Improved Channel State Dependent Scheduling for WLANs

By

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Abstract

This thesis focuses on the study of Channel State Dependent Scheduling (CSDS) based scheduling schemes for Wireless Local Area Networks (WLAN). CSDS based scheduling schemes can improve the usage efficiency of scarce radio resource since packets transmitted on wireless channels are often subject to burst errors which cause back-to-back packet losses. By taking into account the channel state in scheduling decisions, CSDS based schemes can achieve a large improvement in total throughput compared to FIFO scheme, which is currently used in WLAN systems. However, if not properly designed, a CSDS scheme can cause unfair resource allocation among users. Various mechanisms have been proposed for addressing the fairness problem in the literature, but unfortunately most of them are too complicated to be employed in WLAN.

The main contribution of this thesis is to propose a simple compensation mechanism which is easy to implement. Based on the compensation mechanism, three CSDS based scheduling schemes are designed for WLAN. Among them, Max S* selects the best channel state S*, which is calculated according to the compensation mechanism; IWRR (Improved Weighted Round Robin) adopts dynamically changing weights for users. The weight is derived based on the compensation mechanism. A hybrid scheme, IWRR+Max S*, is proposed which possesses the advantages of both of IWRR and Max S*. A WLAN system simulation is used to show that the proposed schemes can yield substantial improvements in short-term fairness compared to CSDS+RR (Round Robin) in most test scenarios, while still maintaining high channel efficiency.
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Glossary

Acronyms

ACK  Acknowledgement
AP   Access Point
AWGN Additive White Gaussian Noise
BPSK Binary Phase Shift Keying
BSS  Basic Service Area
CDF  Cumulative Distribution Function
CSMA/CA Carrier Sense Multiple Access with Collision Avoidance
CSDS Channel State Dependent Scheduling
CW   Contention Window
DCF  Distributed Coordination Function
DIFS Distributed Coordination Function Interframe Space
DSSS Direct Sequence Spread Spectrum
EIFS Extended Interframe Space
FHSS Frequency Hopping Spread Spectrum
FIFO First Come First Out
GPS  Generalized Processor Sharing
HOL  Head of Line
LCR  Level Cross Rate
LLC  Logical Link Control
LQF  Longest Queue First
MAC  Medium Access Control
MPDU  MAC Protocol Data Unit
OPNET  Optimized Network Engineering Tools
PCF    Point Coordination Function
PER    Packet Error Rate
PHY    Physical Layer
PIFS   Point Coordination Function Interframe Space
PLCP   Physical Layer Convergence Protocol
PSDU   PLCP Service Data Unit
QoS    Quality of Service
RR     Round Robin
RTS/CTS Request To Send/Clear To Send
SIFS   Short Interframe Space
SNR    Signal to Noise Ratio
STA    (wireless) Station
TCP    Transmission Control Protocol
WFQ    Weighted Fair Queuing
WLAN   Wireless Local Area Network
WRR    Weighted Round Robin
**Symbols**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$fd$</td>
<td>Doppler Frequency</td>
</tr>
<tr>
<td>$f_{win}$</td>
<td>Fairness window</td>
</tr>
<tr>
<td>$P_{dw}$</td>
<td>The product of $fd$ and $f_{win}$</td>
</tr>
<tr>
<td>$Nu$</td>
<td>The number of users</td>
</tr>
<tr>
<td>$S_{av}$</td>
<td>Average SNR</td>
</tr>
<tr>
<td>$S$</td>
<td>Measured SNR</td>
</tr>
<tr>
<td>$TT$</td>
<td>Transmission Threshold</td>
</tr>
<tr>
<td>$TT_{opt}$</td>
<td>The TT value corresponding to an optimal performance</td>
</tr>
<tr>
<td>$TT_{\eta, opt}$</td>
<td>The TT value corresponding to an optimal total throughput</td>
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Chapter 1 Introduction

The primary objective of this thesis is to study the employment of CSDS (Channel State Dependent Scheduling) schemes in improving the performance of wireless communication networks such as wireless LANs. In this chapter, a brief description of relevant previous works, motivation and contributions of the research project is given.

1.1 Background

Wireless LAN has gained in popularity since it was introduced in the late 1980s. It is an attractive alternative to replace wired LAN at hotspots such as airports, office buildings, and residential areas especially when wires and cables are difficult to deploy and/or the network structure is frequently changing. The IEEE 802.11 standards were first published in 1997 by IEEE 802.11 committee and some of the sub work groups are still working on new drafts. Now most of the Wireless LAN products support the 802.11b and g standards. The key difference between them is that 802.11g supports higher data rates.

In this thesis, we focus on the 802.11b standard. The 802.11 WLAN network architectures can be ad-hoc or infrastructure, the latter being usually deployed at hot spots, and is the only type of architecture considered in this thesis. The default scheduling scheme in 802.11 WLAN is FIFO (First Come First Out); it is simple and uses only one queue for all incoming packets, and yields good performance in a wired network. However, in a wireless environment, due to the time-varying channel capacity and the location dependent bursty errors, a FIFO scheme will cause a HOL (Head of Line) blocking effect under the control of retransmission mechanism applied in 802.11 MAC protocols, and lead to a large number of
retransmissions and low channel efficiency. This is typically not a problem in a wire-line network because error frames tend to occur at random. In order to improve the performance of the system, scheduling mechanisms based on channel state information -- CSDS (Channel State Dependent Scheduling) have been proposed in the literature. In the next section, we will briefly introduce fair packet-scheduling algorithms proposed for wired networks and the problems encountered when employed in wireless networks, CSDS schemes are introduced followed by a description of how they operate.

1.2 CSDS Based Scheduling Schemes

In a WLAN, the radio channel is shared by multiple mobile terminals. Therefore, efficient utilization of the wireless channel is important. Two common objectives of a well-designed scheduling algorithm focus on two subjects: i) fairness, or controlled sharing of the channel among multiple packet streams, and ii) high system throughput.

In the literature, fairness can be evaluated by throughput discrepancy or channel capacity (i.e. allocated service time in WLANs) discrepancy [38], [6]. In this thesis, we will adopt throughput based fairness constraint. And a popular fairness index which is used to measure fairness performance will be introduced in Chapter 3. Besides, fairness can refer to both long-term and short-term. Generally, short-term fairness implies long-term fairness, but not vice-versa. In this thesis, both are considered.

Many efficient and fair packet-scheduling algorithms have been proposed for wire-line networks. Among them are Generalized Processor Sharing (GPS), Packet-by-packet GPS
also known as Weighted Fair Queuing (WFQ), Start-Time Fair Queuing (STFQ), Worst-case Fair Weighted Fair Queuing (WF²Q, or called WGSP), Self-Clocked Fair Queuing (SCFQ), etc. Most of the proposed packet scheduling algorithms imitate fair scheduling scheme for stream traffic – Fair Flow Queuing (FFQ), and try to obtain a similar fairness performance. Another popular scheduling scheme family, which is widely used in a packet switching environment, is Round Robin (RR)-based. Its advantages include simple implementation and relatively good performance.

However, these scheduling algorithms proposed for wire-line networks cannot be directly applied to wireless networks due to the time-varying, location dependent channel capacity. Therefore channel-state-dependent packet scheduling (CSDS) mechanism was proposed [1] to improve channel utilization. The basic idea behind CSDS is to consider channel conditions when selecting the Head-Of-Line (HOL) packet for next transmission. Since links between different pairs of communication terminals (typically between base station/access point and mobile stations) undergo independent fading and exhibit bursty error characteristics, the probability of success transmission will be enhanced by avoiding the transmissions to those terminals suffering a deep fading channel condition and furthermore channel utilization can be enhanced. Architecture of a CSDS-based scheduler is shown in Figure 1.1.

Besides a high throughput, service fairness is often an important system requirement in a wireless network. For example, users located near the Access Point (AP) or Base Station (BS) will generally earn better channel states than distant ones. Hence, in the long run users
near the AP may obtain much more services. To remedy this problem, fairness control is needed in the scheduling mechanism. CSDS can be combined with many different fair packet-scheduling algorithms used in wire-line networks such as WFQ-based, RR-based schemes etc. to achieve somewhat fairness performance.

![Diagram of a CSDS based scheduler](image)

Figure 1.1: The architecture of a CSDS based scheduler

There are two common methods for combining CSDS and proposed fairness policies: "threshold-based" and "weight-based". In "threshold -based" schemes, the channel state is used as a transmission threshold and the combined scheduling algorithm selects HOL according to its rule among queues eligible for transmission. Examples include IWFQ [2], and WDRR [5]. Usually they can guarantee long-term fairness among all sessions through service compensation, and short-term fairness among error-free sessions. In order to further provide graceful service degradation for leading sessions, in other words, control and obtain a reasonable compensation period, some of such schemes (CIF-Q [3], WDRR [5], LTFS [4]) also involve special-designed compensation mechanisms. The disadvantages of threshold-based schemes include computation overhead and complexity.
In a "weight-based" scheme, the channel state is considered as a part of transmission weight; the other part of weight is decided by the employed scheduling algorithm. The next packet to be transmitted is the HOL packet from the queue with the highest weight. Examples include OSP [6], WCFQ [7], which can achieved a tradeoff between fairness and total throughput. No special compensation mechanism is involved. Generally, the fairness measures used in these schemes are long-term fairness. At one extreme is a scheme in which the channel state completely determines the weight, results in maximum total throughput. At the other extreme is absolute fairness when the weight is completely determined by the fair scheduling algorithm. Since threshold-based combination method is simple and can achieve good total throughput, our proposal will be developed based on that method.

1.3 Motivation

The basic idea behind CSDS scheduling is that users with better channel states can obtain higher bandwidth, so that the total throughput is enhanced. However fairness may be sacrificed. The threshold-based CSDS schemes mentioned above improve fairness compared to the original scheme in [1] by means of various service compensations. However, they are too complicated to be deployed in 802.11 WLAN. A suitable scheduling algorithm should be designed based on the features of 802.11 WLAN MAC layer and should not modify it or add much scheduling computation overhead since an important feature of the IEEE802.11 standards is a very simple MAC layer. Moreover, the main traffic type in a WLAN system is packet data traffic, which requires high reliability. Therefore in the 802.11 standards, retransmission at the MAC layer instead of higher layer is provided to support fast recovery from errors. If the scheduling scheme applied in the system is too complicated, the efficiency
of the whole system will be greatly reduced. Therefore, a simple and efficient scheduling scheme with good total throughput and fairness performance is especially suitable for such a system like WLAN.

Till now, most of the proposed schemes involve complicated compensation schemes to guarantee long-term fairness among sessions and incur a high computation overhead cost. Returning to the fairness problem mentioned in the previous section, namely users near the AP receive more service; a simple and direct solution about compensation mechanism is to consider "relative channel state" or "average channel state" (referred to as Sav) of each user. "Average channel state" here means average SNR level of the user in a relatively long period. Under the assumption of infrastructure WLAN with fixed or very slow moving users, Sav is mainly determined by the distance between the AP and the user. Because every user has independent position and channel characteristics, the Sav should be a reasonable parameter to decide how much compensation it should obtain under good channel states. For instance, a distant user with a certain channel state (expressed by SNR level at the receiver) should have a higher priority for transmission than a nearby user with the same SNR level. This compensation mechanism can be applied together with other scheduling algorithms like Round Robin. Hence, our goal is to design an algorithm which provides good fairness while maintaining a high overall throughput by taking the Sav into account.

