broadcast packets. All other nodes measure the signal level of the received packets. The signal strength is used to indicate the potential interference level from the transmitting node to each other node. This measurements delivers, however only an estimate of the real interference. This is due to the following:

1. The signal strength varies in time, dependent on environmental changes. Hence, initial measurements are not valid all the time.

2. The estimated interference is valid in the scenario used to estimate it. Due to the variable nature of traffic, the potential interference is not observed all the time. Additionally, protocol based dependencies on the node state (transmitting, receiving) change the dynamic pattern of the real interference.

In the following section, we develop a passive measurement-based approach for interference relations determination as well as interference level estimation. Estimation of noise level will not be considered in this study as methods to compute this value at receivers are known from the communication handbooks.

3.2 Suggested Interference Estimation

In fact, the real impact of interference depends both on the interference signal level and the frequency of the interference event. The later is strongly dependent on the traffic profile. We determine interference relations among links and estimate interference level at a node through measurements conducted while the network is operating. This trend is advocated by standarization bodies which develop mechanisms to facilitate measurements during network operation(e.g the 802.11k standard). While we confine our attention to the Received Channel Power Indicator (RCPI), recently standardized in 802.11k, other signal level indicators such as RSSI can be used if the RCPI measure is not supported. As an IEEE 802.11 standard feature, the RSSI is defined in the standard as a measure by the Physical Layer (PHY) of the power level observed at the antenna used to receive the current PPDU at the receiver antenna during packet reception, measured during the PLCP (Physical Layer Convergence Protocol) of an arriving packet. In contrast, the RCPI value is measured over the entire frame at the antenna connector used to receive that frame. Hence, the RCPI value seems to be a better metric to represent the signal power level of a received packet.

The following approach for determining and estimating interference will be considered. We focus on Passive observations of interference. However, passive observations can lead to identification of interfering transmitters only if the interfering packet is captured and decoded, providing the source address. Thus, in first approach, we account only for the interference which packets we are able to receive. Similarly, we do not recognize interference comming from nodes outside the communication range.

Our proposed approach works as follows:

- An AP requests the STAs it accommodates to monitor the wireless medium for a period of time T.
- During the measurement period, a measuring STA monitors all transmitted frames over the medium and records the following information elements: The number of transmitted frames from each source address, the length of each frame, the rate at which each frame was transmitted, and the power level at which each frame is received.
- Since frames have different lengths and can be transmitted using different physical rates, an interference metric has to account for these facts. A STA k captures the interference level from a source address as follows:

$$InterferenceLevel_k = \frac{1}{T}\sum_{i=1}^{N}\frac{L_i P_i}{R_i} \tag{3.1}$$

  where L_i and P_i denote the length in bits and received power level in dBm of frame i, respectively. P_i is captured from RCPI or RSSI. R_i denotes the physical rate in bits/second at which frame i is received, and T denotes the length of the measurement period.
- Each measuring STA k sends the measurement information to its AP. ***From this report, the set of potential interferers for each STA as well as the interference level that each STA experiences can be identified.***
- The duration of the measurement is fundamental. This period should be as small as possible to reduce the time a STA spends listening to the channel but large enough to assure that transmissions from interferers fall within the measurement time and consequently improve the accuracy of estimation.

- A STA periodically conducts this measurement and post the measurement report to its AP.

We make the following notes on the above interference estimation approach:

1. It does not only consider the power levels of transmissions from interfering nodes, but also the duration of these transmissions. This is important since the cost of packet collisions due to interference depends on the time period collided packets occupy the medium (normally the longest packet).

2. By considering the time of each frame and dividing over the whole measurement duration, we capture the activity level of an interferer.

3. The accuracy of the approach for the determination of interference relations among nodes is subject to further study and will have to be evaluated. It is limited by the number of recognized interferers. By using additional methods of interferers recognition, the accuracy can be increased.

Chapter 4

Slot Assignment

In this chapter we present two slot assignment algorithms. Let there be an ESS, whereby each BSS is operated by an AP over some channel. For the sake of simplicity we consider the downlink direction and reduce the collision rate at the STAs.

4.1 An Optimal Slot Assignment Algorithm

We first propose an optimal slot assignment approach based on graph colouring that assures a slot for each STA while minimizing the total number of required slots. The interference measurement information first has to be transported to slot scheduler.

Problem Definition
The following information is given:

- The set of APs $\tilde{a} := \{a_1, .., a_{\mathrm{A}}\}$ assigned channels $(ch_1, .., ch_{\mathrm{A}})$, respectively.
- The set of STAs $\tilde{s} := \{s_1, .., s_{\mathrm{S}}\}$ where a STA s_i is associated to some AP $b_i \in \tilde{a}$, $i = 1..S$
- The matrix $L_{i,k} := \{1$, iff a_k interfere s_i
  0, otherwise$\}$

An AP is assumed to interfere a STA iff the interference level measured by this STA from the AP is above certain threshold, (empirically selected to be -83dBm in our evaluations).

