OFDM-MAC algorithms and their impact on TCP performance in next generation mobile networks

A Thesis
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Publications based on this Thesis

1. Prashanth.L.A. and K. Gopinath, OFDM-MAC algorithms and their impact on TCP performance in next generation mobile networks, COMSWARE, 2008.
2. Prashanth.L.A. and Sajal Kumar Das and K. Gopinath, MAC design for heterogeneous application support in OFDM based wireless systems, CCNC, 2008.

Abstract

With the increasing adoption of wireless technology, it is reasonable to expect an increase in the demand for supporting both real-time multimedia and high rate reliable data services. Next generation wireless systems employ Orthogonal Frequency Division Multiplexing (OFDM) based physical layer owing to the high data rate transmissions that are possible without increase in bandwidth. Towards improving the performance of these systems, we look at the design of resource allocation algorithms at medium-access layer, and their impact on higher layers.

While TCP performance has been extensively studied for interaction with link layer ARQ, little attention has been given to the interaction of TCP with MAC layer. In this work, we explore cross-layer interactions in an OFDM based wireless system, specifically focusing on channel-aware resource allocation strategies at the MAC layer and its impact on TCP congestion control. Both efficiency and fairness oriented MAC resource allocation strategies were designed for evaluating the performance of TCP. The former schemes try to exploit the channel diversity to maximize the system throughput, while the latter schemes try to provide a fair resource allocation over sufficiently long time duration.

First, we evaluate the resource allocation schemes from a TCP goodput standpoint and show that the class of MAC algorithms that incorporate a fairness metric and consider the backlog outperform the channel diversity exploiting schemes. Second, we introduce a cross layer strategy of using congestion window instead of the backlog at the base-station resource scheduler. We compare the schemes previously designed with and *without cross layer feedback and show that the pure cross layer strategy of using congestion window is not warranted as the MAC algorithms considering the queue length at BS produced good results.*

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Keywords

channel-aware scheduling, fairness, TCP, MAC, wireless networks, OFDM, resource allocation, throughput

Categories and Subject Descriptors

C.2.1 [**Computer Communication Networks]: Network Architecture and Design-Wireless Communication**

C.2.2 [Network Protocols]: Applications-TCP/IP

Notation and Abbreviations

ARQ	**Automatic Repeat Request**
BS	**Base Station**
CNR	**Channel to Noise Ratio**
FDMA	**Frequency-Division Multiple Access**
HARQ	**Hybrid Automatic Repeat Request**
L1	**Layer 1 (physical layer)**
L2	**Layer 2 (data link layer)**
L3	**Layer 3 (network layer)**
L4	**Layer 4 (transport layer)**
MS	**Mobile Station**
OFDM	**Orthogonal Frequency Division Multiplexing**
RAT	**Radio Access Technology**
RTP	**Real-Time Protocol**
RTCP	**Real-Time Control Protocol**
SNR	**Signal to Noise Ratio**
TCP	**Transmission Control Protocol**
TTI	**Transmission Time Interval**
UDP	**User Datagram Protocol**
UE	**User Equipment (same as MS)**

Chapter 1

Introduction

1.1 Motivation

Wireless systems have graduated from the voice-centric 2G systems to 2.5G and 3G systems that offer both voice and data services. However, the 3G systems are unable to meet the demands of higher rate requirements and support of complex applications. Next generation wireless broadband systems attempt to grow beyond the limitations of 3G and provide high communication quality while meeting the QoS requirements of heterogeneous applications. They employ Orthogonal frequency division multiplexing (OFDM) physical layer owing to the high data rate transmissions that are possible without increase in bandwidth ([1]). OFDM systems combat inter-symbol interference and achieve high bandwidth efficiency by dividing the bandwidth into a large number of closely spaced subcarriers. Each subcarrier is modulated conventionally at a low symbol rate (handles ISI) and the subcarriers are orthogonal in a mathematical sense, allowing the spectrum of each sub-channel to overlap another without interfering with it. OFDM works as a multiple access technique by assigning different OFDM sub-channels to different users.

Meeting the QoS needs of the various user applications requires intelligent allocation of the available resources, Network designers need to grapple with the time varying fading channel and user mobility, while devising resource scheduling schemes. The resource scheduling schemes can be broadly classified into two groups. Opportunistic schemes try to exploit the channel variations among users by allocating the channel to the user experiencing good conditions, while the traditional schemes seek to normalize and present a smoothed wireless channel across users. Apart from attempting to utilize the channel variations favorably, the network designer also tries to strike a balance between the conflicting objectives of maximizing the system utilization and achieving fairness among users.

Apart from performing adaptive resource allocation, the network designer also needs to evaluate the proposals from a protocol design perspective. The traditional approach to networking has been to design the individual layers independently. Each layer solves a specific problem using the services provided by the layer below. With the advent of wireless communication, the wireless channel and the QoS requirements present the protocol designer with significant problems due to independent module design. A new paradigm of cross layer design is emerging, where the emphasis is on adaptive protocol design. The various protocol layers co-operate by exchanging information and collectively improve the performance given network QoS level ([2]).

TCP has been extensively analyzed over different wireless links, specifically the interaction between TCP congestion control and link layer recovery in [3, 4, 5]. To the best of our knowledge MAC level resource allocation algorithms and their impact on TCP have not been studied in OFDM based wireless systems. From an error control perspective, congestion window evolution at the TCP sender depends on the resources (subcarriers) that are allotted at the MAC layer of Base station (BS). This motivated us to explore the cross-layer interactions between TCP and MAC in an OFDM based wireless system. The joint optimization of congestion control and scheduling in a wireless network is certainly beneficial as it leads to effective buffer management, keeps the control loops of TCP sender and BS in sync and achieves significant performance gains([6]).

First, we perform vertical calibration of the protocol stack i.e. jointly tune both TCP and MAC layers to achieve better performance. We assume knowledge of Channel state Information (CSI) at BS and design both efficiency and fairness oriented MAC layer schemes. We study the impact of resource allocation schemes on transport layer protocols such as TCP. The rationale behind this approach is that the lower layers typically change faster than the upper layers. For example, the PHY and MAC layers of a cellular network have been continuously evolving, while catering to the same congestion control algorithm at TCP layer. From a cross layer analysis perspective, it is easier to assume the higher layer behavior and modify the lower layer than vice-versa. Hence, we use the congestion control algorithms in place for TCP and study the MAC layer resource allocation algorithms. This approach ensures that our proposals are well within the layered framework that currently exists.