1.4 Thesis Contributions

In this thesis, first part of the contribution is the proposed compensation mechanism, which is based on the average SNR (Sav) of a fading channel and is simple to implement.
Chapter 1 Introduction

The principle of the compensation mechanism is to provide higher priority to users with low \( S_{av} \) if they have similar current SNR level with users with high \( S_{av} \). To achieve this target, a modified SNR level \( S' \) of the current SNR \( S \) is calculated based on \( S_{av} \) of that channel and a certain value of current SNR with a lower \( S_{av} \) will result in a higher \( S' \). For \( S \geq S_{av} \), \( S' \geq S \), otherwise \( S' < S \). Moreover, a parameter \( \phi \) is employed to control the amount of compensation, which increases with \( \phi \). The compensation mechanism is proposed to improve the long-term fairness. However, short-term fairness is more important in a real network. Therefore, short-term fairness is used as a criterion to evaluate the performance of scheduling schemes in this thesis.

The second part of the contribution is that three CSDS-based scheduling schemes are developed for 802.11 WLAN network based on the proposed compensation mechanism. All three schemes are simple for implementation and manage to yield an improved short-term fairness performance and maintain a high total throughput simultaneously. Among the schemes, Max \( S^* \) attempts to maximize the total throughput by selecting the HOL with the best modified SNR value \( S' \); IWRR scheme also employs the compensation mechanism, but in this scheme the modified SNR level \( S' \) acts as transmission weight. IWRR+Max \( S^* \) represents a combination of the above two schemes to benefit from the advantages of both. In this thesis we mainly studied the effect of Doppler frequency \( (f_d) \), short-term fairness window size \( (f_{win}) \) and the number of users \( N_u \) to the performance of the proposed schemes. The simulation results show that IWRR+Max \( S^* \) yield no worse performance than the traditional scheme CSDS+RR for any value of the product \( P_{dw} = f_d \times f_{win} \) (\( \epsilon [1, 100] \)) and \( N_u \) (\( \epsilon [2, 20] \)) and can achieve substantial improvement for \( P_{dw} \geq 5 \), and any \( N_u \). For \( N_u = \)}
Chapter 1 Introduction

8 and Pdw ≥ 25, the three proposed schemes can achieve similar performance, which shows a fairness improvement to CSDS+RR over 15%. And the fairness improvement increases with the decreasing of Nu. We did not compare their performance with that of the default FIFO scheme in WLAN since CSDS+RR shows much better performance than FIFO did in [1]. In conclusion, our proposed scheduling schemes can supply good performance not only for long-term fairness but also for short-term one; the benefit of high throughput from CSDS is maintained as well.

1.5 Overview of Thesis

The rest of this thesis is organized as follows. In Chapter 2, related works of the CSDS based scheduling schemes in the literature are presented. Then the proposed compensation mechanism and scheduling schemes based on the compensation mechanism are developed in Chapter 3. Additionally, channel model and fairness index definition are also included. In Chapter 4, simulation system is build up to imitate a real 802.11b WLAN environment. Verification by simple tests in OPNET is also involved. Chapter 5 presents simulation results to investigate the effect of Doppler frequency, fairness window and the number of users to the performance of the proposed schemes and the performance comparison is also studied. Finally, a conclusion of the presented work and suggestions to future work are given in Chapter 6.
Chapter 2 Related works

The original CSDS scheme was proposed in [1] for wireless LAN network. The key feature of CSDS is to avoid bursty errors at the link layer instead of relying on the transport or application layer for error recovery to improve overall throughput performance. The basic idea behind CSDS scheme is to defer the transmission effort when the channel is in a bad state and the destination is currently unreachable, to proceed with transmission to receivers enjoying good channel states.

A CSDS scheduler consists of two modules. One is channel-state measuring or predicting module. The other is scheduling (dequeuing) module. The former performs the measurement of the channel state. Based on the information, the prediction of channel state is made for the next packet selection. This step is not necessary when measurement value is obtained frequently or the channel is changing slowly relative to transmission rate. The scheduling module implements dequeuing decision. CSDS schemes always avoid or limit allocating resource to queues in poor states. In [1], CSDS is combined with RR (Round Robin), ETF (Earliest Timestamp First) and LQF (Longest Queue First) scheduling algorithms. A threshold is used to indicate if a channel state is “Good” or “Bad”. If “Good”, transmission of the session is allowed based on the rule of the scheduling algorithm, otherwise transmission is delayed. No compensation mechanisms is designed in [1].

Typically in proposed schemes, CSDS works with fair packet scheduling algorithms proposed for wired networks or with QoS requirements to achieve acceptable resource allocation. Some of them also include compensation mechanisms to improve fairness.
Proposed CSDS based scheduling schemes in the literature can be classified as "threshold-based" or "weight-based".

2.1 Threshold-based CSDS scheduling algorithms

In "threshold–based" schemes, the policy is similar to the CSDS scheme in [1]: channel state is used to set a transmission threshold (TT). If the state is good enough, the session transmits as determined by the scheduling algorithm. Otherwise transmission is denied, except when none of users is above TT. Any of the scheduling algorithms can be employed: RR based, GPS based, and QoS requirements based schemes, such as WRR (weighted round robin), DRR (Deficit Round Robin), WFQ (Weighted Fair Queue), WF^{2}Q (Worst-case Weighted Fair Queue), CBQ (Class-Based or Credit-Based queue), LQF (Longest Queue First), etc.

Some proposed schemes [2], [3], [4], [5] use compensation mechanisms, which implement service compensation to lagging sessions. Generally, scheduling algorithms such as WFQ and LQF that include tag or stamp factor to indicate historical service allocation can naturally implement service compensation. Therefore, the compensation mechanism designed in these schemes is to achieve a controlled compensation period. For example, in IWFQ [2], the HOL (head of line) of each queue is tagged with a time stamp, which is a factor in queue selection. If a queue is denied transmission due to poor channel state, its HOL time stamp will be unchanged and the queue will be given higher transmission probability when its channel state rises above TT. However, if not controlled, the compensation period may cause starvation of in-sync or severe penalty to leading sessions, which is called
Chapter 2 Related works

"blackout" problem. To ease the problem that can lead to poor short-term fairness, a compensation mechanism was proposed in [2]. Typically, this kind of compensation mechanism is complicated but can achieve good fairness performance. However, scheduling algorithms such as RR do not include any compensation policy. Therefore, some of the compensation mechanisms designed in RR-based schemes attempts not only to improve short-term fairness performance of pure RR but also to achieve a reasonable compensation period as in IWFQ. Others are simple and suboptimal but efficient and working well with the RR policy. Some of the threshold-based schemes are introduced respectively below.

**IWFQ** (idealized wireless fair queuing) uses WFQ or WF^2Q and includes a compensation policy to control the "blackout" problem in an error-prone scenario. IWFQ and WFQ are identical in error-free scenario. To avoid unlimited channel occupation by lagging sessions and provide a reasonable compensation period, IWFQ sets bounds on the lead and lag of each session. However, this mechanism does not guarantee graceful service degradation for leading sessions.

**CIF-Q** (Channel-condition Independent packet Fair Queuing) and LTFS (Long-Term Fairness Server) were proposed in [3] and [4] to achieve more acceptable service degradation for leading sessions. CIF-Q uses Start Time Fair Queuing (STFQ) as its error-free service model while LTFS can use any wired fairness scheduler as its error-free model. CIF-Q uses a parameter to control the rate at which a leading session gives up its lead to a lagging session, while LTFS reserves bandwidth for compensation in advance.
WDRR+CSDS [5] scheme uses WDRR (Wireless Deficit Round Robin) as its error-free fairness algorithm, which is derived from DRR (Deficit Round Robin). Combined with CSDS, the compensation mechanism enables the scheduler to provide short-term fairness among sessions that perceive a clean channel, long-term fairness among all sessions, and graceful service degradation among sessions that received excessive service. WDRR uses a parameter to keep historical records of throughput obtained by each session so that long-term fairness can be achieved among all sessions. Furthermore, to achieve graceful service degradation of leading sessions and further to obtain better short-term fairness in error-prone scenarios, an additional parameter is used to control the maximum amount of service a leading session has to give up in each round.

In [9] a simple compensation mechanism was proposed for TCP traffic short-term fairness improvement in the 802.11b WLAN system. The proposed scheme is an LLC (Logical Link Control)-layer algorithm that aims at enhancing fair access to the medium for every user, by awarding longer transmission opportunities to sessions that experiences short channel failures. The award mechanism works by monitoring the successful medium accesses over a measurement window, and allowing short or long transmission bursts depending on the session’s recent history (which means, how much service it received during the previous measurement window).

Same as [1], the applied scheduling algorithm is Round-Robin. Upon entering a good channel state, a queue that was in a bad state is rewarded with the possibility to send to the MAC layer a maximum number of back-to-back frames (hereinafter refer to as “TXburst”),
proportional to its forced silence period. Based on the fractional throughput a queue enjoyed in the previous measurement window, the TXburst length will be set longer (as a reward) or shorter (as a penalty) than the default value to improve short-term fairness performance among sessions.

Although this simple compensation mechanism cannot guarantee tight short-term and long-term fairness among users, simulation results show a much better fairness performance than with the default scheduling scheme (FIFO) of WLAN. Moreover, in a simple network like 802.11 WLAN, a scheme which is uncomplicated and efficient is especially expected. Among all proposed schemes, [9] is most closely related to our research.

2.2 Weight-based CSDS Scheduling algorithms

In weight-based CSDS, the channel state is transformed to a transmission cost (or weight), and the scheduling algorithm contributes the other part of whole weight. The HOL selection decision is based on the total weight, and the next packet to be transmitted is the HOL with the highest weight. These schemes can attempt to achieve balance between fairness and total throughput performance.

One extreme example is CSDS with optimal total throughput performance. Here, the HOL selection is based solely on the channel state of each queue. At each packet transmission moment, the queue with the best channel state is selected (referred to as Max S, where S is the SNR level of the channel). Max S yields the highest total throughput but provides no fairness feature. At the other extreme is fairness scheduling only, where the HOL
is selected only by the applied fairness scheduling algorithm. In this case, fairness as defined by the adopted scheduling scheme can be guaranteed at the cost of low total throughput. Some proposed schemes that attempt to strike a balance between fairness and total throughput are described below.

The objective of OSP (Opportunistic Scheduling Policy) [6] is to maximize the average system performance while satisfying pre-determined fairness constraints. An opportunistic policy is defined to achieve this goal:

$$Q^*(\bar{U}) = \arg\max_i (U_i + v_i)$$

(2.1)

where $U_i$ is the channel-state-dependent throughput value achieved by user $i$, $v_i$ is the offset used to satisfy the time-fraction assignment constraint, i.e. for any $\varepsilon>0$:

$$P\{U_i + v_i - \varepsilon \geq \max_j (U_j + v_j - \varepsilon)\} \leq r_i \leq P\{(U_i + v_i \geq \max_j (U_j + v_j))\}$$

(2.2)

where $r_i$ is the time-fraction assignment of user $i$. By doing so, $P(Q^*(\bar{U}) = i) = r_i$ is satisfied so that fairness constraint is guaranteed. Under this constraint, the "relative-best" user is scheduled for transmission. Therefore, the opportunistic transmission scheduling policy maximizes the average network performance under the fairness requirement (e.g. fair sharing).

WCFQ (Wireless Credit-based Fair Queuing) [7] applies CBFQ (Credit Based Fair Queuing) as its fairness scheduling algorithm. The packet selection criterion is to select the HOL packet that satisfies:

$$f = \arg\min_i \frac{L_i - K_i + U_i}{\phi_i}$$

(2.3)
Chapter 2 Related works

where \( L_i \) is the HOL packet length for session \( i \); \( K_i \) is the credit counter, which calculates the accumulated credit according to CBFQ to provide a balanced bandwidth sharing among sessions; \( U_i \) is the transmission cost; and \( \Phi_i \) denotes the assigned weight for session \( i \). At each decision moment, scheduler will select the HOL with the lowest channel cost (i.e. best channel state), unless one session’s cumulated credits outweigh a poor channel state. Therefore, transmission cost function (which decides transmission cost under each channel state) can control the tradeoff between fairness performance and total throughput. [7] shows that a transmission cost function can be derived to satisfy a given fairness requirement so that a loose or tight short-term fairness is guaranteed. However, due to the model’s complexity it is generally difficult to derive such a function in practice.