The problem is to find the scheduling with minimal number of time slots for downlink traffic (from APs to all STAs) so that any reception at any STA is not interfered from other APs at any time.

Mathematical Formulation

Mathematically, this problem can be converted into a graph colouring problem as follows: If a_k is sending to s_i, then a_q is allowed to send at the same time if it operates on a different channel, i.e.

$$ch_k \neq ch_q$$

or if a_q does not interfere s_i, i.e.

$$L_{i,q} = 0$$

From the above criteria and given the input parameters listed above, it is possible to generate a graph $G = \{\tilde{v}, \tilde{e}\}$ where the nodes of the graph represent the STAs, i.e $\tilde{v} = \tilde{s}$. An edge $(i, j) \in \tilde{e}$ between two STAs s_i and s_j represents whether the two STAs are allowed to receive from their associated APs at the same time. Assuming that L is a symmetric matrix, the definition of $\tilde{e}$ is the following:

$$\tilde{e} := \{(i, j) : \ ch_{b_i} = ch_{b_j} \text{ and } L_{i,b_j} = 1, \ \forall (i, j) \in \tilde{s}^2\}$$

Now we apply an integer program (IP) to solve the graph colouring problem over G. Let $C_{i,c}$ be the matrix of binary decision variables for the resulting colour assignments; note that here the colour assignment means slot assignment to the STA, i.e., it determines which AP in which slot should send to which STA. $C_{i,c}$ is one, iff s_i has colour c assigned. Further, let A be the matrix form of G, i.e. $A_{i,j}$ is one, iff $(i, j) \in \tilde{e}$. The IP model can be written as:

$$\min \quad \sum_c x_c \tag{4.1}$$

$$\text{s.t.} \quad \sum_c C_{i,c} = 1 \qquad \forall i \tag{4.2}$$

$$C_{i,c} + C_{j,c} \leq 2 - A_{i,j} \qquad \forall i \neq j, \text{and } \forall c \tag{4.3}$$

$$x_c \geq C_{i,c} \qquad \forall i, c \tag{4.4}$$

The objective function (4.1) is the total number of the colours extracted from C with the help of a constrained vector $\overline{x}$. Constraint (4.4) ensures that $x_c = 1$ iff colour c is used by any node in graph G, and 0 otherwise, thus the sum of $\overline{x}$ gives the total number of colours used. Constraint (4.2) is for assigning exactly one colour for each node, and constraint (4.3) ensures that no two adjacent nodes can get the same colour.

After solving the above IP, the matrix C will contain the slot assignments with the objective of minimizing the total number of slots for the whole system, thus maximizing the spatial reuse of the slots.

4.2 A Heuristic Slot Assignment Algorithm

Despite that the optimal algorithm presented in the previous section provides an optimal assignment of the time slots, it is rather computationally expensive specially for large number of STAs and APs. Hence, the question about a heuristic algorithm is relevant. In this section, we develop such heuristic algorithm.

The slot assignment problem is solved separately for each channel. Let there be a set of $\boldsymbol{I}$ APs that operate over the same channel and provide communication services to $\boldsymbol{S}$ associated STAs. Basically, AP a_1 and AP a_2 (a_1,$a_2 \in \boldsymbol{I}$) can simultaneously transmit (i.e within the same time slot) to two different STAs *iff*: **neither of the two STAs is interfered by the AP to which the other is associated.** Therefore, what do we really need to know is the set of APs that interfere each STA. As explained previously in section 3.2, this can be properly achieved through measurements. Again the measurement information first has to be transported to a central point where the scheduler is running.

The scheduler starts with the STA that measures the highest interference and finds out all STAs (all downlinks) that can receive frames parallel with it. This set of STAs are marked as **done** and should be assigned a time slot. Then, it proceeds with the next STA and again finds out all STAs that can receive in parallel with it starting with those that are not marked as **done** yet. The algorithm proceeds until all STAs are marked as **done**. The algorithm is shown in Algorithm 1.

Algorithm 1 Heuristic Slot Assignment

$\boldsymbol{S}$= {Set of all STAs}, **Done**={}.
Sort $\boldsymbol{S}$ (descending) according the interference level.
SlotCount=0.
MAX : a maximum upper bound on the number of slots that can be allocated.
Repeat {
Select the Next STA s_m from $\boldsymbol{S}$ **AND** $\notin$ **Done**.
Find the set of STAs $\boldsymbol{K} \subset \boldsymbol{S}$ that can receive parallel to each other and to STA s_m **AND** $\notin$ **Done**.
Done= **Done** U s_m U $\boldsymbol{K}$.
Find the subset $\boldsymbol{T} \subset$ **Done** that can receive parallel to each other and to s_m and every STA $s_n \in \boldsymbol{K}$, starting with those that occupy less slots.
Assign SlotCount to STAs s_m U $\boldsymbol{K}$ U $\boldsymbol{T}$
SlotCount = SlotCount + 1
if (SlotCount > MAX) distribute all remaining links among the slots in a way that keeps interference among scheduled links in each slot minimal.
} Until all STAs $\in$ **Done**