The benefits of this comparative analysis of MAC algorithms are two-fold. Firstly, it gives valuable insight about the behavior of the various MAC algorithms from a TCP performance standpoint. Secondly, whether explicit cross layer feedback is necessary, is answered. If the vertical calibration provides acceptable TCP performance, then it is not necessary to share information explicitly between TCP and MAC: an approach that possibly introduces performance overheads and adds to the complexity of the system.

Performing adaptive resource allocation and assessing it in true cross layer spirit requires information exchange across layers (even non-adjacent) either implicitly or explicitly. We introduce the explicit cross layer feedback of using TCP congestion window instead of the queue length for resource allocation at BS. The MAC algorithms previously designed are evaluated with and without cross layer feedback. It is observed that the pure cross layer strategy of using congestion window is not warranted as the MAC algorithms considering the queue length at BS produced results on par with the algorithms using congestion window.

1.2 Contributions of this Thesis

We propose novel resource allocation schemes at MAC layer considering elastic traffic in an OFDM system. The MAC algorithms use the knowledge of Channel State Information (CSI) and the backlog information to adaptively assign the subcarriers to the different users. TCP performance measurements are used to characterize the behavior of these

MAC algorithms. We also design a few algorithms to solve the MAC resource allocation problem, considering heterogeneous service needs, that includes both real-time and non real-time traffic.

The contributions considering TCP-based data applications can be summarized as follows:

- To the best of our knowledge, we are the first to explore the interaction between resource allocation schemes at MAC layer and TCP congestion control in a OFDM based wireless system.
- The subcarrier allocation and assignment algorithms designed and evaluated include both throughput as well as fairness oriented schemes.
- The novelty of this work is the design of *maximize throughput*, *max-min, throughput, time fraction and proportional fairness with queue length* MAC resource allocation schemes. These algorithms have not been designed and evaluated before, especially from a TCP goodput standpoint.
- To the best of our knowledge, a pure cross layer scheme of using congestion window instead of Mobile Station's (MS) queue length at BS has not been investigated before.
- We developed a simulation framework by abstracting the frequency and time domain correlation of the OFDM channel using the nakagami-m fading model. Various MAC algorithms are implemented above the OFDM channel and a comparative analysis of these algorithms from a TCP performance standpoint is performed.
- Analysis of TCP and the System performance for FTP traffic shows the following:
    - The class of MAC algorithms that do not consider the queue length of the individual MS's perform poorly as compared to the ones which consider the backlog.

- The algorithms that incorporate a fairness metric (Throughput, Time fraction, Max-min and proportionally fair with queue length) show good results for TCP and System throughput.
- The performance of the algorithms adopting a fairness metric was similar to the local optimization algorithm's performance.
- The class of MAC algorithms that do not adopt a fairness metric result in unfairness w.r.t. MSs, as expected.
- The pure cross layer strategy of using the congestion window as an input to the MAC algorithm was found to be unnecessary. This is because, no significant performance gains were seen with this and the MAC algorithms that considered the smoothed queue length of a node at BS produced good results.

1.3 Organization of the Thesis

The rest of the thesis is organized as follows.

Chapter 2 provides an overview of OFDM MAC resource allocation and transport protocols for real and non-real time traffic. An outline of the challenges involved in the calibration of the individual layers and a discussion of the current literature of cross layer design is presented.

Chapter 3 proposes various algorithms that attempt to solve the resource allocation problem in an OFDM system. Details of the channel model adopted to abstract the OFDM channel and the various resource allocation algorithms built using this model are presented in this chapter. These algorithms are extensively analyzed from a TCP performance standpoint and from the simulation results, we show that the queue length considering fair algorithms outperform the greedy channel diversity exploiting schemes.

Chapter 4 concludes the thesis and discusses future extensions of this work.

Chapter 2

Background and Related Work

Resource management in multi-carrier systems is an active research topic and has received extensive attention in the wireless research community. In this chapter, an overview of various protocol entities and the cross-layer optimization opportunities present therein, are presented as follows:

- Section 2.1 gives an introduction to the resource scheduling problem in an OFDM based system is given.
- Section 2.2 provides a brief introduction to TCP congestion control and outlines the TCP performance issues in a wireless environment.
- Section 2.3 provides an overview of RTP/RTCP protocols and discusses the challenges involved in meeting the QoS needs of real time applications in a wireless system.
- Section 2.4 surveys existing literature on cross layer design, specifically in the context of the interactions between transport layer protocols with lower layers.

2.1 OFDM resource scheduling algorithms

2.1.1 Need for OFDM

In the air channel, as the data rate increases in a multipath environment, the channel fading goes from flat fading to frequency selective fading (last reflected component arrives after symbol period). Also the channel delay spread can cause ISI. Frequency selective fading and Inter-symbol Interference cause heavy degradation of bit error rate in the signal transmission. Use of adaptive equalizers or array antennas can help overcome these issues to some extent, but at the cost of increased complexity. A very promising solution is to solve this problem is multi-carrier transmission.

In Multi-carrier Modulation (MCM) the channel is broken up into several sub-bands such that the fading over each sub-channel becomes flat, thus eliminating the problem of ISI. Single carrier systems transfer data streams using a serial transmission, while multi-carrier systems use parallel transmissions. The ability to sustain a higher throughput in a single carrier system becomes diminished as the symbol duration becomes smaller for supporting high data rate. But, the serial data stream can be divided into parallel data streams. Each of these is individually modulated by a narrow-band carrier, and then summed up and transmitted in parallel from the same source. Since a single stream of data is split up to individually modulate these multiple carriers, these systems are referred to as multi-carrier systems. Here, as the high speed data stream is divided into several parallel paths, the data rate at each of the parallel path will be reduced and the symbol duration can be increased. So, the bandwidth (BW) requirement will be reduced (Signal BW < Coherence BW), which implies that it will be robust against the multi-path frequency selective fading and ISI.

But, there are several typical implementation problems associated with the usage of large number of sub-carriers.

- Due to the large number of sub-carriers, the sub-carriers frequencies have to be assigned very close to each other. We know that receiver needs to synchronize itself to every sub-carrier frequency in order to recover data related to that particular sub-carrier. When spacing is very little, the receiver synchronization components need to be very accurate, which is still not possible with low-cost RF hardware. So, bandwidth utilization will be very poor.