**SPS** (SNR-based Packet Scheduling) scheme [8] can be viewed as a CSDS + WFQ policy. Each SNR level (dB) has a corresponding weight according to a piece-wise linear function. A good channel state (i.e. high SNR level) will be given a heavy weight. As in WFQ, the HOL with the earliest virtual finish time will be selected for transmission. However, the virtual finish time is calculated by:

\[
F_i^n(t) = \max(v(t), F_i^{n-1}(t)) + L_i / r^*_i
\]

(2.4)

where \( F_i^n(t) \) is the virtual finish time of \( n \)th packet in session \( i \), \( v(t) \) is the arrival time of packet \( n \), \( r^*_i \) is the bandwidth currently allocated to session \( i \) based on its weight, \( L_i \) is packet length of session \( i \). Note that \( r_i \) is the deserved bandwidth of session \( i \). Therefore, an active session’s allocated bandwidth is dynamic according to its channel state instead of constant as in WFQ. The difference between SPS and the threshold-based IWFQ scheme is that SPS does not avoid transmission when user’s channel state is low, but allocate low bandwidth.
(priority) instead. Therefore, a tradeoff between total throughput and fairness is achieved. The difference between SPS and WCFQ is the transmission cost (weight) function, which in SPS is identical for all sessions.

In all the weight-based CSDS schemes discussed above, the sessions with relatively poor channel states can still get a transmission opportunity, when the fairness control factor overweighs the channel condition factor. The main difference among the schemes is the function used to select the HOL for transmission. No special compensation mechanism is involved.
Chapter 3 New CSDS scheduling algorithm developments

Most of the proposed CSDS scheduling algorithms described in Chapter 2 are designed for cellular networks, and are not very applicable to WLANs. The common characteristics of several proposals for WLAN are simplicity and low overhead of scheduling computation, e.g. [9], [1]. Due to its simplicity, the network can be rapidly developed and widely deployed. A low protocol overhead also results in high system efficiency. The limitation is that the network does not provide tight QoS guarantees.

GPS based scheduling algorithms seem too complex for WLAN, due to the need for time stamping of each packet, updating the virtual time function, and so on. RR based scheduling policies are simpler and adopted in our proposed scheduling algorithm for WLAN. In this chapter we describe the new CSDS based scheduling algorithm in detail. But before this we briefly discuss the 802.11 standards and the wireless channel models used in WLAN simulation. Then a new compensation mechanism and the corresponding scheduling schemes are introduced.

3.1 Overview of 802.11b WLAN [19]

3.1.1 Network architecture

A basic service set (BSS) is the basic unit of the network. It consists of wireless stations (STA) that compete for access to the shared wireless medium. Two types of WLAN can be deployed: Ad-hoc or infrastructure. An Independent BSS (IBSS) is an ad-hoc network, in which all stations are able to communicate with each other directly. In an infrastructure
WLAN the BSS also includes an access point (AP) that provides access to backbone distribution systems. AP is also a STA, but it simultaneously owns access ports to the fixed network. In reality, its function is similar to that of a base station (BS) in a cellular network. Infrastructure networks are currently more popular than ad-hoc networks, because they meet the needs of coverage networks of large size and complexity. In this thesis we will focus on infrastructure networks with one AP and several stationary or low mobility STAs. Transmission from the AP is referred to as downlink; transmission from any other STAs is termed uplink. In infrastructure network, communications are only allowed between the AP and the non-AP STAs.

3.1.2 MAC sublayer functions

The Distributed Access Function (DCF) is the basic protocol of the 802.11 MAC layer and uses a carrier-sense multiple access/collision avoidance (CSMA/CA) [19] protocol as the fundamental access method. An optional access method is the Point Coordination Function (PCF), which is deployed at the AP and resolves contention by polling stations in turn. In this thesis, only DCF is studied. It operates as follows: when a STA is ready to transmit a MAC protocol data unit (MPDU), which is a complete data unit passing from MAC layer to PHY layer, it must sense the medium to determine if it is busy. If the medium is idle for at least the DCF interframe space (DIFS) duration, transmission is allowed. If the medium is sensed busy, after detecting the channel to be idle without interruption for a period equals to DIFS the STA will backoff for an additional period of \( n \times \text{time_slot} \), where \( n \) is an integer randomly selected over the interval \([0, CW (\text{Contention Window})]\) and \( \text{time_slot} \) is decided by the correspondingly named PHY characteristic (In Direct Sequence Spread Spectrum...
Chapter 3 New CSDS scheduling algorithm developments

(DSSS), \( \text{time}_\text{slot} = 20 \text{ us} \). The size of CW, which is bounded by a maximum value \( CW_{\text{max}} \), is doubled after each unsuccessful transmission to reduce the collision probability. Following each successful transmission, CW is reset to the minimum value \( CW_{\text{min}} \). During backoff period, a STA decreases its backoff counter by one if the medium is idle for a \( \text{time}_\text{slot} \) and keeps it frozen when the medium is busy. When the backoff counter reaches zero, the STA will transmit its MPDU immediately.

If the MPDU is received successfully by the destination STA, an Acknowledgement (ACK) frame will be sent back to the source after a Short Interframe Space (SIFS). In the case of unsuccessful transmissions requiring ACK, backoff will begin at the end of ACK timeout interval, i.e. after an Extended IFS (EIFS) period following detection of a frame that was not received correctly. Therefore, after a successful or unsuccessful transmission, another contention procedure will begin for all STAs ready for transmission. Retransmission may be triggered at the source STA if it does not receive an ACK within ACK_timeout period. A frame is dropped when its retry limit is reached. The parameters \( \text{dot11ShortRetryLimit} \) and \( \text{dot11LongRetryLimit} \) are specified in the IEEE 802.11b WLAN standard as retry limits corresponding to different frame lengths. When a MAC frame of length is greater than \( \text{dot11RTSThreshold} \), which is the threshold of frame length to apply RTS/CTS method, \( \text{dot11LongRetryLimit} \) is used; otherwise \( \text{dot11ShortRetryLimit} \) is applied. The values of the three parameters are defined as PHY management information base (MIB) attributes and are given in Annex C of [19], which equal to 7, 4, and 3000 bytes respectively.
DCF also includes an optional transmission method of RTS/CTS, which requires transmission of Request To Send (RTS) and Clear To Send (CTS) frames prior to the transmission of actual MPDU. RTS/CTS can alleviate the hidden terminal problem and can reduce the waste in transmission time of long frames caused by collisions. However the efficiency is reduced for short frames. RTS/CTS mechanism is not used in this project since it is optional.

3.2 Wireless channel model

As mentioned above, a wireless channel has properties which are quite different than wire-line channel. Fading will cause a time-varying channel capacity. There are various mathematical models to simulate the properties of a wireless channel.

The Gilbert model [17] is a wireless channel model that is frequently used in the study of scheduling algorithms. It is a discrete-time Markov chain with two states: error-free ("good") or error-prone ("bad"). The channel moves between the two states according to a certain transition probability matrix. The bad state (good state) is often assumed to have a packet error rate (PER) = 1(0). In a variant of Gilbert model, packets are successfully received with high probability when channel is in Good state (\(\text{PER} \approx 0\)) and with low probability when channel is in Bad state (\(\text{PER} \approx 1\)). Another popular variant is Finite-state Markov Chain with \(n\) states. It has been shown in [18] that this model can simulate Rayleigh fading channel well. Each of \(n\) states corresponds to a small range of signal levels. A \(n \times n\) matrix of state transition probabilities characterizes the wireless channel behavior. One simplified version is a birth-death chain in which only transitions between neighbor
states are possible. Usually the BER for each state depends on the corresponding signal level range.

Since the channel states in Markov chain based channel models are discrete, it seems they are too simple to be accurate. Therefore, in our simulation we use a practical multipath fading channel model as in [25], in which the signal power level at the receiver is given by:

\[ P_r = P_0 - 10\beta \log(d_r/d_0) + F_r \] (3.1)

where \( P_0 \) is the power received at a close-in reference point at a small distance \( d_0 \) from the transmitting station, \( d_r \) is the distance from the receiver to the transmitter, and \( \beta \) is the attenuation factor. Note that

\[ d_0 \geq \frac{2D^2}{\lambda} \] (3.2)

where \( D \) is the largest physical linear dimension of the antenna and \( \lambda \) is the wave length. Additionally, \( d_0 \) is chosen to be smaller than any practical distance used in the mobile communication system [36]. The first two terms model the channel path loss by propagation. \( F_r \) is the envelope of the time-correlated multipath fading signal and is simulated by Jake’s model [26]. In this model, according to mathematical analysis, a complex signal \( T(t) \), which is expressed by:

\[ T(t) = \frac{E_0}{\sqrt{N}} \left\{ \sqrt{2} \sum_{i=1}^{N_0} \left[ e^{i(\omega_c t \cos \alpha_z + \varphi_0)} + e^{-i(\omega_c t \cos \alpha_z + \varphi_0)} + e^{i(\omega_c t + \varphi_\alpha)} + e^{-i(\omega_c t + \varphi_\alpha)} \right] \right\}, N_0 = \frac{1}{2} (\frac{1}{2} N - 1) \]

(3.3)

is approximately a complex Gaussian process if \( N \) is big enough based on the Central Limit Theorem, so that \(|T|\) is Rayleigh distributed. Typically \( N \geq 6 \) is sufficient to obtain a good
Rayleigh approximation. $N_0$ is the number of frequency components involved and $\omega_m$ is the maximum Doppler frequency. Figure 1.7-2 in [26] shows the block diagram of such a simulator. $N_0$ low-frequency oscillators with frequencies equal to the Doppler shifts $\omega_m \cos(2\pi n/N)$, $n=1,2,\ldots,N_0$, plus one with frequency $\omega_m$ are used to generate signals frequency-shifted from a carrier frequency $\omega_c$. The phases are uniformly distributed. In our simulation model, $N_0=38$ is used as the model in [31]. The advantage of this Rayleigh fading channel model is that it can provide continuously changing channel states so as to achieve better precision than those model mentioned above. Similar to them, SNR level is used to represent the dynamic channel states.

3.3 Fairness definition and Compensation mechanisms

3.3.1 Fairness definition

Fairness can be measured by service allocation difference. There are at least two ways to describe service difference, one is by throughput, and the other is by service time. Throughput discrepancy is a more popular way for fairness measurement. Therefore, we use traditional throughput difference as the fairness measure.

Fairness can be short-term or long-term. [27] gives definitions of both: a system is said to be long-term fair if all users gain equitable access to its resources in the long run, although there may be transient periods of unbalanced access; short-term fairness, instead, refers to equitable sharing of resources in the short run. Usually, short-term fairness implies long-term fairness, but not vice-versa. Actually, the difference between them is not precisely defined. In most cases, it depends on the type of applications. For example, in [9] 10 s is specified as the
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fairness window for short-term fairness for TCP application. In [1] it is also noted that TCP applications can be tolerant to several seconds delay. However, this may be different for other applications. In our work, we assume TCP traffic, and short-term fairness is measured in seconds.

The fairness index used in this thesis to indicate fairness performance is the definition proposed by Jain et.al in [28], which is widely used by researchers. The definition is as follows: in a system allocating resources to \( n \) contending users, such that user \( i \) receives an allocation \( x_i \), the fairness index is defined as

\[
f(x) = \frac{\left( \sum_{i=1}^{n} x_i \right)^2}{n \sum_{i=1}^{n} x_i^2} \quad x_i \geq 0, \ x = (x_1, x_2, ..., x_n)
\]  

(3.4)

This index measures the "equality" of user allocation \( x \). If all users get the same service amount, i.e. \( x_i \)'s are all equal, then the fairness index is 1, which means the system is 100% fair. As the disparity increases, fairness decreases and a scheme which favors only a selected few users has fairness index near 0.