The proposed algorithm has the following features, which differentiate it from other algorithms proposed in the literature:

1. The algorithm does set an upper bound on the number of time slots to be used in scheduling which is impractical due to delay constraints, i.e a node can not be blocked from accessing the channel for a long time. This happens when the number of nodes that share the channel gets large. ***Nonetheless, this problem can be easily overcome by scheduling minimal interfering links together whenever it is impossible to schedule all links without exceeding a pre-defined maximum SlotCount threshold.***

2. In order to minimize the number of needed slots and the search time, the algorithm first sorts the set of STAs in descending order according the interference level each measures.

3. Note that step (8) achieves the objective of maximizing the number of STAs that use a slot, while in the meanwhile it tries also to improve fairness by considering the ones that already got minimal slots as first candidates.

Chapter 5

Coordination Protocol

The interference mitigation framework we propose in this report involves two types of signalling. The complete specification and analysis of the signalling protocols is still under development. For now, we assume that information exchange works perfectly, i.e. we do not consider errors in data exchange for the sake of coordination. Here, we just generally outline the information to be exchanged among network nodes.

The first signalling will be needed for ***the shipment of interference measurements from STAs to their respective APs***. As shown in figure 5.1, STAs report to their respective APs:

- The interference level measured using equation (3.1).
- The collision rate at the STA side.
- The identity of nodes from which interference in coming.

The collision rate is the ratio of number of packets corrupted due to collisions to the total number of corrupted packets. Methods for collision rate estimation are described in [29]. On the other hand, APs inform their STAs via access scheme messages about the channel access mode to be used in a BSS.

The second signalling will be needed for: ***the sharing of interference measurements among coordinating APs, the distribution of access scheme selector decisions, the distribution of slots allocation results, achieving reliable mode switching (i.e. assuring that all nodes switch operation mode at the same time), the decision on the scope of nodes within which an operation mode (CSMA/CA or slotted time) shall be used since the usage of a mode can not happen for an arbitrary subset of BSSs, and interference impact among groups that employ different access modes***. Obviously, slot allocation results are distributed if the access scheme selector decides a switch to the time slotted modus. Figure 5.2 depicts the information to be exchanged among coordinating APs. Primarily, the information includes:

- Access scheme change messages.
- Interference measurement information.
- Slot assignment results once a change to the time slotted access mode is decided.

Interference measurement information includes the amount of estimated interference in the BSS and the set of interferers for each STA in the BSS. Slot assignment results include the identity of nodes that can access the channel at the beginning of each time slot.

As pointed out, the challenges regarding the signaling protocols are to be further studied and developed in the future.