- On the transmitter side, arrays of sinusoidal generators and on the receiver side, arrays of coherent demodulators are required to support a multi-carrier system. This makes the system very complex and expensive.

These issues are resolved by the usage of orthogonal frequency carriers - known as OFDM, and FFT techniques.

2.1.2 OFDM - Resource allocation

In general, the Mobile Stations(MS) can experience different radio conditions depending on their mobility and the natural environment (e.g. shadowing by buildings). The (uplink) feedback channel contents (radio channel quality) of each MS is used to allocate its downlink radio resources by the (downlink) scheduler at BS. For an optimized allocation process of radio resources, the feedback of the MS quality report of each ms measurement must provide the radio channel quality with sufficient granularity. This feedback information will assist the scheduler in adaptation of downlink radio resource allocation according to the changes in the dynamic radio channel.

OFDM systems support simultaneous downlink (DL) transmission by assigning different subcarriers to multiple users (terminals) using FDMA. Static assignment of subcarriers to terminals does not result in any power or bit rate gain as compared to dynamic assignment schemes which adaptively assign subcarriers to terminals based on the subcarrier channel gains, desired bit rate and/or overall power requirement. This is due to *multi-user diversity* i.e., varying subcarrier channel gains for different subcarriers and for different terminals. Hence, the radio channel quality experienced by each MS is conveyed to the Base Station (BS) via a uplink feedback channel and this feedback information is used by the scheduler in adaptation of downlink radio resource allocation. This is illustrated in Fig. 2.1.

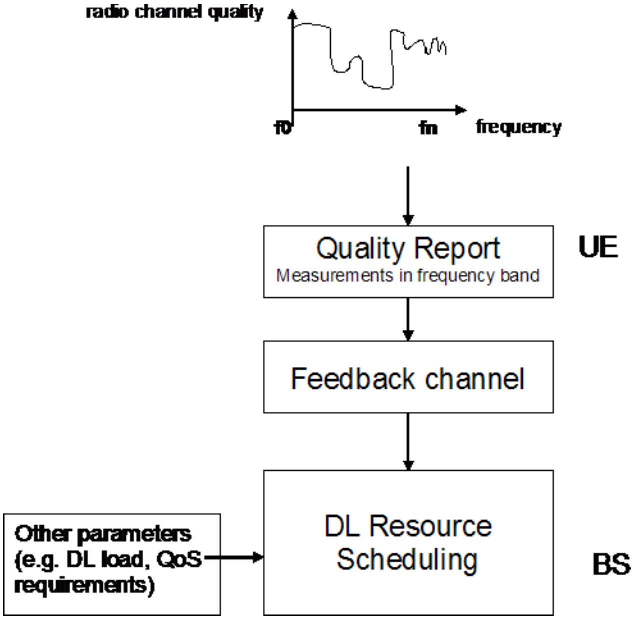

Figure 2.1: Downlink resource allocation

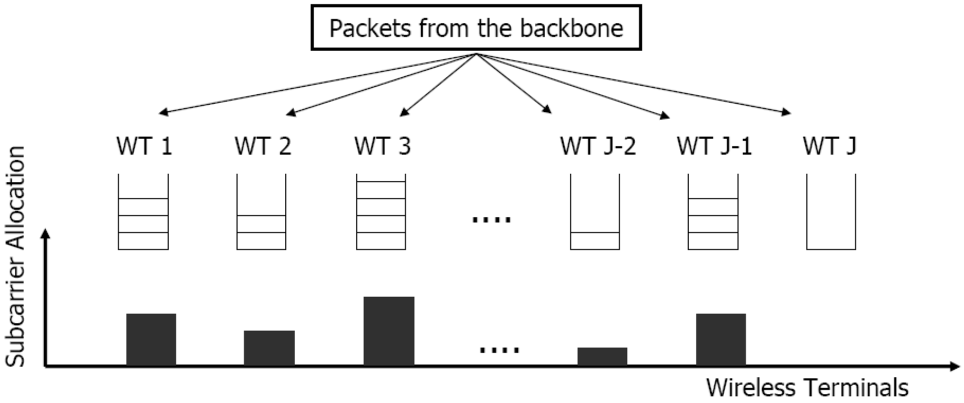

Figure 2.2: Subcarrier Allocation in downlink

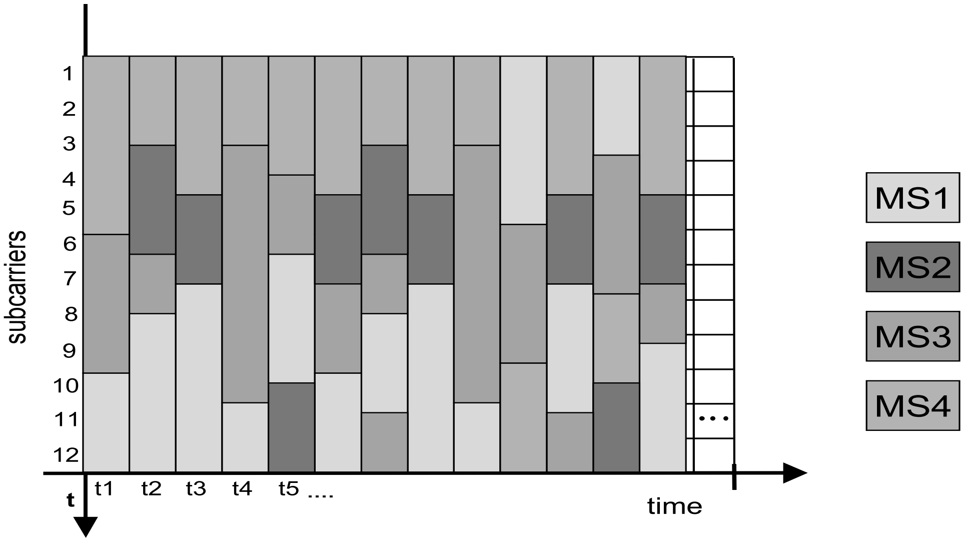

Figure 2.3: Illustration of DL resource allocation in one TTI

The radio resource allocation in DL comprises of:

- Subcarrier Allocation - power and number of subcarriers per user. Fig. 2.2 shows subcarrier allocation at the BS. As shown in Fig. 2.2, each MS has a data queue at the BS and it is a reasonable approach to allot the subcarriers to the individual UEs based on their queue sizes.