3.3.2 Compensation mechanisms

As described in Chapter 2, simple fairness scheduling algorithms like Round Robin are preferable to complicated scheduling algorithms for WLAN system. To support good fairness performance, a compensation mechanism should be included in such a scheduler.
The goal of a compensation mechanism is to improve fairness performance between users, not only long-term fairness but also to support good enough short-term fairness. Generally a compensation mechanism can only guarantee long-term fairness in an error-prone environment because short-term fairness is related to fluctuating channel states. In IWFQ [2], long-term fairness in error-prone conditions is guaranteed whereas short-term fairness is supported only among error-free users. Short-term fairness in error-prone cases cannot be guaranteed due to the time-varying nature of the channel. In [2] for error-prone scenarios, a lower bound is obtained on the short-term throughput, which depends on the accumulative period a user stays in good state during the measurement interval. Subsequently proposed WFQ-based compensation mechanisms support graceful service degradation of leading sessions at the cost of more complexity and worse short-term fairness. In such a scheduling policy, not only is timestamp employed, but also leading and lagging sessions need to be marked to calculate service gap.

RR-based scheduling algorithms need specially designed compensation mechanism to improve fairness performance, such as WDRR [5] etc. Performance comparable to WFQ-based compensation mechanisms can be achieved. The drawbacks are complexity and computation overhead.

In TCP short-term fair scheme [9], RR is applied as the basic scheduling rule and a simple compensation mechanism is proposed to improve short-term performance of TCP applications. This compensation mechanism is simple to adopt in a WLAN environment. Compensation is implemented based on service allocation during the previous period of
fairness measurement window. Users who obtained lower throughput than average during the previous measurement window are considered as lagging and are rewarded by additional packet transmissions during the current window. On the other hand the leading sessions will be penalized by reducing their transmission times. The number of additional packets transmissions are chosen empirically from simulation results. This mechanism is simple and easy to deploy in a WLAN system, and can improve the short-term fairness. However it will not provide a big improvement in fairness, especially long-term fairness because compensation depends only on the service allocation in the previous measurement window of 10 seconds, which means that service is considered fair before that. This is in contrast to more complex compensation mechanisms in which the service gap is determined by service obtained in the whole past.

In this thesis we propose a simple compensation mechanism for 802.11 WLAN. The basic idea is to give high priority to users with low average SNR level (S_{av}) when they have similar channel state to those users with high S_{av}. This target can be achieved by calculating “Modified SNR Level” S' for each user. In other words, according to the relative channel condition (difference between measured SNR level and the average SNR level), the measured SNR level is assigned a weight - “modified SNR level” according to:

\[ S_i' = S_i + \left( \frac{S_i}{S_{iav}} \right) \phi (S_i - S_{iav}) \]  

(3.5)

where \( S_i \) and \( S_{iav} \) are the measured and average SNR level of user \( i \) respectively and \( \phi \) is the compensation control parameter. The difference between measured and modified SNR increases with \( \phi \). Thus a user with a low average SNR level, which currently enjoys a good channel state, will be assigned a high priority to transmit provided that the long-term fairness
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performance can be improved. From (3.5), if $S_i^{av} < S_j^{av}$ and $S_i = S_j$, $S_i' > S_j'$, also if $(S_i - S_i^{av}) < 0$, $S_i^{av} < S_i$.

3.4 New scheduling schemes

Based on the proposed compensation mechanism, new scheduling schemes can be designed for 802.11 WLAN networks which are expected to have better fairness performance while maintaining a high total throughput. In this thesis three new scheduling schemes are proposed. The first one is based on “Maximum SNR first” and the second on Weighted Round Robin (WRR). The third scheme is a combination of the first two schemes.

3.4.1 Max S*

In this scheme, the scheduling algorithm is the simple “Max S” policy. The original algorithm selects the HOL packet with the best channel state each time. This yields an optimal total throughput performance at the cost of poor fairness performance.

The Max S* scheme is the Max S algorithm combined with the proposed compensation mechanism to improve fairness performance. Specifically, each time Max S* chooses the HOL packet with the highest Modified SNR level $S'$ for next transmission. As discussed in the previous section, the compensation mechanism gives precedence to a user with a low average SNR when it has a similar channel state to a user with a high average SNR. Hence it is possible that the compensation results in a decrease in total throughput. To avoid large total throughput degradation, a threshold is used to control the compensation procedure. If
the measured SNR level (referred to as S) is higher than the threshold, the modified SNR level \( S' \) will be used; otherwise, the SNR level is not modified. The \( \text{Max} \ S^* \) scheme thus operates as follows:

\[
\text{Set} \quad S^* = \begin{cases} 
S' & S \geq \text{threshold} \\
S & S < \text{threshold}
\end{cases}
\]  

At each scheduling instant, the queue with the highest \( S^* \) is selected for transmission. If there is more than one such queue, one is selected in a RR fashion.

The threshold is chosen based on the packet error rate (PER), which is related to packet length. In our simulations the threshold is set to 10.5 dB, at which the PER is close to \( 10^{-2} \) for 8800 bits packet length. This PER value is considered as a bound of good channel state in [39]. If the channel state of a user with low average SNR is good enough (i.e. \( S \) is higher than the threshold), it can receive service compensation from those with a high average SNR so that better long-term fairness performance can be achieved and simultaneously a high total throughput performance can also be expected.

### 3.4.2 Improved WRR (IWRR)

As in the original CSDS scheme [1], backlogged users are selected in a Round Robin fashion. However, in IWRR, a Weighted Round Robin including the proposed compensation mechanism is applied to obtain a better fairness performance than the original CSDS+RR scheme [1]. In contrast to traditional WRR schemes [41], a dynamic weight is used instead of a predetermined one: the weight of each user is calculated per packet transmission slot
according to its current channel state. For user $i$ whose SNR level is higher than TT, the weight is calculated by

$$\text{weight}_i = \frac{S_i}{\sum_{s \leq TT} S_i}$$  \hspace{1cm} (3.7)$$

For a user with SNR level lower than TT, its weight is set to 0. If the weights of all users are zero, a user with the best channel state is selected. If there is more than one such user, the tie is broken by RR method. The implementation of this scheme is as follows:

A round is adopted and its length, $L_{\text{round}}$, is fixed to a certain number of packet transmission slots. For each backlogged user $i$, a counter $C_i$ is employed to indicate the number of packet transmission slots used so far by user $i$ in the current round. At the beginning of each round, $C_i = 0$. In each round, users are served in cycles; during each cycle, user $i$ can be allocated at most one packet transmission slot. If user $i$ has a weight greater than 0, its allocated packet transmission slots will be calculated as $A_i = L_{\text{round}} \times \text{weight}_i$, then if $C_i < A_i$, the user will be allowed for transmission and $C_i$ is increased by one. If none of users satisfies above conditions of $C_i < A_i$, a user with none zero weight is selected in order. Otherwise, the user with the highest S is selected since in this case all weights are zeros. The flow chart of the operation of IWRR is shown in Figure 3.1, where “picked” is the queue which obtained previous transmission slot, N is the number of users, R is the counter of a round.
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Figure 3.1: Flow chart of IWRR scheme
3.4.3 Combined scheduling scheme (IWRR+Max S*)

In order to inherit the advantages of the two above schemes, a combined scheme is proposed in which the weight of user $i$ is calculated in the case that some users have channel states above TT as follows:

$$weight_i = \frac{B_i}{\sum_i B_i} \quad (3.8)$$

where

$$B_i = \begin{cases} 
10(\gamma^{0.1} - \gamma) \frac{S_i'}{\sum_{S_i \geq TT} S_i'} + (1 + \gamma^4)^{S_i'} & \gamma \in [0,1] \\
0 & S_i < TT
\end{cases} \quad (3.9)$$

In the case that no user has an S greater than TT, the weight of user $i$ is calculated by (3.8), where

$$B_i = 10(\gamma^{0.1} - \gamma) \frac{S_i'}{\sum_i S_i'} + (1 + \gamma^4)^{S_i'} \quad \gamma \in [0,1] \quad (3.10)$$

Note that if none of the users has an S above the TT, the weight of each user is not set to zero but is decided by S. The maximum S will correspond to the heaviest weight to approximate the rule (selecting the best S when all S < TT) applied in Max S* and IWRR.

The first term in the RHS of (3.9) reflects the IWRR, and the second part reflects the Max S*. When $\gamma = 0$, the first term is 0, and the second part is a constant 1; the combined scheme approximates RR since all users have the same weight. As $\gamma$ increases from 0 to 0.1, the first term rapidly overweighs and the scheme approaches IWRR. When $\gamma \approx 0.1$, the first term dominates the whole weight and the scheme approximates IWRR. As $\gamma$ increases to 1,
the scheme approaches $\text{Max S}^*$. When $\gamma = 1$ the first term is again 0 and the second term becomes dominant and the scheme approximates $\text{Max S}^*$, in which the weight is determined by the modified SNR $S'_i$; the exponential function amplifies the gap between different $S'_i$ values. The functions

\begin{align}
  f_1 &= 10(\gamma^{0.1} - \gamma) \\
  f_2 &= 1 + \gamma^4
\end{align}

are shown as a function of $\gamma$ in Figure 3.2.

![Figure 3.2: Functions of $\gamma$ in (3.10) and (3.11)](image)

The implementation of IWRR+Max S* is similar to IWRR. The only difference is that the case that all weights of users are zero will never happen. In the case that all users' channel states are lower than TT, transmission slot will be given to a user whose current $A_i$ is not zero in a RR fashion. The flow chart of IWRR+Max S* is shown in Figure 3.3.
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Init R=Lround; All \( C_i = 0 \)

\[ i = \text{picked} \]

\[ i = i + 1; \]
if \( i > N, i = \text{mod}(N) \)

weight\(_i\) > 0?

Y

\[ C_i < A_i? \]

Y

\[ C_i = C_i + 1; \]
\[ U_i \text{transmits} \]

N

i = picked -1?

N

Y

R = 0?

N

R = R -1

Figure 3.3: Flow chart of IWRR+Max S*
Chapter 4 Simulation environment

The most popular WLAN products are based on the IEEE 802.11b WLAN standard and are deployed in the 2.4 GHz. The newly proposed 802.11g standard in 2003 uses the same frequency band; the only difference is the PHY layer modulation scheme which allows 802.11g to support higher transmission rates. We base the simulations on 802.11b. In the following sections, we describe the function of different modules in the simulation system, following by the verification tests, which were done with the help of Optimized Network Engineering Tools (OPNET).

4.1 Fading channel module implementation and verification

The channel module is an important component whose output is input to both the scheduling algorithm and traffic sink modules. In our simulation scenarios, the Jake’s model is employed to simulate Rayleigh fading channel as described in Chapter 3. Inputs of the module are average received signal level $P_r$ and Doppler frequency $f_d$. In [29], the range of $f_d$ is set to 1.34 Hz to 80 Hz, corresponding to user speeds of 0.4 mph (0.18 m/s) and 22.4 mph (10 m/s). Pedestrian speeds of 1~2 m/s [30] correspond to Doppler frequencies of 8~16 Hz approximately. In our simulation, the maximum Doppler frequency is set to 10 Hz. The Rayleigh fading channel simulator was obtained from [31]. AWGN can also be added to the received signal.

To verify the Rayleigh distribution of the channel model, the empirical Cumulative Distribution Function (CDF) of the simulation results in our C++ programming system, which are the samples of dynamically changing received signal level, can be obtained and
compared with the standard function in MATLAB. Verification parameters are as follows: $f_d = 10$ Hz, average received power $P_r = 20$ dBm, simulation time $t_s = 100$ s, sample rate $s_r = 1250$ points/s. The CDF comparison results are shown in Figure 4.1, it can be seen that our channel model simulates Rayleigh distributed signal levels well.