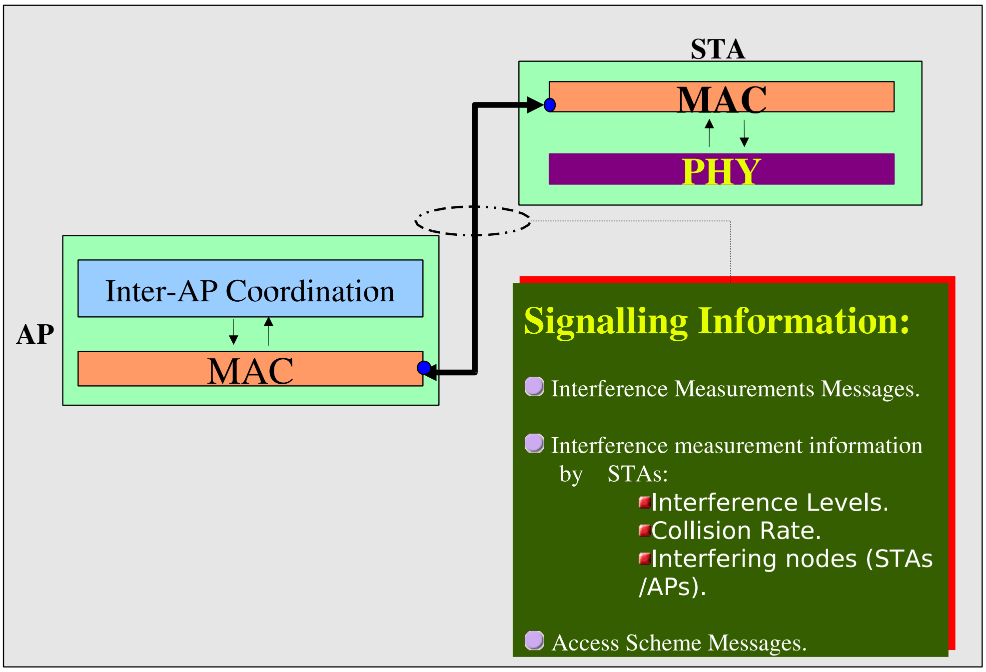

Figure 5.1: Signalling among a STA and its AP

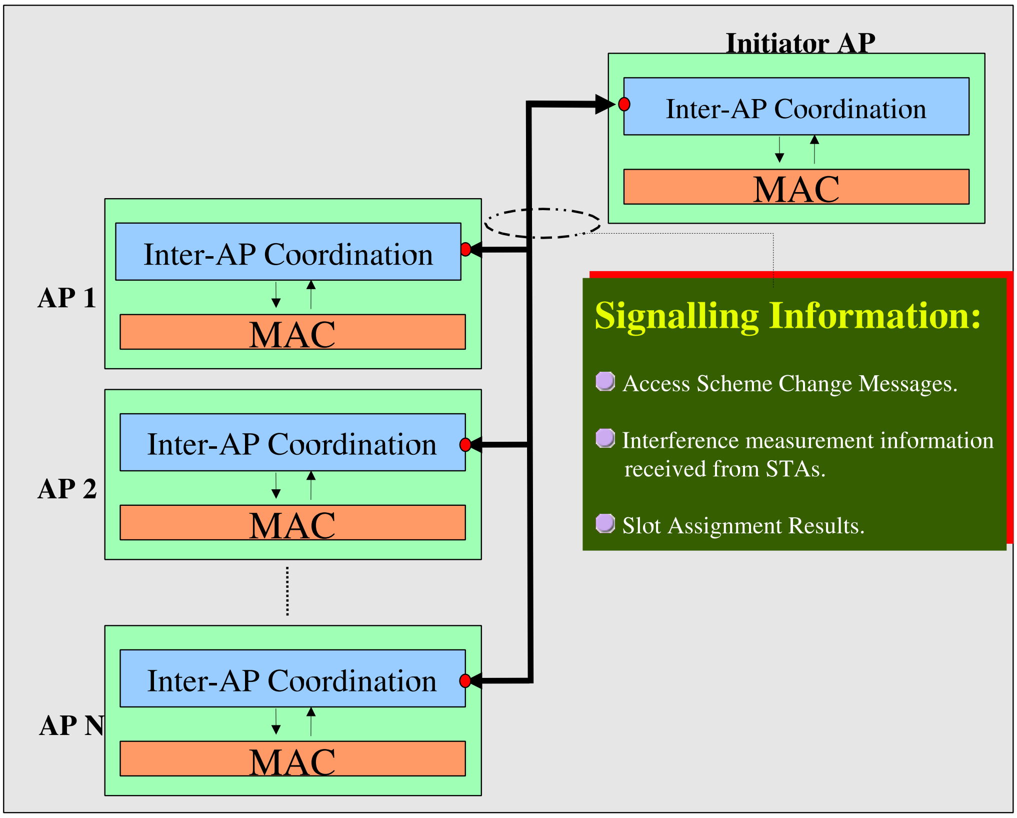

Figure 5.2: Signalling among APs

Chapter 6

Performance Evaluation of a Framework Instance

In this chapter we assess the performance of the interference mitigation framework developed in this report. We have conducted a number of simulation experiments using the NCTUns simulation package [32]. The MAC protocol of NCTUns is ported from NS-2 network simulator which indeed implements the complete IEEE 802.11 standard MAC protocol. MAC layer goodput is used as a first metric to be observed. Every STA and AP measures it for each successful packet during a second and logs the total per second value at the end of every simulation second. Additionally we use Jain's fairness index [33] to capture the fairness level among WLAN users. The slot assignment algorithm, interference estimation algorithm proposed in section 3.2 are fully implemented in the simulation, while the signalling protocol for the exchange of information among STAs and their respective APs and among the APs themselves is not. We simply make the measurement information accessible to APs. On the other hand, we also implemented the heuristic slot assignment (Algorithm 1) of section 4.2) on top of the 802.11 MAC. Additionally, we realistically implemented the coordinated channel access in a small infrastructure WLAN of two APs and five STAs.

6.1 Comparison between the Optimal and Heuristic Slot Assignment Algorithms

We first compare the number of time slots required for each channel for different number of users with the heuristic and optimal slot assignment algorithms. The optimization model of section 4.1 has been solved using the well known CPLEX tools. Table 6.1 shows the results obtained from both algorithms. In each case, users are distributed randomly among 10 APs (four APs on channel 6, three APs on channel 1, and three on channel 11). Wether a user experiences interference from an AP that also operates on a channel being used by its AP is randomly decided during this evaluation phase.