- Subcarrier Assignment - exact subcarrier assignment that maximizes the capacity/total rate or minimizes the power consumed. Fig. 2.3 illustrates subcarrier assignment at the BS for one TTI. Each entry in the matrix represents the channel quality for a particular terminal on a particular subcarrier and the highlighted boxes reflect the actual assignment of subcarriers. For example, subcarrier 1 is assigned to terminal 6, subcarrier 2 is assigned to terminal 1 in this TTI.

As shown in Fig. 2.3, in each TTI t1...tn, we allocate and assign the 12 subcarriers to the individual terminals MS1...MS4.

Example:

We illustrate radio resource allocation steps outlined above using another example. Assume there are 100 subcarriers, say s1..s100 and 5 terminals, say t1..t5.

Subcarriers can be allocated as follows:

t1 - 10 subcarriers

t2 - 35 subcarriers

t3 - 15 subcarriers

t4 - 15 subcarriers

t5 - 25 subcarriers

Subcarriers can be assigned as follows:

t1 - s1 through s10

t2 - s11 through s45

t3 - s46 through s60

t4 - s61 through s75

t5 - s76 through s100

Different approaches can be adopted for subcarrier allocation/assignment. We illustrate some of the possibilities below:

- Static Groups: From the above example, we can have s1...s20 form the first group, s41...s50 form the second, s51...s65 form the third, s66...s80 form the fourth and s81...s100 form the fifth group of subcarriers.In each TTI, we assign these groups to the individual terminals. For example, in TTI 1, a possible assignment is group1 to t1, group2 to t2 and so on.

- Dynamic Groups: The number of groups and the number of subcarriers per group is decided dynamically in each TTI. Here we can either have the subcarriers comprising a group contiguous or disperse. The contiguous approach is advantageous for stationary terminals while the dispersed approach favors moving terminals.

In the reverse-link, the mobile stations have a data queue per application and the BS is unaware of the queue status at the various mobile stations. Scheduling and radio resource allocation on the reverse link, hence, is a harder problem owing to the distributed nature and lack of knowledge at the BS. In [7], the authors discuss distributed schemes for uplink data services support.

2.1.3 Subcarrier Assignment Algorithms

The subcarrier assignment problem is harder than the set-partitioning problem which is NP-complete. This is because QoS and classification of flows - delay sensitive or not, need to be considered for allocating and assigning the subcarriers. Hence, in practice a heuristic based scheme is preferred over optimal algorithms.

In [8], the authors propose scheduling schemes based on the proportionally fair rule, which explicitly makes use of the channel state information and also provides fair allocation of bandwidth across users. [9] show the multi-user diversity gains due to a technique called opportunistic beam-forming, considering multi-user scheduling based on the proportional fair rule. Authors in [10, 11, 12] propose downlink resource scheduling algorithms in an OFDM system to achieve high system utilization while considering the buffer occupancy and delay constraints. In [13], the authors propose simple algorithms for subcarrier allocation and assignment, considering power and transmission rate constraints. These algorithms are shown to be computationally efficient and to exhibit reasonable performance gains (via simulations) in terms of power consumption and outage probability.

Opportunistic scheduling algorithms that exploit the channel diversity and an optimization framework for opportunistic scheduling is presented in [14].

In [15] subcarrier assignment is performed using a graph algorithm that solves the maximum weight perfect matching problem. Though the solution computed is optimal, it is computationally expensive. In [15], the authors propose using heuristic algorithms for solving the problem of subcarrier assignment after a fixed allocation of subcarriers. In bDA (basic dynamic Algorithm), the subcarrier assignment is valid for one downlink phase/time unit during which the subcarrier channel gains don't change significantly. The algorithm works as follows: For each time unit, the wireless terminals are assigned different priorities. Iterating over all terminals, ordered by the terminal priority, the algorithm assigns the allotted number of subcarriers considering CNR values. To balance the unfairness, the terminal priority is switched (decreased by one) after each time unit. The aDA(advanced Dynamic Algorithm) improved upon the bDA by introducing a ”weight” attached to the subcarrier. During each iteration of the algorithm for a particular terminal, weight of a subcarrier conveys information about its suitability for all other terminals with a lower priority. aDA then performs the subcarrier assignment considering the weight ratio between CNR and weight. The heuristic algorithms claim to have performance comparable with that of the optimal algorithm. The advanced heuristic algorithm (aDA) increases the performance but with a slight increase in the computation complexity.

The subcarrier allocation and assignment algorithms referred above are mostly focused on maximizing the system throughput at the BS and do not consider their impact on the transport layer protocol esp. TCP. Analysis of these algorithms have been mostly confined to the MAC and layers below (For e.g. [16],[17]) and a study across layers of these resource scheduling proposals have not been hitherto performed.

2.2 TCP over wireless

Transport Control Protocol (TCP) provides reliable data transport service to data applications (ftp, email, web, etc), building upon the best-effort datagram delivery service provided by IP . TCP was conceived and performance-tuned for traditional wired networks. It thus assumes all packet losses occur mostly due to congestion. In wireless networks, however, major losses can be attributed to RF (radio frequency) link errors and handovers. This can result in degraded end-to-end performance of TCP. This section briefly introduces TCP congestion control and outlines the challenges involved in deploying TCP over cellular wireless networks. For further information, the reader is referred to [18] for TCP details and [19] for the congestion control algorithms.