![CDF function comparison](image)

Figure 4.1: CDF of Rayleigh distributed fading channel

Another key feature to evaluate the channel module is the level crossing rate (LCR) function, which shows how frequently the channel state crosses a certain threshold level in the downward direction.

Assuming a fixed packet length of 8800 bits, and a transmission rate of 11 Mb/s, the duration of one packet transmission is 800 us. Figure 4.2 shows sample LCR results as a
function of the received power $P_r$ (dBm) for sampling rate $sr = 1250, 12500, \text{ and } 125000 \text{ pps}$ ($fd = 10 \text{ Hz and average received power } \overline{P_r} = 20 \text{ dBm}$). These rates correspond to 1 points/pkt, 10 points/pkt and 100 points/pkt respectively. LCR function shows difference for the first two scenarios, which means the channel is changing during a packet transmission period and sampling rate of 1250 pps is not accurate enough. However the function shows no difference when sampling rate is changed from 12500 points/s to 125000 points/s. To ensure accurate simulation PER results, the sampling rate $sr$ is chosen to be 100 points/pkt, i.e. 125000 pps through all simulation results in this thesis.

![LCR functions of Rayleigh fading channel](image)

*Figure 4.2: LCR functions of Rayleigh fading channel*
4.2 IEEE 802.11b WLAN simulation system implementation and verification

4.2.1 System implementation

The simulation is programmed in C++. The network is one BSS with one AP and \( N \) user nodes as shown in Figure 4.3. We assume that the distances between AP and user nodes are not identical. Communication is only allowed between AP and user nodes. No direct communication among user nodes is possible. In this thesis the focus is on downlink scheduling policy at the AP, but to simulate a more realistic 802.11 environment with contention, a light uplink traffic load is included.

![Figure 4.3: Topology of an infrastructure 802.11b WLAN](image)

The simulation system includes two-way communication. All the \( N+1 \) nodes including the AP contend for the shared wireless channel according to the CSMA/CA protocol specified in 802.11 standards. If no collision is detected and the AP gets the opportunity of transmission, downlink transmission is triggered and the scheduling algorithm is employed to select the HOL of queues; if a user node gets the opportunity of transmission, uplink transmission is triggered. In the uplink direction a FIFO scheduling scheme is employed. A
flow chart of the operation at a node \( i \) is shown in Figure 4.4.

![Flow chart of operation at a Node i](image)

- Backoff counter reset
- Backoff counter - 1
- Backoff counter=0?
  - Y (Collision)
  - Other nodes backoff counter=0?
    - Y
      - AP?
    - N
      - Downlink AP transmission process
- N
  - Uplink Node \( i \) transmission process
- Contention Window doubled

Figure 4.4: The flow chart of the operation at a Node \( i \)

The simulation system consists of several modules: node module, which includes traffic-arrival sub module, enqueue/dequeue sub module, and scheduling-algorithm sub module, channel module, and traffic sink module. On the downlink transmission, all modules are involved. On the uplink direction, the node module only includes the first two sub modules. The function blocks of both directions are shown in Figure 4.5 and Figure 4.6.
On the downlink, at each scheduling moment, the algorithm sub module selects the HOL of one queue for transmission based on channel state information. The traffic sink module is used to determine whether the incoming packet is successfully received. If not, a retransmission procedure would be triggered according to the rule of the scheduling.
mechanism. When the retransmission limit is reached, the packet is dropped. Similar events occur on the uplink, except that only one queue exists at each node and the scheduling algorithm is FIFO. The functions of each module in the system are introduced next.

• Node module

The main function of a node module is to set the backoff counter for channel contention. Each node involves several sub modules. On the downlink, the AP node includes the traffic arrival sub module, enqueue/dequeue sub module and scheduling algorithm sub module; on the uplink, only the traffic arrival and enqueue/dequeue sub modules are needed.

• Traffic arrival sub module

The traffic arrival module generates packets. On the downlink, $N$ traffic arrival processes are built up at the AP corresponding to $N$ traffic sinks. In our simulation this function can be ignored since saturated downlink traffic is assumed so that queues are never empty. On the uplink, independent, identically distributed (iid) Bernoulli arrival process is assumed in each node. The sub module also records the retransmission time of HOL in the case of an unsuccessful transmission. If the retransmission limit reaches, the HOL will be dropped, and the information is recorded in this module as well.

• Enqueue/dequeue sub module

The main functions of the enqueue/dequeue sub module are to set up queues and deal with enqueue and dequeue cases. For the downlink, $N$ queues need to be set up in the AP node. An enqueue process is triggered by the traffic arrival process and a dequeue process is
Chapter 4 Simulation environment

based on the output of the scheduling algorithm sub module. In our test scenario, enqueue cases are ignored for downlink traffic since a saturated traffic load is assumed. On the uplink, only one queue is used per node and the enqueue process is triggered by a traffic arrival. Dequeue follows the FIFO rule.

- **Scheduling algorithm sub module**

  This module is only involved in downlink transmission. For algorithm comparison, Scheduling algorithms including CSDS+RR, MAX S, Max S/Sav, Max S*, Improved WRR (IWRR), and combined scheme IWRR+Max S* are simulated. According to the channel states of the $N$ sessions, the scheduling algorithm selects an appropriate HOL for next transmission and the results are sent back to the enqueue/dequeue sub module. Implementations of the scheduling algorithms are introduced next.

- **Traffic sink module**

  The traffic sink module is used to determine whether the transmission of the selected HOL is successful or not, based on the current channel state. In the case that $N$ active sessions are in the simulation scenario, $N+1$ traffic sinks are built up for bidirectional communication. The traffic sink module of AP is invoked in an uplink transmission; other $N$ sink modules are involved in downlink transmission. The PER of a channel state is calculated by the channel module and transferred to the sink for reception decision. If the reception is not successful, information is sent to the corresponding node module: AP node if downlink, other nodes if uplink. And then the retransmission process is implemented based on the scheduling rule applied at the node.
• Channel module

The functions of the channel module are to generate time-correlated Rayleigh distributed signal level and calculate PER based on packet length, modulation mode and current channel SNR level. The PER is transferred to the traffic sink module and the current SNR level is used by the scheduling algorithm module at the AP for HOL selection. In our simulation, perfect channel knowledge is assumed.

CSDS+RR: In this algorithm, a SNR threshold is chosen. Channels with SNRs higher than the threshold are in “Good” state; otherwise the channel is marked as in “Bad” state. The scheduling algorithm selects the queues with Good channel state in a Round Robin fashion. If all queues are in bad state, a queue is selected for transmission according to RR as well. We simulated the CSDS+RR scheme according to the original policy proposed in [1].

MAX S: This algorithm was proposed as an extreme case in weight-based CSDS schemes, such as [7], [38]. At each scheduling moment, the queue with the highest SNR is selected for transmission. If there is more than one such queue, one is selected at a RR fashion. As mentioned in Section 2.2, optimal total throughput can be achieved by selecting the user with the best channel state each time. Therefore, this algorithm can be employed as a performance criterion of total throughput of other CSDS scheduling schemes.

MAX S/Sav: At each scheduling moment, the queue with the best relative channel state defined as the ratio of current SNR state ($S$) to the queue’s average SNR ($S_{av}$) is selected for transmission. As in the MAX S scheme, ties are broken by a RR fashion. This scheme was
mentioned in [35] and is naturally related to our new schemes since all of them include the factor of average channel states. Max S/Sav is simple and was introduced to be fair in [35] for STAs with different average received powers, so here it is involved for performance comparison.

4.2.2 Verification of C++ simulation model with simple OPNET test scenarios

In order to verify that our C++ IEEE 802.11b WLAN MAC layer simulation program (hereafter referred to C++) is correct, simple test scenarios were implemented and compared with reference scenarios built up in OPNET. The objective is to verify that the C++ simulated MAC layer protocols perform in a comparable way to the OPNET results.

- Introduction to OPNET WLAN simulation environment

OPNET supports an 802.11b WLAN simulation module. Unfortunately, no wireless multipath fading channel model is included and only a FIFO policy is implemented as the scheduling algorithm on both directions. However, the MAC layer protocol performance of our C++ simulator can be verified by comparison with test scenarios supported in OPNET.

The MAC layer functions of WLAN module in OPNET are based on 802.11 standards. The main features are as follows [32]:

**Access Mechanism**: Carrier sense multiple access and collision avoidance (CSMA/CA) distributed coordination function (DCF) scheme as defined in the standard. The point coordination function (PCF) is also supported.
Frame Exchange Sequence: Data and Acknowledgment frame exchange to ensure the reliability of data transfer. Optional RTS/CTS frame exchange for media reservation.

Deference And Backoff: Interframe spacing: DIFS, SIFS, EIFS for DCF and PIFS for PCF implementation. The values of the intervals are selected based on the PHY layer characteristics.

Data Rate: 1 Mbps, 2 Mbps, 5.5 Mbps, 11 Mbps

Recovery mechanisms: Retransmission mechanism for data frames used when ACK frame is not received. Long and Short retry counters as defined in the standard.

Fragmentation and Reassembly: optional, based on data packet size

Buffer Size: length defined by the user

For PHY layer, OPNET can model FHSS, DSSS, and Infrared technologies from the IEEE802.11 standard specification. In order to model the 802.11b physical layer, we set the channel data rate at 11 Mbps with DSSS physical characteristics. However all control packets are transmitted at a data rate of 1 Mbps as specified by the standard. The radio transceiver pipeline, which consists of 14 stages, is used to model wireless transmission of packets [33]. These stages include Received power, Background noise, Bit error rate, Signal to noise ratio etc. Based on the outputs of these stages, the pipeline can provide error information of received packets to the MAC layer. Background noise and Interference stages are used to model wireless channel characteristics. Both of them are constant values, which mean no multipath fading effect is included in the module. In the WLAN model of OPNET, path-loss propagation model is included in the received power stage, and the received signal power is computed by:
Reception power (mW) = Transmission power (mW) × path_loss  \hspace{1cm} (4.1)

where \( \text{path\_loss} \) is calculated by:

\[
\text{path\_loss} = \frac{\lambda^2}{16\pi^2 l^2} \hspace{1cm} (4.2)
\]

where \( l \) is the distance between the transmission node and the receiving node.

- Comparable test scenarios in OPNET and C++ for verification

We can see from (4.1) and (4.2) that the received power is only a function of the distance between the transmitter and the receiver. No fading is included in the OPNET simulation system. Now the comparable test scenarios can be built up in C++ and OPNET simulation systems by translating test parameters in OPNET to the inputs of C++ simulation. Given the distance between the AP and the STA, according to the pipeline introductions in OPNET [33], the received SNR is calculated as:

\[
\text{SNR (dB)} = \text{reception\_power (dBm)} - \text{noise (dBm)} \hspace{1cm} (4.3)
\]

where the reception power can be computed by (4.1) and noise can be obtained by background and interference noise stages in pipeline [33]. The transmission power is set to 0.1 mW in our verification tests.

Two verification scenarios are considered, one is simple with only one AP and one STA, and only downlink traffic is considered. The STA’s channel state is set to be “Bad”, which means PER is higher than \( 10^{-2} \). For packet length of 8800 bits, the SNR level is lower than 10.5 dB. The other is with one AP and two STAs, one with a “good” channel state, and the other with a “bad” state. In this test bidirectional traffic is considered. The topology of the second test scenario is shown in Figure 4.7. The environment is assumed a free-space office.
The distance between the AP and the wlan_stal is about 50 m (received SNR = 20 dB) and the distance between the AP and wlan_sta2 is about 160 m (received SNR = 8 dB). Note that if wlan_stal is removed, the topology is exact of the test scenario 1.