From table 6.1, we see that the heuristic algorithm requires just few slots more than the

	Optimal			Heuristic		
Users	**Ch l**	**Ch 6**	**Ch 11**	**Ch 1**	**Ch 6**	**Ch 11**
30	5	11	6	5	11	6
50	10	16	12	10	16	13
70	14	19	17	14	19	17
90	14	28	19	14	28	19
110	22	26	18	23	26	18
130	26	30	24	26	32	26
150	31	26	32	31	29	33

Table 6.1: **Number of Slots Required for each channel with optimal and heuristic slot assignment algorithms for a WLAN of 10 APs.**

optimal assignment algorithm which indicates the efficiency of the proposed heuristic algorithm. Moreover, we found that for small number of users the heuristic algorithm performs very close to the optimal.

6.2 Coordinated Channel Access

6.2.1 Simulation Setup

The scenario is composed of 10 BSSs and 50 STAs. Three orthogonal channels (1,6, and 11) are assigned to the 10 APs, where every two adjacent APs are configured on different channels. All nodes implement the 802.11b technology. STAs are randomly distributed in the coverage area of the 10 APs. At the physical layer, we have used a two ray ground reflection path loss model with the received power P_{rx} given as:

$$P_{rx} = \frac{P_{tx} G_{tx} G_{rx} h_{tx} h_{rx}}{d^2} \tag{6.1}$$

where P_{tx} is the transmit power (in mW), G_{tx},G_{rx} denote the transmitter and receiver antenna gains respectively, h_{tx} and h_{rx} are the antenna heights of transmitter and receiver, and d is the distance between them. The received power is further influenced by Rayleigh fading. A Rayleigh fading model provided by the NCTUns simulator is used. It takes as parameters the received power P_{rx} and a fading variance set to its default value of 10dB. The received power level of a packet (with respect to both path loss and fading attenuations) is computed at the beginning of the packet and assumed to be constant over the whole packet length. It is passed to an error module provided by the simulator along with packet length and modulation type. This module determines whether a received packet is correct or corrupted due to fading and path loss attenuation. A sender selects a physical transmission rate based on the distance d to the receiver and the rate remains fixed during the simulation time (i.e no rate adaptation is used). Table 6.2 lists the values of the parameters as used in simulations.

Parameter	Value	Parameter	Value
PLCP header T_H	48 μs	T_{SIFS}	10 μs
PLCP preamble T_P	144 μs	T_{DIFS}	50 μs
Cell overlap	20 %	T_{Slot}	20 μs
Fading Variance	10 dB	$W_{\min}$	31
APs/STAs Tx Power	100 mW	$W_{\max}$	1023
d $\leq$ 40	11Mbps	40 $<$ d $\leq$ 80	5.5Mbps
80 $<$ d $\leq$ 120	2Mbps	d $>$ 120	1Mbps

Table 6.2: Constant Parameters

Over a measurement period of 50ms, a STA monitors the wireless channel, it computes the interference level as described in section 3.2. A STA reports this information to its respective AP. An AP is identified as interferer to a STA if the measured interference level from that AP is greater than a cutoff value of -83dBm. Throughout this study, the length of a slot in the time slotted modus was selected to be 15ms and the maximum number of slots was set to 15.

6.2.2 Traffic Model

In a first experiment, each user downloads infinite number of UDP packets from a server via its AP. The interval between two successive packets is drawn from an exponential distribution with 10ms mean, while all packets are of same size chosen to be 1500 Bytes. In a second experiment, each user downloads UDP packets for 300 seconds using the traffic profile provided in table 6.3. It starts with a low load phase, followed by a high low phase and then back to low load.

Simulation Time	Offered Load (Pkt/s)	Packet Size (B)
0 - 100	10	1500
101 - 200	200	1500
201 - 300	10	1500

Table 6.3: Traffic Profile

6.2.3 Simulation Results

1) Effect of Coordinated Channel Access on MAC Goodput: For different load levels, figure 6.1 shows the aggregate MAC goodput experienced by users when the network just employs CSMA/CA and when it employs coordinated channel access. From these results, we draw the following observations: **(i)** At high load, the aggregate goodput has been improved if APs coordinate channel access. Note that the goodput starts to degrade again at extremely high load conditions. We attribute this to the allocation of same time slot to some interferring STAs, where the impact of this interference starts to be harmful at very high loading. **(ii)** However, coordination degrades the goodput when the load becomes low. This is because we employed fixed slot assignment during our experiments, meaning that a slot is wasted if slot owner(s) has no data to sent at the beginning of this time slot. Addionally, the probability of collisions with low load is lower and the CSMA/CA MAC can handle corrupted frames through retransmissions between successive arriving frames. **(iii)** A closer look on how the goodput is distributed among users reveals that under high load and without coordination, large number of users experience small goodput as shown in figure 6.2. For example, at 200 Packets/second load, we found that only 44% of the users (22 users) experience a goodput of 5KB/s or even less. In contrast, coordinated channel access was able to relief many other users and improve their QoS under this load level.