2.2.1 TCP Concepts

TCP splits the application data into numbered segments. Reliability is achieved by retransmitting lost segments. TCP receiver sends an ACK acknowledging all contiguously received data to TCP sender. A Duplicate acknowledgment (DUPACK)

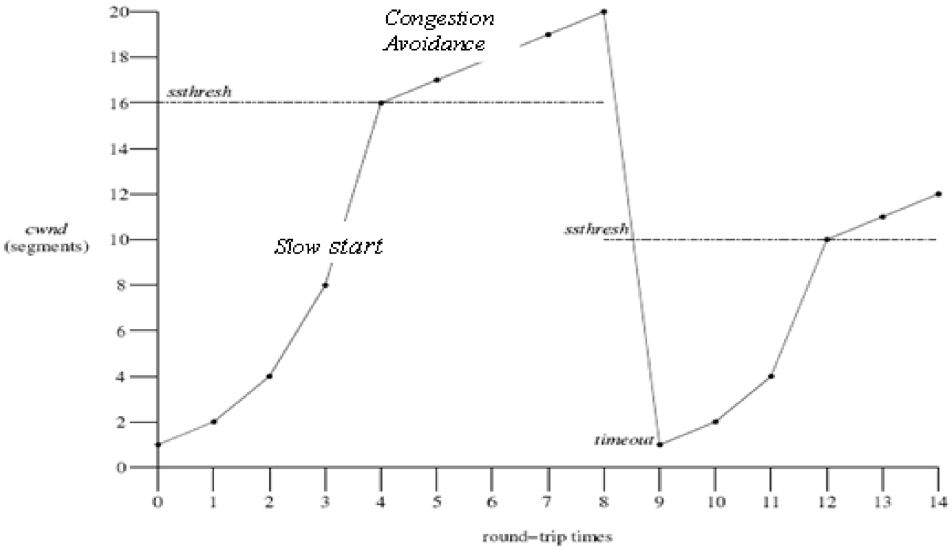

Figure 2.4: Slow start and Congestion avoidance with timeout

may be sent when out-of-order segments are received (due to a loss or network reordering of segments during transmission). The sender identifies the loss of a packet either by the arrival of several duplicate cumulative acknowledgments or the absence of an acknowledgment for the packet within a timeout interval.

TCP reacts to packet losses by reducing the congestion window and initiating the congestion control algorithms. The congestion window (cwnd) controls the amount of data - the number of segments - that can be sent per round trip time. The next section introduces the congestion control algorithms of TCP.

2.2.2 TCP Congestion Control

As explained in [19], the four congestion control algorithms in TCP are - slow start, congestion avoidance, fast retransmit and fast recovery.

Slow Start and Congestion Avoidance

The slow start algorithm is used at the beginning of a data transfer and gently probes for the available network capacity by exponentially growing the congestion window. Slow start ends when congestion window reaches the slow start threshold (ssthresh) and

Table 2.1: TCP Tahoe - Congestion Control Algorithm

```
cwnd = 1 MSS (maximum segment size)
slow-start threshold = arbitrarily high value
1. On each new ack
   if ( cwnd ¡ slow-start threshold )
   {
      Slow Start ⇒ Exponential growth
      cwnd = cwnd + 1;
   }
   else
   {
      Congestion Avoidance ⇒ Linear growth
      cwnd = cwnd + 1/cwnd;
   }
2. On a packet loss (either RTO or DUPACKs)
   slow-start threshold = cwnd / 2
   cwnd = 1;
```

Table 2.2: TCP Reno - Congestion Control Algorithm

```
1. On each new ack
   Behavior similar to Tahoe
2. On arrival of DUPACKs (≥3)
   Fast retransmit + Fast recovery
      Retransmit next expected packet
      Halve the window
         slow-start threshold = cwnd / 2
         cwnd = slow-start threshold
   Temporarily expand cwnd
      cwnd = slow-start threshold + number of dupacks
   Deflate the window when a new ack comes
      cwnd = slow-start threshold and congestion avoidance is kicked in
3. On a timer expiry
   Behavior similar to Tahoe
```

thereafter congestion avoidance algorithm is used. This is illustrated in Fig 2.4. During congestion avoidance, the congestion window continues to increase, but at a linear rate. On a timeout, TCP reduces its transmit window (cwnd) to 1 and initiates slow start.

Fast retransmit and Fast Recovery

TCP sender may also employ the fast retransmit algorithm to detect and repair loss based on the receipt of duplicate acknowledgments. During fast retransmit, the sender retransmits the lost segment on receipt of 3 DUPACKS (without waiting for timeout). Also, the sender does not reduce the congestion window (cwnd) drastically to 1 as in slow start; DUPACKs indicate that segments are most likely leaving the network and hence not congested. Fast recovery governs the data transmission after fast retransmit. During fast recovery, congestion window is set to ssthresh + number of DUPACKs and incremented by one for additional DUPACK received. On receipt of a non-DUPACK, the congestion window is deflated to ssthresh. The reader is referred to [19] for further details.

2.2.3 Challenges using TCP over wireless

As mentioned before, wireless networks suffer from significant losses due to link errors and handovers. TCP protocol is performance-tuned for traditional wired networks. But, in wireless networks with lossy links, TCP performance is degraded because of the invocation of congestion control and avoidance procedures for all packet losses. To elaborate, TCP cannot distinguish between packet losses due to congestion and transmission errors. The TCP sender identifies a packet loss scenario, either by the arrival of duplicate acknowledgments or absence of the acknowledgment in the timeout period (RTO). TCP responds to packet losses by reducing the congestion window and initiating the congestion control algorithms. Reducing the throughput for transmission errors is unnecessary and results in degraded performance. Some of the concerning aspects of TCP performance over wireless links from [5] and [20] are presented below:

- Latency - The TCP source has to maintain a window size larger than or equal to the bandwidth delay product (BDP) of the connection in order to use the whole available bandwidth. In this way, the source can fill the link until the window slides forward upon the arrival of an ACK.

- Link Data Rate - The data link rate offered by the radio bearer is dynamic. This rate variability is caused by changes in the traffic load of the radio cell, and alterations in the propagation conditions and user mobility.
- Delay Spikes - A delay spike is a sudden increase in end-to-end delay, which may cause a spurious retransmission timeout (RTO) in the TCP source, since packets are just delayed at the link layer and not dropped. The most frequent reasons for a delay spike are:
  - The ARQ algorithm recovering from an outage
  - A handover
  - Blocking due to the presence of higher-priority traffic in the channel
  - Withdrawal of the channel when the network must provide access to higher-priority users
- ACK Compression - affects the self-clocking nature of the TCP flow control. The queuing of ACK packets in the reverse path of a TCP flow may result in the almost instantaneous arrival of bursts of ACKs at the sender. This can break the TCP self-clocking operation and cause long packet bursts.
- Packet losses - Depending on the link layer configuration, the radio bearer can support a low packet loss rate even in the presence of a transient high frame loss ratio in the channel. The ARQ mechanism may mask almost every packet loss in the wireless channel, but the recovery at the link layer appears to the higher layer as delay jitter. However, even if the link layer is reliable, packets may be lost because of frame losses in the downlink and the resulting buffer overflow.