Figure 4.7: Test topology in OPNET environment with one AP and two user nodes

For each scenario, tests are repeated five times to obtain average system downlink throughput for comparison. In the first scenario, PER comparison is also included. The details of simulation parameters are introduced respectively as follows.

**Test scenario 1: 1 AP and 1 STA.** The parameters of both C++ and OPNET are as follows:
- Channel condition: $S_{av} = 8$ dB (no fading effect is considered);
- traffic source: 200 pkt/s, constant interval, downlink traffic only;
- packet length: 8800 bits;
- modulation mode: BPSK;
- data transmission rate: 11 Mb/s;
- control message transmission rate: 1 Mb/s;
- simulation time:
25 s. The results of downlink total throughput and overall PER are shown in Table 4.1 and Table 4.2 respectively. Note that the theoretical result of PER is also provided as a reference by the calculation in Matlab as follows:

For SNR = 8 dB, pktlength = 8800 bits, modulation mode: BPSK,

\[ \text{PER} = 0.7728. \]

<table>
<thead>
<tr>
<th>Throughput (pkt/s)</th>
<th>Test1</th>
<th>Test2</th>
<th>Test3</th>
<th>Test4</th>
<th>Test5</th>
<th>Avg</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPNET</td>
<td>56.96</td>
<td>56.8</td>
<td>59.08</td>
<td>58.32</td>
<td>56.4</td>
<td>57.512</td>
</tr>
<tr>
<td>C++</td>
<td>58.6</td>
<td>57.24</td>
<td>56.04</td>
<td>56.92</td>
<td>59.4</td>
<td>57.64</td>
</tr>
</tbody>
</table>

Table 4.1: Throughput comparison between OPNET and C++ simulation for test scenario 1

<table>
<thead>
<tr>
<th>PER</th>
<th>Test1</th>
<th>Test2</th>
<th>Test3</th>
<th>Test4</th>
<th>Test5</th>
<th>Avg</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPNET</td>
<td>0.7746</td>
<td>0.764</td>
<td>0.770</td>
<td>0.7733</td>
<td>0.7718</td>
<td>0.7707</td>
</tr>
<tr>
<td>C++</td>
<td>0.7704</td>
<td>0.7722</td>
<td>0.7749</td>
<td>0.7761</td>
<td>0.7684</td>
<td>0.7724</td>
</tr>
</tbody>
</table>

Table 4.2: PER comparison between OPNET and C++ simulation

**Test scenario 2: 1 AP and 2 STAs.** The parameter values are as follows:

Channel condition: \( S_{av1} = 20 \, \text{dB}, \, S_{av2} = 8 \, \text{dB} \), both downlink and uplink traffic are involved. Downlink traffic is as in scenario 1, uplink traffic: 5 pkts/s, constant interval,
Chapter 4 Simulation environment

scheduling scheme in AP for downlink: FIFO (destination is randomly selected between STA1 and STA2). Other parameters are set as in scenario 1.

The results of downlink throughput obtained by STA1 and STA2 are shown in Table 4.3 as below.

<table>
<thead>
<tr>
<th>Throughput (pkt/s)</th>
<th>OPNET STA1</th>
<th>OPNET STA2</th>
<th>C++ STA1</th>
<th>C++ STA2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test1</td>
<td>58.96</td>
<td>49.08</td>
<td>59.36</td>
<td>50.08</td>
</tr>
<tr>
<td>Test2</td>
<td>60.32</td>
<td>50.6</td>
<td>59.88</td>
<td>49.76</td>
</tr>
<tr>
<td>Test3</td>
<td>58.12</td>
<td>48.14</td>
<td>60.12</td>
<td>50.16</td>
</tr>
<tr>
<td>Test4</td>
<td>57.72</td>
<td>48.36</td>
<td>57.12</td>
<td>48.28</td>
</tr>
<tr>
<td>Test5</td>
<td>56.08</td>
<td>47.36</td>
<td>56.64</td>
<td>47.64</td>
</tr>
<tr>
<td>Avg</td>
<td>58.24</td>
<td>48.708</td>
<td>58.624</td>
<td>49.184</td>
</tr>
</tbody>
</table>

Table 4.3: Throughput comparison between OPNET and C++ simulation for test scenario 2

From the results in Table 4.1, Table 4.2, and Table 4.3, it can be seen that the C++ simulation results are quite similar to those obtained by OPNET.
Chapter 5 Simulation results and analysis

5.1 Simulation assumptions and test scenarios

In the simulation, only results related to downlink scheduling is generated, even though bidirectional traffic is included. The downlink traffic queues are assumed to be always backlogged (i.e. queues are never empty); while on the uplink a light traffic load is assumed. Scheduling decisions are made on per packet basis and perfect knowledge of channel states is available.

Our 802.11b MAC layer simulation system includes CSMA/CA access mechanism, backoff and retransmission procedures, and DIFS, SIFS, EIFS, and MAC/PHY overhead of MPDU. The assumptions and parameters used in every test scenario are specified in Table 5.1.

<table>
<thead>
<tr>
<th>Network structure</th>
<th>Infrastructure, one AP with several user STAs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel model</td>
<td>Rayleigh fading + AWGN noise</td>
</tr>
<tr>
<td>Downlink traffic</td>
<td>backlogged</td>
</tr>
<tr>
<td>Uplink traffic</td>
<td>i.i.d Bernoulli distribution with generation probability 0.05% (packets per time_slot)</td>
</tr>
<tr>
<td>Packet length:</td>
<td>8800 bits</td>
</tr>
<tr>
<td>Modulation mode</td>
<td>BPSK</td>
</tr>
<tr>
<td>RTS/CTS</td>
<td>NO</td>
</tr>
<tr>
<td>Data transmission rate</td>
<td>11 Mbps</td>
</tr>
<tr>
<td>Fragmentation</td>
<td>NO</td>
</tr>
<tr>
<td>Control frame transmission rate</td>
<td>1 Mbps</td>
</tr>
<tr>
<td>Buffer size</td>
<td>Unlimited</td>
</tr>
<tr>
<td>Retransmission limit</td>
<td>7</td>
</tr>
</tbody>
</table>

Table 5.1: Simulation model parameter values
Other parameter values as specified in [34] are shown in Table 5.2.

<table>
<thead>
<tr>
<th>Time_slot</th>
<th>20 us</th>
<th>PLCP_overhead_control</th>
<th>192 us</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIFS</td>
<td>10 us</td>
<td>Default_PLCP_overhead</td>
<td>57 bits</td>
</tr>
<tr>
<td>DIFS</td>
<td>50 us</td>
<td>MSDU_header_size</td>
<td>224 bits</td>
</tr>
<tr>
<td>EIFS</td>
<td>112 us</td>
<td>ACK timeout</td>
<td>112 us</td>
</tr>
<tr>
<td>CW_min</td>
<td>31</td>
<td>CW_max</td>
<td>1023</td>
</tr>
</tbody>
</table>

Table 5.2: Other simulation parameters

In this chapter, simulation results are provided to illustrate the effect of Doppler frequency, fairness window size and the number of users on our proposed scheduling schemes. Results for CSDS+RR, Max S and Max S/Sav are also presented for comparison. Although our compensation mechanism is targeted to improve long-term fairness, for real applications, short-term fairness is more important and should be considered. So for all simulation scenarios, the size of the short-term fairness window is specified in seconds according to TCP traffic requirements. Since good short-term fairness implies good long-term fairness, long-term fairness results are not explicitly included. The simulation time is set to 300 s for all scenarios to obtain meaningful statistic results.

To evaluate the average short-term performance over the whole simulation period, simulation time is divided into disjoint intervals, each equal in duration to the short-term fairness window. For each interval, the fairness index and the normalized total throughput on the downlink are calculated. Recall that the fairness index is defined in Section 3.2 as
Chapter 5 Simulation results and analysis

\[
f(x) = \left( \frac{\sum_{i=1}^{n} x_i^2}{n \sum_{i=1}^{n} x_i^2} \right)^2 \quad x_i \geq 0, \text{ } \vec{x} = (x_1, x_2, ..., x_n)
\]

where \(x_i\) is the throughput that user \(i\) obtains during the interval of fairness window. The normalized total throughput is equal to the ratio of total throughput in bps to channel capacity (i.e. 11Mb/s in our simulation). Then the average values of them over the whole period are obtained and are used as criterions for performance comparison.

Tests scenarios including 1 AP and the number of users \(N_u = 2, 4, 8, 12, 16, 20\) users are simulated separately; in each scenario, results for a given Doppler frequency and fairness window size pair are collected. Given the fading characteristics in 802.11b indoor WLAN [30], the Doppler frequency \((f_d)\) is chosen from the range 1 Hz to 10 Hz. And based on the TCP traffic delay requirements, the short-term fairness window \((f_{\text{win}})\) is set to between 1 s and 10 s.

The results with different \((f_d, f_{\text{win}})\) pairs for the proposed and reference schemes are first presented. Then the effect of different \(N_u\) is studied. Finally, the selection of the parameter \(\gamma\) in the IWRR+Max S* scheme is described based on the simulation results.

5.2 Results for different Doppler frequencies and fairness window size

We assume a scenario with one AP and eight equi-distant user nodes as shown in Figure 5.1. Assuming that the received power at 1 m from the AP is 1 dBm, the WLAN coverage range is approximately 200 m according to the receiver minimum input level
sensitivity of -76 dBm specified in the standard [19]. Then according to the path-loss model mentioned in Chapter 3, the average SNR level at the receiver of a user can be calculated as [37]:

\[
S_i^{av} \, (dB) = RxPower_i \, (dBm) - KTB \, (dBm) - NF \, (dB) \tag{5.1}
\]

where \( K = 1.379 \times 10^{-23} \) is Boltzmann’s constant, \( T \) is the temperature (290°K), \( B \) is the bandwidth (20 MHz), \( NF \) is the receiver noise figure (20 dB) and

\[
RxPower_i \, (dBm) = P_0 \, (dBm) - 10 \beta \log(d_i / d_0) \tag{5.2}
\]

where \( P_0 = 1 \) dBm is the received power at the reference point, which is at distance \( d_0 = 1 \) m from the AP, \( d_i \) is the distance from the node to the AP and \( \beta = 3.3 \) is the attenuation factor [25]. Therefore the average SNR values at the eight equi-distant nodes are:

35.4 dB, 25.5 dB, 19.7 dB, 15.6 dB, 12.4 dB, 9.7 dB, 7.5 dB, 5.6 dB

Figure 5.1: Deployment of an equi-distant 8-user WLAN
Simulation results were obtained for the following \((f_{id}, f_{win})\) pairs: \((10 \text{ Hz}, 1 \text{ s}), (1 \text{ Hz}, 10 \text{ s}), (2.5 \text{ Hz}, 4 \text{ s}), (1 \text{ Hz}, 1 \text{ s}), (1 \text{ Hz}, 5 \text{ s}), (5 \text{ Hz}, 5 \text{ s}), (10 \text{ Hz}, 5 \text{ s}), (10 \text{ Hz}, 10 \text{ s})\). Test results are shown in Figure 5.2 - Figure 5.9, in which the x-axis shows the average total throughput and the y-axis shows the average fairness index. In each figure, in addition to the three proposed scheduling schemes, three other CSDS based schemes are also involved. They are \(\text{(see Section 4.2.1)}\): Max S, Max S/Sav, and CSDS+RR.

The performance of the Max S and Max S/Sav schemes are represented by two individual points since no tuning parameters is involved in these schemes. For CSDS+RR, IWRR, and IWRR+Max S*, test results with different transmission threshold (TT) values of 12 dB, 10.5 dB, 9.5 dB, 8.5 dB, 7.5 dB are shown as three curves. For \((f_{id}, f_{win}) = \text{(10 Hz, 1 s)}\), additional TT values of 16 dB and 22 dB are also included to study the differences among these algorithms with high TT values. The compensation control parameter \(\phi\) in IWRR and IWRR+Max S* is set to 10.5 for all test cases. For Max S*, the threshold as defined in (3.6) is set to 10.5 dB for all test cases and the test results for \(\phi\) values of 2.5, 5.5, 7.5, 10.5, and 20.5 are shown.