3) Tracking high interference conditions: Now we run the simulation with the traffic profile of table 6.3 (subsection 6.2.2). In this experiment, APs observe packet delay every 20 seconds in the CSMA/CA modus for a time period set to 5 seconds. APs that operate over the same channel switch to the slotted modus whenever each one measures an average delay D_{th} of 12ms or more during the observation period. This threshold value is empirically found to work good for the topology considered. After operating in the time slotted modus for 20 seconds, APs change back to CSMA/CA and again observe packet delay. If the average delay of APs drops lower than 12ms, APs stay in the CSMA/CA modus, otherwise return to the time slotted modus. The delay observation periods are not shown in the figures. Figure 6.3 plots the aggregate goodput with this experiment. The figure shows that, the aggregate goodput has been improved when APs coordinate channel access during the high load period. We plot the portion of goodput that each user got during this period in figures 6.4 and 6.5, which reveal the advantage of coordination for many users who suffer degraded performance with CSMA/CA. Further, figure 6.6 plots Jain's fairness level [33] among the 50 users, which also indicates a gain in fairness level among users as a result of coordinated channel access during the high load period.

6.3 Coordinated Channel Sharing - Real Experiments

In this experiment, we would like to observe the total system throughput and how this throughput is distributed among the five STAs with and without coordinated channel access in a realistic network.

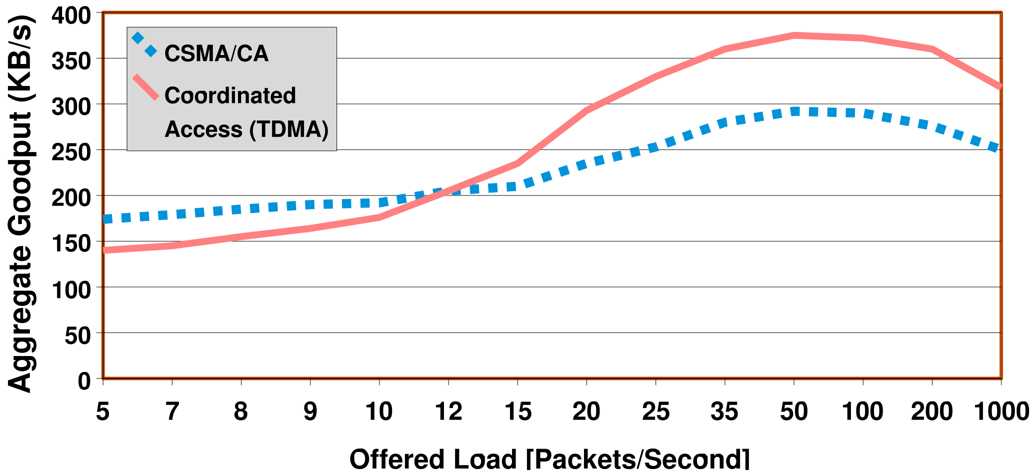

Figure 6.1: Aggregate Goodput experienced by all users with CSMA/CA and with coordinated access for different load levels.

6.3.1 Experiment Setup

The experiment set-up is shown in figure 6.7. Two APs and five stationary STAs were deployed in two different LABs. The APs are WLAN adaptors from Atheros configured in the master mode (AP mode) through the MADWIFI driver. The APs are connected via an Ethernet Switch. Over the ethernet connection, a master program runs on one AP synchronizes both APs. APs are assigned the same channel. Through transmit power control, APs are hided from each other. Two STAs are deployed in overlapping area of the two BSSs. APs transmit UDP traffic to the five STAs. In this experiment, the five STAs are scheduled as shown in table 6.4:

Slot	Stations
T1	STA 1
T2	STA 3
T3	STA 4, STA 2
T4	STA 5, STA 2

Table 6.4: Scheduling of the five STAs

6.3.2 Experiment Results

In fact, the real experiments have shown two main points: The first is the ability of coordination to improve system performance under high loading, and the second is the necessity of driving the whole adaptation by measurements.

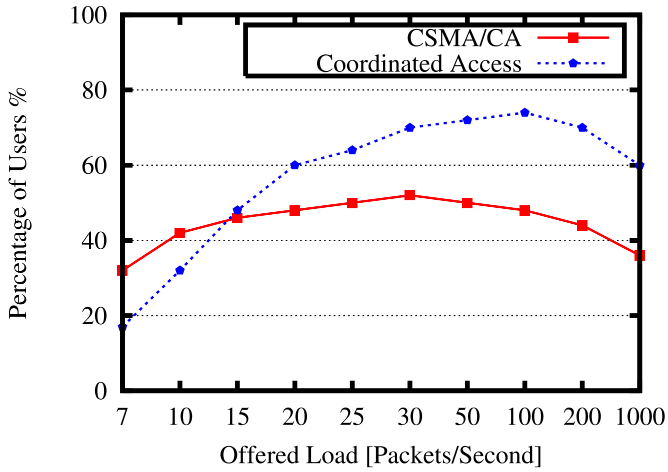

Figure 6.2: Percentage of users that experience a minimum goodput of 5KB/s with CSMA/CA and with coordinated access for different load levels.