2.2.4 TCP Enhancements

The schemes proposed to improve TCP performance over lossy wireless links can be broadly classified into two groups based on whether they can change the TCP protocol or not. Several enhancements are proposed to improve TCP performance over wireless links. They can be broadly classified into two groups:

1. Hide non-congestion related losses from the sender: The rationale here is that by hiding non-congestion related losses, we are preventing the TCP sender from reducing the congestion window unnecessarily. Example techniques: link layer retransmission using FEC/ARQ([4, 21]), split connection approaches such as Indirect-TCP and TCP-aware link layer schemes such as snoop-TCP (See [22]). Authors in [23, 24] provide an analytical framework for studying the TCP performance over a wireless link, while proving the effectiveness of the link level recovery schemes. [25, 26] summarize the recommendations of IETF group that looked into link layer design issues for the TCP/IP protocol suite. Other proposals in this group include ACK suppression via ARQ snoop agent introduction to enhance TCP performance is presented ([27]).

2. Let sender know the cause of packet loss: This class of schemes modify the TCP behavior using control messages or flags to make TCP sender realize that the losses are not due to congestion and hence, trigger appropriate action by sender. Example techniques: Explicit Congestion Notification (ECN), Explicit Bad State Notification (EBSN) and Explicit Link Failure Notification (ELFN) sent to the TCP sender to distinguish between congestion and other losses (See [22]), congestion control algorithm modification to allow for link layer error recovery as in TCP-DCR ([28]).

A detailed comparison of the various schemes can be found in [22, 29]. A stochastic model of the TCP protocol using Markov renewal-reward process and the performance analysis of different versions of TCP in wireless context is available in [3]. An analytical expression for TCP throughput in terms of the loss probability and round trip time is developed by authors in [30].

2.3 RTP/RTCP based adaptation

2.3.1 RTP/RTCP overview

RTP typically sits on top of UDP/IP transport and provides a mechanism for robust, real-time media delivery above an unreliable transport layer. Design of RTP uses application level framing and follows the end-to-end principle of the internet. It enhances the UDP/IP transport with the following: Sequence number for loss detection, reception quality reporting, timestamps to enable timing recovery, synchronization, payload type and source identifiers, marking of significant events within the media streams, rules for timestamps and sequence number usage although these rules are somewhat dependent on the profile and payload format in use. RTP Control Protocol (RTCP) provides the following: reception quality feedback (periodic), participant identification and synchronization between media streams (e.g. lip synchronization between audio and video). It helps to adapt transmission according to reception quality feedback.

2.3.2 RTP/RTCP over wireless

As outlined in [31], cross-layer methods resulting in multi-user gain with QoS need to address the following questions:

- How can multiple real-time data users be supported simultaneously with good quality of service (QoS) for all real-time users, namely, with packet delays not exceeding given thresholds with high probability?
- How can a mixture of real-time and non-real-time users be supported simultaneously with real-time users receiving their desired QoS and non-real-time

users receiving the maximum possible throughput without compromising the QoS requirements of real-time users?

- How can bandwidth be fairly allocated among various users, especially when some users inherently demand more channel access time than others, even if their data rate requirement is the same, or less than others?

Multimedia applications need to be designed with capability to adapt to system and network constraints and at the same time meet the end-user requirements. An intelligent video transport mechanism that takes into account the application QoS requirements as well as the network QoS level is presented in [32]. Authors in [33, 34] propose physical and link layer combined approach to OFDM resource allocation and queue management, catering to video transmissions. An earlier work by authors in [35] for a CDMA/HDR system show that throughput optimal scheduling utilizing the channel variations provides the desired QoS guarantees for real-time users as well as maximizes the system capacity (in terms of the number of users supported).

In [36], the authors propose channel state dependent scheduling policies catering to real-time traffic in TDM based wireless networks, while in [37], channel adaptive scheduling algorithms are investigated for heterogeneous traffic. An early work on scheduling algorithms that cater to both real-time and non real-time traffic in [38] showed a difference in behavior between steady state arrival and short overload traffic scenarios. Also observed in [38] was that the lifetime of real-time packets have a significant impact on the performance of scheduling algorithms. In [39], the authors propose a scheduling algorithm that provides the flexibility of trading off efficiency for fairness and also exploiting the channel variations of an UMTS system. In [40], channel aware scheduling algorithms are analyzed in a CDMA system and it is found that greedy, myopic strategies may result in sub-optimal performance in a dynamic setting.

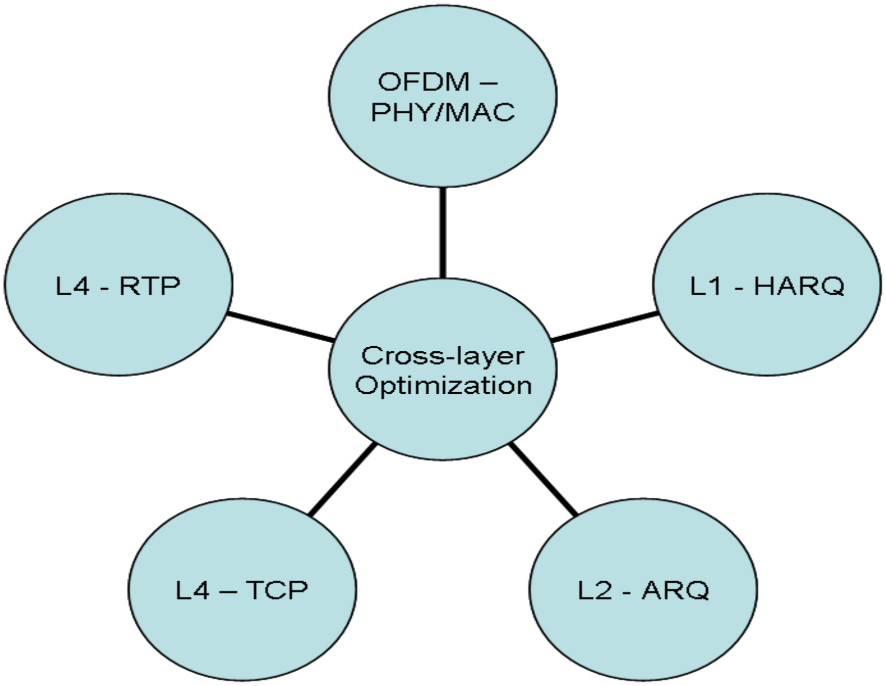

Figure 2.5: Cross layer optimization

2.4 Cross layer design

Considering the poor performance of 3G systems and the ever increasing demand for higher data rate, better communication quality and complex QoS requirements, a new paradigm of network called cross-layer design is emerging. In the traditional protocol stack model (for e.g. OSI), the networking problem is split into hierarchical layers and each layer solves a particular subproblem using the services provided by the layer below. In contrast to this, cross layer design encompasses all proposals that choose to violate one or more of the layered architecture rules. An overview of cross layer design is available in [41] and [42]. In [2], the authors provide a definition of cross layer design and survey of the current proposals in literature.