In Figure 5.2, which shows the results for \((f_{id}, f_{win}) = \text{(10 Hz, 1 s)}\), it can be seen that the proposed schemes (i.e. Max S*, IWRR, and IWRR+Max S*) can provide better performance than CSDS+RR. The Max S scheme achieves the highest total throughput as expected, but has the poorest fairness performance among the schemes. Max S/Sav scheme has a good fairness performance but poor total throughput. For Max S*, when \(\phi\) is small, the performance is close to that of Max S; as \(\phi\) increases, the fairness is greatly improved while
the total throughput decreases only by a small amount. The reason is that the service compensation to sessions with poor average SNR is small for small $\varphi$, but increases with $\varphi$. And the compensation procedure is only performed when channel SNR exceeds the threshold. If all of them are below the threshold, the session with the best channel SNR is selected. In the case that the channel SNR exceeds the threshold, the PER is low (In this test, it is lower than $10^{-2}$ since the threshold is set to 10.5 dB) so that the waste of channel resource is limited. Therefore, the compensation mechanism can improve fairness performance whilst maintaining high channel efficiency.

CSDS+RR, IWRR and IWRR+Max S* were tested for different TT values. Figure 5.2 also shows that the performance of CSDS+RR decreases when the threshold exceeds a certain value, $TT_{\eta,\text{opt}}$, defined as the SNR level beyond which the total throughput decreases as the threshold increases. This is because when TT is less than $TT_{\eta,\text{opt}}$, an increase in TT causes the average PER of channel states above TT to decrease, thus resulting in a lower probability of failed transmission. However, the fairness index decreases since the users have different average SNR’s. When TT is above $TT_{\eta,\text{opt}}$, it is quite likely that all user SNR’s will be below TT, resulting in a RR allocation. Therefore, the total throughput decreases with TT when TT is greater than $TT_{\eta,\text{opt}}$. In Figure 5.2, it can be seen that $TT_{\eta,\text{opt}} = 16$ dB. From Figure 5.2 we observe that IWRR also degrades in a similar manner as CSDS+RR but IWRR+Max S* achieves the best performance among all compared schemes when $\gamma$ is chosen optimally. In Figure 5.2, $\gamma$ is set to 0.1 when $TT \leq TT_{\eta,\text{opt}}$ and $\gamma$ is set to 1.0 otherwise. In the following tests an empirically optimal value of $\gamma$ is used. These values are tabulated in Section 5.4. The combined scheme performs similar to Max S* in all tests when TT is higher
than the TT_{\text{opt}}, therefore, in the following figures only the test results with the TT values lower than the TT_{\text{opt}} are included.

Figure 5.2: The comparison results of (10 Hz, 1 s) in the 8-user test scenario

Figure 5.3 and Figure 5.4 show the results for \((f_d, f_{\text{win}}) = (1 \text{ Hz, 10 s})\) and \((2.5 \text{ Hz, 4 s})\) respectively. From the figures we observe that all the schemes have similar performances as in Figure 5.2. The fairness index improvement of IWRR and IWRR+Max S* over CSDS+RR is about 0.1. Max S/Sav achieves a performance similar to that of CSDS+RR with a TT between 7.5 dB and 8.5 dB. Figure 5.2 - Figure 5.4 suggest that different test scenarios with the same value of P_{\text{dw}} = f_d \times f_{\text{win}} = 10 yield similar performance results. It is thus necessary to only study the effect of the product P_{\text{dw}} rather than of each of these two parameters. In our simulation, \(f_d\) is in the range of 1 Hz to 10 Hz, \(f_{\text{win}}\) is between 1 s and 10 s and thus P_{\text{dw}} is between 1 and 100. The effect of P_{\text{dw}} is studied in the following tests.
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Figure 5.3: The comparison results for (1 Hz, 10 s) in the 8-user test scenario

Figure 5.4: The comparison results for (2.5 Hz, 4 s) in the 8-user test scenario
Figure 5.5 shows the results for \((f_d, f_{\text{win}}) = (1 \text{ Hz}, 1 \text{ s})\), i.e. \(P_{\text{dw}} = 1\). IWRR+Max S* exhibits similar performances as CSDS+RR, whereas the other four schemes have worse performance. Max S/Sav has a poorer fairness index than CSDS+RR because it always selects the user with the best S/Sav. Thus, when the channel is changing slowly (i.e. \(f_d = 1 \text{ Hz}\)) service allocation fluctuates widely during short intervals (i.e. \(f_{\text{win}} = 1 \text{ s}\)) yielding a poor fairness index value. Max S* is also based on the “best channel state selection” method. Therefore, although its overall performance is better than those of Max S and Max S/Sav, it is still worse than that of CSDS+RR. IWRR shows better performance than the other three although it is worse than CSDS+RR. Compensation procedure applied in IWRR also causes a bigger fluctuation of service allocation than CSDS+RR when \(P_{\text{dw}}\) is small, however the effect to RR-based schemes is less than that to “best channel state based” schemes. In Figure 5.6 - Figure 5.9, the results of \(P_{\text{dw}} = 5, 25, 50, 100\) are shown respectively.
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Figure 5.6: The comparison results for (1 Hz, 5 s) in the 8-user test scenario

Figure 5.7: The comparison results for (5 Hz, 5 s) in the 8-user test scenario
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Figure 5.8: The comparison results for (10 Hz, 5 s) in the 8-user test scenario

Figure 5.9: The comparison results of (10 Hz, 10 s) in the 8-user test scenario
Figure 5.6 to Figure 5.9 show that the performance of CSDS+RR does not change much with Pdw; the fairness index difference between IWRR and IWRR+Max S* on the one hand and CSDS+RR on the other increases, as Pdw increases from 5 to 25. Beyond Pdw = 25, the difference remains fairly constant. The fairness index of Max S/Sav and Max S* increases rapidly with Pdw for Pdw < 25; for Pdw >25, the improvement is smaller.

From Figure 5.2 to Figure 5.9, it can be concluded that when Pdw is greater than 10, the new schemes yield improved fairness index and total throughput simultaneously. For 10 ≥ Pdw ≥ 5, IWRR and IWRR+Max S* have the best performance. Overall, IWRR+Max S* provides a reasonably good performance among the three new schemes in any test scenario.

Besides, it can be seen that in each test case at the optimal TT value TTopt ≈ 10 dB, IWRR and IWRR+Max S* yield the best overall performance which means both total throughput and fairness index are close to the highest values. This means that Pdw will not affect TTopt much. Note that when SNR = TTopt, PER ≈ 10^{-2}, which is considered as a bound of good channel state in [39], can be obtained for 8800 bits packet length.

5.3 Effect of number of users

In this section, the Doppler frequency is fixed at 10 Hz, and the fairness window size is set to 1 s for all test cases. The number of users, Nu, is set to 2, 4, 8, 12, 16, 20. For Nu = 4 to 20, the user nodes are equally spaced in the coverage area of the AP. For Nu = 2, we assume that one user has a good average channel state (25 dB) and the other has a poorer one (8 dB). The parameter values used for the different schemes are the same as those in the previous
section except that the TT value used in Max S* is 8.5 dB instead of 10.5 dB when Nu = 2 and 4. The results with 8 users are shown as Figure 5.2. The results for 2, 4, 12, 16, 20 users are shown in Figure 5.10 - Figure 5.14.

The results for the 2-user and 4-user test cases are shown in Figure 5.10 and Figure 5.11 respectively. Comparing with Figure 5.2, we see that the value of TT_{opt} for CSDS+RR, IWRR, and IWRR+Max S* is lower than that in the 8-user case. In the two-user case, TT_{\text{n,opt}} is around 9.5 dB and in the four-user case, it is around 10.5 dB. The reason for this is that when Nu is small, it is more likely that the SNRs of all users fall below the TT simultaneously if the TT is kept fixed. In this case, the performance of CSDS+RR tends to that of pure RR: channel resource is wasted and both total throughput and fairness are impaired.

In Figure 5.10 Max S/Sav exhibits the highest fairness index and the lowest total throughput among the compared schemes. Among the other four schemes, Max S* and IWRR+Max S* have the best performances for all TT values. The fairness index improvement of Max S* and IWRR+Max S* over CSDS+RR is approximately 0.15.

In Figure 5.11, IWRR, Max S* and IWRR+Max S* have similar performances and are generally better than CSDS+RR. The fairness index improvement of IWRR+Max S* to CSDS+RR is about 0.12.
Figure 5.10: The results of (10 Hz, 1 s) in 2-user test scenario

Figure 5.11: The results of (10 Hz, 1 s) in 4-user test scenario
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Figure 5.12: The results of (10 Hz, 1 s) in 12-user test scenario

Figure 5.13: The results of (10 Hz, 1 s) in 16-user test scenario
Figure 5.14: The results of (10 Hz, 1 s) in 20-user test scenario

The results for 12, 16 and 20 users are shown in Figure 5.12 to Figure 5.14 respectively. It can be seen that IWRR and IWRR+Max S* have the best performances in each test scenario; the fairness index improvement of IWRR and IWRR+Max S* compared to CSDS+RR decreases somewhat with Nu as shown in Table 5.3:

<table>
<thead>
<tr>
<th>Nu</th>
<th>2</th>
<th>4</th>
<th>8</th>
<th>12</th>
<th>16</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fairness index Improvement</td>
<td>0.15</td>
<td>0.12</td>
<td>0.1</td>
<td>0.08</td>
<td>0.06</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Table 5.3: The fairness index improvement of IWRR+Max S* to CSDS+RR

Figure 5.2, Figure 5.10 to Figure 5.14 also show that Max S provides the best total throughput as expected; however it decreases with Nu. The reasons for this are that more uplink traffic is carried due to a larger number of users involved in the network and the
channel resource is wasted by more collisions as well. Furthermore, we observe that the fairness index for Max S/Sav and Max S* decreases with Nu while that for CSDS+RR changes slightly except that when Nu increases from 4 to 8.

Among all the compared scheduling schemes, IWRR+Max S* and IWRR yield the best overall performance at TTopt. From Figure 5.2, Figure 5.10 to Figure 5.14 it can be seen that when Nu ≥ 8, TTopt ≈ 10 dB, which is fairly constant, and decreases when Nu is small. For Nu = 2 and 4, TTopt ≈ 9 dB.

5.4 Selection of γ for IWRR+Max S*

For IWRR+Max S*, the parameter γ ∈ [0,1] should be chosen to provide close to optimal performance. In this section, we focus on the effect of Doppler frequency, fairness window, and number of users to the selection of γ. From the discussion in Section 5.2, the effect of Doppler frequency (fd) and fairness window size (fwin) can be simplified to considering the product Pdw = fd * fwin. In this section, we use the test scenario of one AP and eight user nodes in Section 5.2 to study the effect of Pdw on the selection of γ. The results with Pdw = 1, 5, 10, 25 are shown in Figure 5.15 to Figure 5.18 respectively. In each test case, for a given value of TT, a performance curve of IWRR+Max S* parameterized by γ is plotted. As in Section 5.2, the values of TT are equal to 7.5, 8.5, 9.5, 10.5, 12 dB (The curve for 10.5 dB is not included since the other four are enough to illuminate the results.) and two additional values of 16 and 22 dB are included in Figure 5.17, where Pdw = 10. Besides, the curves for Max S/Sav, Max S, CSDS+RR schemes are also included for comparison proposes.
Figure 5.15 shows the performance curves of IWRR+Max S* parameterized by \( \gamma \) under different TT values for \( P_{dw} = 1 \). For each TT value, the performance points for \( \gamma = \{0, 10^{-11}, 10^6, 0.001, 0.1, 0.3, 1.0\} \) are plotted. From the results we observe that for each TT value, IWRR+Max S* with \( \gamma = 0 \) shows the best performance, which is similar with that of CSDS+RR. This means that when \( P_{dw} = 1 \), the best choice is \( \gamma = 0 \) at which IWRR+Max S* has a similar performance to CSDS+RR.