Figures 6.8 and 6.9 plot the results of the real experiments. We make the following comments on both figures: **(A)** The total throughput with CSMA/CA and with coordinated channel access is comparable. **(B)** With CSMA/CA, STA 1 (in the overlapping area) experiences degraded performance compared to other STAs due to increased collisions. **(C)** Although STA 2 is outside the interference region of AP 2, it also experiences degraded performance with CSMA/CA due to the time its AP (AP 1) spends retransmitting packets to STA 1. This means, in fact, that the whole BSS of AP 1 suffers communication problems. On the other hand, STA's 3 performance is not degraded with CSMA/CA despite it is located within the interference region of AP 1. By measuring the received power at both STAs in the overlapping region, we found that the reason is the capture effect which helps STA 3 to maintain good performance. **(D)** With coordinated access, STA's 2 throughput is higher than other STAs as it is scheduled in two time slots.**(E)** The overall conclusion: With almost the same aggregate throughput, coordinated channel access was able to relief two users and consequently improve the fairness among WLAN users.

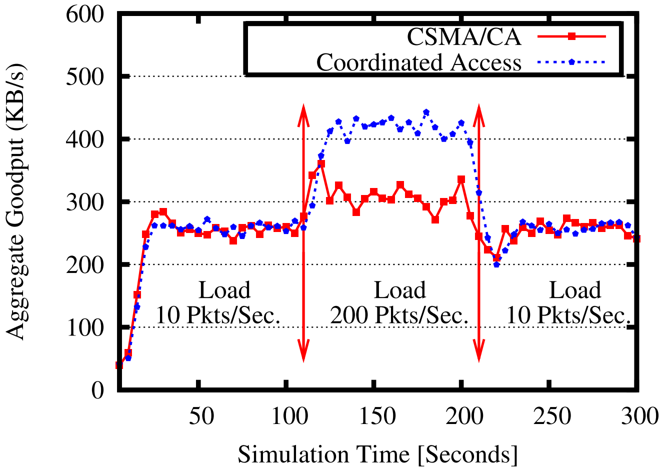

Figure 6.3: Aggregate Goodput with CSMA/CA and Coordinated Access during Different Load Conditions

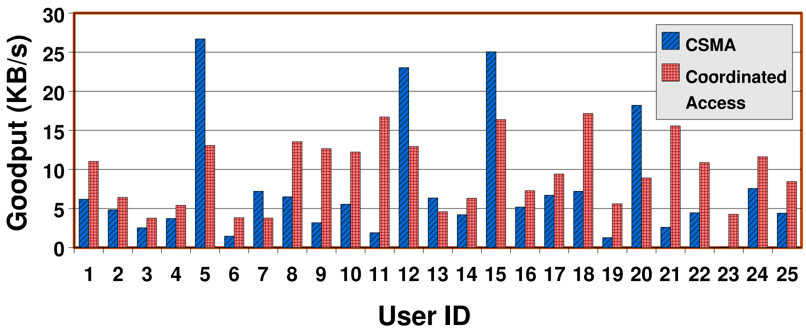

Figure 6.4: User Goodput during high interference periods

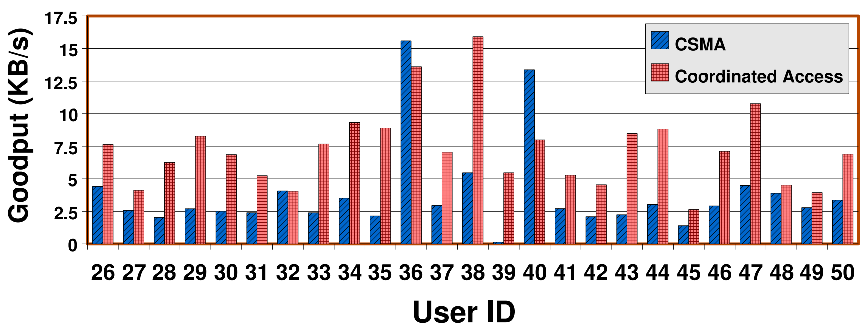

Figure 6.5: User Goodput during high interference periods

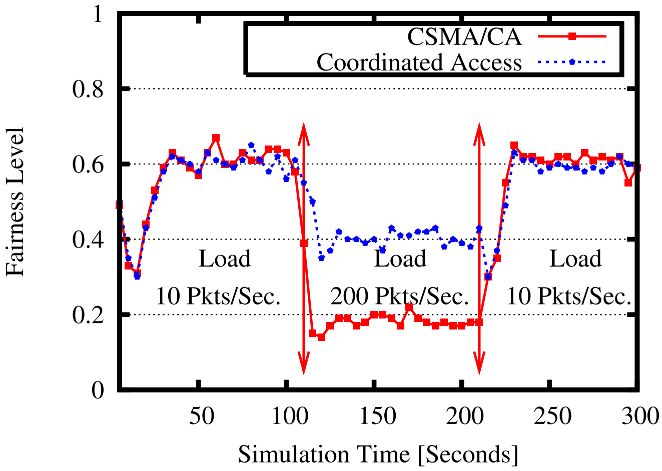

Figure 6.6: Jain's Fairness Level among the 50 users during Different Load Conditions