Analysis of MAC layer scheduling algorithms that cater to heterogeneous applications with diverse QoS requirements is reported in [43]. Cross layer modeling of wireless links is discussed in [44, 45, 46, 47]. TCP aware resource allocation in CDMA networks has been studied for CDMA networks in [48], while TCP performance has been studied for wireless MIMO systems in [49]. It is proved in [50], under some strong assumptions, that scheduling with error rate consideration supports TCP performance comparable to packet combining Hybrid-ARQ (HARQ).

To facilitate analytical study of cross layer proposals, authors in [51] provide an optimization framework, while viewing layering as an optimization decomposition. The interaction between various layers such as TCP, LLC, MAC, PHY is modeled as a convex optimization problem. Reverse engineering of TCP has revealed congestion control as a distributed solution of a basic NUM (Network utility maximization) problem. The utility functions for the various versions of TCP are available in [52] and [53].

As illustrated in Fig. 2.5, Cross layer optimization algorithms' interact with protocol entities across the layered architecture. For this purpose, cross-layer optimizations opportunities need to be explored at OFDM-PHY, L1-HARQ, L2-MAC/ARQ, L4-TCP and L4-RTP/VoIP. In this work, we restrict to medium access layer and transport layer interactions in the context of an OFDM based wireless network. The rationale behind this approach is that the transport layer protocols have been hitherto analyzed with utmost link layer protocols and not below. Specifically. TCP has been extensively analyzed over wireless links with interaction between TCP congestion control and link layer recovery in [3, 4, 5, 54, 55, 56] and similar works. But, fewer results are available for MAC level resource allocation algorithms and their impact on TCP. The closest to our work in a CDMA based wireless system is [57], but the focus in this work again is on link/mac level schemes to hide error related losses for TCP.

However, the cross layer optimization schemes can run at cross purposes with sound and long term architectural principles, leading to several negative consequences [[58]]. Hence, it is essential to look at cross layer design alternatives in a holistic perspective and avoiding unintended consequences on overall system performance. Additionally, from the performance analysis of TCP over fading wireless links are available in [59, 3] it is inferred that a clever design of the lower layers of the protocol stack is preferred over modified versions of TCP. Considering these aspects in our work, we address cross layer issues in the context of resource allocation schemes at MAC layer. We design OFDM-MAC resource assignment schemes and comparatively analyze them in the context of TCP-based data application. As noted in Chapter 1, this achieves vertical calibration of the stack w.r.t. TCP/MAC layers and also provides vital inputs on whether explicit feedback exchange between layers is necessary or not. Further, we incorporate explicit cross layer feedback to use the congestion window as an input for resource allocation at BS. The rationale behind this extension is that it helps to compare the pure cross layer schemes against the non-cross layer ones.

Chapter 3

OFDM-MAC design for elastic traffic

In this chapter, we explore cross-layer interactions in an OFDM based wireless system, specifically focusing on channel-aware resource allocation strategies at the MAC layer and its impact on TCP congestion control.

- Section 3.1 provides the channel model adopted to abstract the OFDM channel. Various subcarrier allocation and assignment algorithms are built upon this model.
- Section 3.2 provides a broad classification of MAC resource allocation strategies.
- Section 3.3 details the efficiency oriented schemes. These schemes try to exploit the channel diversity to maximize the system throughput.
- Section 3.4 details the fairness oriented schemes. These schemes try to provide a fair resource allocation over sufficiently long time duration.
- Section 3.6 provides the other resource allocation strategies that were explored in this work, which apply to several schemes designed under efficiency or fairness provision objectives.

- Section 3.8 provides the simulation environment and TCP performance results for various MAC algorithms under different user scenarios. From a TCP goodput standpoint, we show here that the class of MAC algorithms that incorporate a fairness metric and consider the backlog outperform the channel diversity exploiting schemes.
- Section 3.9.1 extends the algorithms to cater to heterogeneous service needs. We design adaptive resource allocation schemes that attempt to balance opportunistic exploitation of the channel variations and fairness among users, while considering both real-time and non-real time application QoS needs.

3.1 Channel Model

In our work, we have considered the wireless channel for fixed as well as mobile users in a typical urban scenario with considerable number of multi-paths. Taking that into account, we have assumed that the channel possesses a constant-gain and linear phase response over a bandwidth (BW) that is smaller than the BW of the transmitted signal, creating a frequency selective fading channel. Though OFDM system is a broadband system, in the above scenario with the high data rate, it is frequency selective instead of frequency flat.

Nakagami-m fading model is well suited for flat fading as well as frequency selective fading channels [60]. As in [61], we adopted the Nakagami-m model to approximate the received SNR. Hence, the received SNR is modeled as a gamma random variable with the following density function following the notation from [43]:

$$p_\gamma = \frac{m^m * \gamma^{m-1}}{\overline{\gamma} * \Gamma m} * exp(\frac{-m * \gamma}{\overline{\gamma}})$$

where $\overline{\gamma}$ is the average received SNR, Γm is the Gamma function and m is the Nakagami fading parameter. The rationale behind adopting the above model is to study the impact of correlation in both time and frequency domain on the performance of TCP.

3.2 A Taxonomy of MAC resource allocation algorithms

We present below taxonomy of the MAC layer algorithms:

- *Efficiency oriented*: This class of algorithms attempts to exploit the multi-user diversity and maximize the system throughput. This is achieved by allocating the subcarriers to users who experience good channel conditions.
- *Fairness oriented*: This class of algorithms attempt to provide a fair bandwidth share to each user over sufficiently long time duration. This is achieved by normalizing a fairness metric of bandwidth usage for each user.
- *Optimization*: The resource allocation is formulated as an optimization problem. The objective in this formulation is to maximize the long term system utility while having the capacity and fairness constraints. Though practically infeasible, this class of algorithms provides an upper bound for the achievable throughput and enables us to evaluate the algorithms in the previous two classes.