From Figure 5.16 which shows the test results for \( P_{dw} = 5 \), it can be seen that when \( 10^{-11} \leq \gamma \leq 0.1 \) IWRR+Max S* exhibits better fairness index than CSDS+RR. The average total throughput of IWRR+Max S* increases with \( \gamma \) for TT = 7.5 dB and 8.5 dB, and remains fairly constant for TT = 9.5 dB and 12 dB. When \( \gamma \geq 0.3 \), the performance of IWRR+Max S* is somewhat worse than that of CSDS+RR.

![Graph showing performance curves of IWRR+Max S* parameterized by \( \gamma \) for different TT values and \( P_{dw} = 1 \), \( Nu = 8 \).](image-url)
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Figure 5.16: The performance curves of IWRR+Max S* parameterized by $\gamma$ for $P_{dw} = 5$, $N_u = 8$

Figure 5.17: The performance curves of IWRR+Max S* parameterized by $\gamma$ for $P_{dw} = 10$, $N_u = 8$
The results for Pdw = 10 are shown in Figure 5.17. As in Figure 5.15 and Figure 5.16, when $\gamma = 0$, IWRR+Max S* has a similar performance to CSDS+RR, but for $\gamma > 0$, IWRR+Max S* has a better performance. For $0 < \gamma \leq 0.1$, the fairness index increases rapidly then remains fairly unchanged with $\gamma$; for $\gamma > 0.1$, it decreases with $\gamma$.

In Figure 5.17, two additional curves with $TT = 16$ dB and $22$ dB are included to show the effect of $TT_{n, opt}$ to the $\gamma$ selection. It can be seen that for $TT = 22$ dB, $\gamma = 1$ achieves the best performance and for $TT = 16$ dB, the curve is similar to that for $TT = 12$ dB. The best average total throughput is achieved for IWRR+Max S* with $\gamma = 1$ and when $TT > TT_{n, opt}$, the average total throughput is decreases. To keep the good performance of IWRR+Max S*, $\gamma = 1$ is chosen for $TT > TT_{n, opt}$.

![Figure 5.18: The performance curves of IWRR+Max S* parameterized by $\gamma$ for Pdw = 25, Nu = 8](image-url)
Figure 5.18 shows the results for $P_{dw} = 25$. Since the test results for $P_{dw} > 25$ are similar to $P_{dw} = 25$, they are not presented in this thesis. In Figure 5.18 it can be seen that the fairness index of IWRR+Max S* increases with $\gamma$. When $\gamma \geq 0.3$, IWRR+Max S* achieve the best performance. Based on the results above we can choose $\gamma$ to achieve close to optimal performance as in Table 5.4.

<table>
<thead>
<tr>
<th>$P_{dw}$</th>
<th>1</th>
<th>5</th>
<th>10</th>
<th>25~100</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma_{opt}$</td>
<td>0</td>
<td>$[10^{-11}, 0.1]$</td>
<td>$[10^{-6}, 0.1]$</td>
<td>$[0.3, 1.0]$</td>
</tr>
</tbody>
</table>

Table 5.4: $\gamma_{opt}$ based on the different value of $P_{dw}$

It can be seen that $\gamma_{opt}$ increases with $P_{dw}$. Note that when $P_{dw} = 5, 10$ and $\geq 25$, a range of $\gamma$ is given because the fairness index of IWRR+Max S* changes slightly in this range and the average total throughput is almost constant for $TT \geq 9.5$ dB and increases slightly for $TT = 7.5$ dB and $8.5$ dB. Also note that Table 5.4 does not include the $\gamma$ selection for $TT > TT_{n, opt}$, in which case $\gamma$ is set to 1 for all $P_{dw}$ values. For simplicity, in Section 5.2 for $TT \leq 16$ dB, $\gamma = 0.1$ for all $P_{dw} \geq 10$ since there is slight performance difference between $\gamma=0.1$ and 1.0 at $TT_{opt}$; $\gamma = 10^{-11}$ for $P_{dw} = 5$ and $\gamma = 0$ for $P_{dw} = 1$. For $TT > 16$ dB, $\gamma = 1.0$.

To study the effect of the number of users on $\gamma_{opt}$, test scenarios with $N_u=2, 4, 8, 12, 16, 20$ as in Section 5.3 are considered. It was found that for $N_u = 4, 8, 12, 16,$ and $20$, $\gamma_{opt}$ is as given in Table 5.4. The value of $\gamma_{opt}$ for $N_u = 2$ can be deduced from the results in Figure 5.19 and Figure 5.20 which are for $P_{dw} = 1$ and 10 respectively. The figures show that in both cases, $\gamma_{opt} = 1$ for any $TT$ values shown. Therefore, it can be extended to other values of $P_{dw} \in [1, 100]$, $\gamma_{opt} = 1$ for any $TT$ values of $N_u = 2$ test case.
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2U f=1 Hz fwin=1 s γ selection for IWRR+Max S* scheme

Figure 5.19: The performance curves of IWRR+Max S* parameterized by γ for Pdw = 1, Nu = 2

2U f=10 Hz fwin=1 s γ selection for IWRR+Max S* scheme

Figure 5.20: The performance curves of IWRR+Max S* parameterized by γ for Pdw = 10, Nu = 2
Besides, the number of users may also affect the value of $T_{\eta,\text{opt}}$. Usually for $\text{Nu} \geq 8$, $T_{\eta,\text{opt}}$ is at least 10.5 dB, which achieves $10^{-2}$ PER for 8800 bits long packet. When $\text{Nu} < 8$, $T_{\eta,\text{opt}} \approx 9$ dB.
Chapter 6 Conclusions and future work

In this thesis, based on the proposed compensation mechanism, which is simple to implement, three scheduling schemes are proposed for 802.11 WLAN network. The key idea behind the compensation mechanism is to provide somewhat service compensation to those users with low average SNR (Sav) by considering the Sav values of the corresponding fading channels. By doing this, a better long-term fairness among users can be expected. Certainly, the short-term fairness is a more important criterion than long-term fairness in a real network. Therefore, to achieve a good short-term fairness and maintain a good total throughput simultaneously, three scheduling schemes are developed by employing the principle of the compensation mechanism. Among the schemes, Max S* attempts to maximize the total throughput by selecting the HOL with the best modified channel state value; the value depends on the compensation mechanism. IWRR scheme also employs the compensation mechanism, but in this scheme the modified channel state value acts as a transmission weight. IWRR+Max S* represents a combination of the above two schemes to benefit from the advantages of both.

WLAN simulation models in C++ are built up to study the performance of the proposed schemes in terms of a short-term fairness index and a total throughput, which are the two fundamental issues when evaluating the performance of a WLAN. The effect of Doppler frequency, fairness window and number of users to the performance of the proposed schemes are obtained and analyzed by simulation. Fairness window is used to indicate the short-term fairness requirement among users. The fairness window size is set between 1 s and 10 s for TCP traffic delay requirements. Doppler frequency is set to be between 1 Hz and 10 Hz.
Chapter 6 Conclusions and future work

according to the channel characteristics of an Indoor WLAN. The number of users is set to typically between 2 and 20 with the equi-distance distribution over the AP's coverage area. We compared the performance of the three proposed schemes with three other CSDS-based schemes: Max S, Max S/Sav and CSDS+RR. FIFO which is the default scheduling scheme employed in WLAN is not included because in [1] CSDS+RR achieves a much better performance than that of it. From the simulation results, we observe that the effect of Doppler frequency and fairness window size can be simplified to considering the product of these two parameters (referred to Pdw). Several conclusions can be drawn based on the simulation results. Here the overall performance refers to the total throughput and fairness index pair.

- For any value of Pdw and Nu, it can be see that Max S* can substantially improve the fairness index of Max S and maintain a close to optimal total throughput. And its fairness index can increase close to that of Max S/Sav, which has a worse total throughput performance. Therefore, it can be concluded that Max S* can achieve a better overall performance than both Max S and Max S/Sav.

- For any value of Pdw and Nu, IWRR+Max S* can yield the best or close to best fairness index and maintain a close to optimal total throughput simultaneously with a TT = TTopt. At the point of TTopt, the overall performance improvement of IWRR+Max S* to CSDS+RR reflects mainly on fairness index, because the difference between their total throughput is not much. Pdw and Nu can affect the improvement of fairness index. When Nu is fixed, the improvement
increases with Pdw; when Pdw is fixed, the improvement decreases with Nu. According to the simulation results, the range of the fairness index improvement of IWRR+Max S* to CSDS+RR is from 0% to over 20% depending on the values of Pdw and Nu. Typically, for Pdw = 1 and Nu ≥ 4, the improvement is 0%; and for Pdw ≥ 25 and Nu ≤ 8, the improvement is over 20%.

- For Nu = 2, IWRR+Max S*, shows a similar performance as Max S*, can achieve the best overall performance among the all compared schemes for any value of Pdw. The TTopt is approximately 9 dB for IWRR+Max S*, IWRR and CSDS+RR, where the fairness index improvement of IWRR+Max S* and IWRR to CSDS+RR are about 12% and 10% respectively for Pdw = 1 and increase with Pdw.

- For Nu ≥ 4, when Pdw = 1, IWRR+Max S* has a similar performance to CSDS+RR and is better than the other compared schemes. For 25 ≥ Pdw ≥ 5, IWRR+Max S* and IWRR show the best overall performance among the schemes, and for 25 ≥ Pdw ≥ 10, Max S* also has a better overall performance than CSDS+RR. Then for Pdw ≥ 25, the three proposed schemes can achieve similar performance which is the best among the compared schemes and the fairness index improvement to CSDS+RR is about 0.2 (25%) for Pdw = 100 and Nu = 8. The TTopt is about 9.5 dB for Nu = 4, and 10.0 dB for Nu ≥ 8. Note that 10.0 dB is the SNR value corresponding to approximate $10^{-2}$ PER for the 8800 bit packet length.

- The results shows that when Nu is fixed, Pdw will not give much effect to the performance of CSDS+RR and Max S, but will improve the fairness index
performance of the other schemes with the increasing of it. When Pdw is fixed, the total throughput of Max S decreases with Nu. Besides, the fairness index of Max S*, Max S/Sav, IWRR and IWRR+Max S* also decreases with Nu; but the fairness index of CSDS+RR slightly increases with it. Therefore, it can be concluded that the effect of Pdw and Nu to CSDS+RR and Max S is small, to the other schemes that are related to Sav is large. Among them, Max S/Sav and Max S* show the biggest changes on the fairness index performance.

In general, the proposed IWRR+Max S* scheme combined the advantages of the other two scheduling schemes and is simple and suitable for slow fading WLAN. It can achieve a better total throughput and short-term fairness performance than all the other compared scheduling schemes. In our test scenarios where Rayleigh fading is assumed, we found that the combined scheme is especially suitable for Pdw ≥ 5 and any value of Nu although its performance is no worse than that of CSDS+RR for small Pdw values and large Nu.

For future work, one direction is to investigate the effect of imperfect knowledge of channel information. In this thesis we assume that perfect knowledge of channel state can be obtained per packet, but in a real system, the channel state information may be erroneous or outdated. These features can affect the performance of the new proposed schemes.

Another direction is to consider the effect of different packet lengths. In this study a fixed packet length is assumed. In practice, packet lengths may change in WLAN networks. The performance of the proposed schemes with dynamic packet lengths should be assessed.
References


References


[34] IEEE Std. 802.11b 1999 – Amendment 1: High-speed Physical Layer (PHY) extension in the 2.4 GHz band – Corrigendum1, 2001.