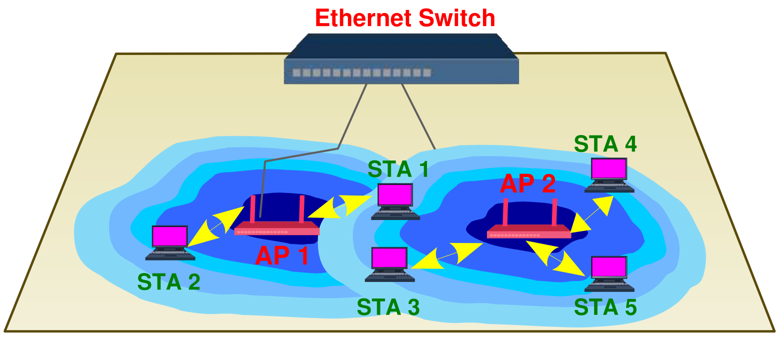

Figure 6.7: Topology used in Real Implementation

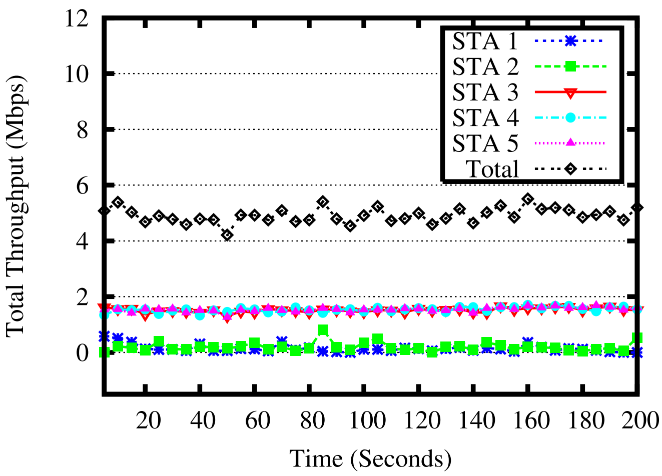

Figure 6.8: Real Implementation- With CSMA/CA

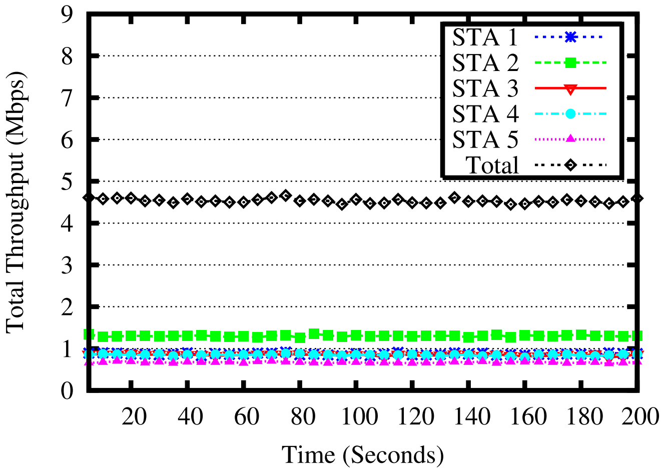

Figure 6.9: Real Implementation- With Coordinated Channel Access

Chapter 7

Conclusions and Ongoing Work

This report proposes a framework for interference mitigation in infrastructure WLANs. A cluster of neighboring interfering APs negotiate, exchange interference information and agree to switch between a CSMA/CA and a time slotted channel access schemes for delivering packets to their users. Observations and measurements of interference conditions, delays, and diagnoses of the packet loss cause drive the decision on the access scheme to be employed. Detailed simulations and real implementations have shown a good gain of the proposed policy in terms of aggregate goodput and fairness among WLAN users.

In order to overcome the drawback of blocking some communication by nodes that do not have the rights to use the channel in a time slot, we exploit the idea of incorporating transmission power control in our proposed solution. The idea is the following: Nodes that do not have the right to transmit in a time slot may use a reduced power level to deliver frames to their receivers whenever their transmissions (with reduced power levels) do not interfere with the transmissions of primary slot owners. With this idea, one could more improve the utilization level of the system capacity. Additionally, the signalling mechanisms are currently under consideration and analysis.

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