It is worth noting here that the above classification is not strict. MAC algorithms can achieve varying degree of tradeoff between maximizing throughput and providing temporal fairness.

3.3 Efficiency oriented algorithms

We designed the *Maximize Throughput and Channel backlog balance* algorithms and implemented the *Best subcarrier* to compare and contrast against other schemes.

3.3.1 Maximize Throughput

Motivation behind this scheme is that maximizing queue weighted sum of rates achieves throughput optimality [62]. Hence, in this scheduling scheme, we create an NxS matrix M for N users and S subcarriers in each TTI, with each entry calculated as follows:

$$M_{i,j}(n) = r_i(n) * d_{i,j}(n)$$

where

$r_i(n)$ is the backlog or queue length for user i in TTI n

$d_{i,j}(n)$ is the instantaneous data rate of user i over subcarrier j

With the above matrix, each subcarrier is assigned to the user with the highest matrix value for this particular subcarrier.

3.3.2 Channel backlog balance

In this scheduling scheme, we attempt to strike a balance between channel quality and the backlog by creating an NxS matrix M for N users and S subcarriers in each TTI, with each entry calculated as follows:

$$M_{i,j}(n) = \alpha * r_i(n) + (1 - \alpha) * d_{i,j}(n)$$

where

α is the weight factor, $0 \leq \alpha \leq 1$

r_i is the normalized backlog for user i in TTI n

$d_{i,j}$ is the instantaneous data rate of user i over subcarrier j With the above matrix, we schedule each subcarrier is assigned to the user with the highest matrix value for this particular subcarrier.

3.3.3 Best subcarrier

In this scheduling scheme, a particular subcarrier is assigned to the user with the best channel condition i.e. Subcarrier j is assigned to user i if $\max_j d_{i,j} = i$. This as we shall see later in the results section is highly unfair and gives poor performance.

3.4 Fairness oriented algorithms

The algorithms in this class incorporate various notions of fairness. To the best of our knowledge, *max-min, throughput, time fraction and proportional fairness with queue length* have not been applied before to DL resource allocations at BS.

3.4.1 Max-min fairness

In this scheduling scheme, subcarrier allocation is performed following the max-min allocation criterion i.e., subcarriers are allotted in the order of increasing demand with no node getting more subcarriers than its demand. Also, nodes with unsatisfied demands get an equal share of the subcarriers. Following this allocation, the assignment of subcarriers is performed by picking the z_j best subcarriers, where z_j is the number of subcarriers allotted to node j.

3.4.2 Throughput fairness

In this scheduling scheme, we maintain throughput fairness factor for each node and iterate through the nodes for subcarrier assignment in the ascending order of this metric. Throughput fairness factor for a particular node is the ratio of cumulative throughput of the node so far to the exponentially smoothed average of total system throughput so far i.e.

$D_i(n)/D_{tot}(n)$

where

$D_i(n)$ is the cumulative throughput for user i till TTI n

$D_{tot}(n)$ is the exponentially smoothed average of the total system throughput till TTI n This scheme may be unfair in short-term but in the long-term (1000 time slots), it attempts to normalize the throughputs of each user.

3.4.3 Time fraction fairness

Considering the fact that the channel quality varies from user to user and from subcarrier to subcarrier for a specific user, achieving throughput fairness may result in low system utilization. This is because, normalizing the throughput across users may require assignment of many subcarriers to a "bad" user (one experiencing bad channel conditions), while the assignment of these subcarriers to a "good" user (one experiencing good channel condition) would have resulted in opportunistic performance gains. In this scheduling scheme, we attempt to overcome this by normalizing the resource access times and not throughput. To elaborate, over a long time duration each user is provided with approximately same time fraction of the access to the resources (subcarriers). Time share factor per user denotes the proportion of subcarriers allotted to the total subcarriers so far (in a cumulative sense, over 1000 time slots) and this, in essence, signifies the share of resources that each node has received i.e.
Time-share factor $= B_i(n)/B_{tot}(n)$ where
$B_i(n)$ is the cumulative number of subcarriers allotted to user i till TTI n
$B_{tot}(n)$ is the total number of subcarriers allotted to all users till TTI n
The algorithm then proceeds to allot the subcarriers to the users in the order of time share factor. This strategy allows for temporary exploitation of multi-user diversity, while over a long time scale it normalizes the resource (number of subcarriers) access times to each user.

3.4.4 Proportional fairness

The proportional fairness metric proposed in [63] is considered by many in the wireless context of resource allocation. Authors in [64] provided downlink scheduling algorithms that satisfy the proportional fairness criterion in a TDM-based CDMA-HDR system. In this scheduling scheme, we adapt the PF algorithm to a multi-carrier setting of OFDM based wireless network. A proportional fairness factor is maintained for each combination of user and subcarrier. The proportional fairness factor is the ratio of instantaneous rate to the exponentially smoothed throughput. In essence, we create a NxS matrix M for N users and S subcarriers, with each entry calculated as follows:

$$M_{i,j}(n) = d_{i,j}(n)/T_{i,j}(n)$$

where

$d_{i,j}(n)$ is the instantaneous data rate for user i on subcarrier j in TTI n

$T_{i,j}(n)$ is the exponentially smoothed throughput for user i over subcarrier j in TTI n and is calculated as follows:

$$T_{i,j}(n+1) = \begin{cases} (1-1/t_c) * T_{i,j}(n) + 1/t_c * d_{i,j}(n) \\ \text{if subcarrier } j \text{ is assigned to user } i; \\ (1-1/t_c) * T_{i,j}(n) \\ \text{otherwise.} \end{cases}$$

t_c is the period over which fairness is reflected. The value 1000 was chosen in our simulation.

With the above matrix, the subcarrier is scheduled to the user who has the maximum value in matrix M for that particular subcarrier. This algorithm is an extension of the proportionally fair scheduling algorithm in a single carrier to multi-carrier ofdm setting.

3.4.5 Proportional fairness with queue length

This scheduling is similar to the previous, except that each matrix entry has a binary weight, which is dependent on the backlog as shown below:

$$M_{i,j}(n) = I_i(n) * d_{i,j}(n)/T_{i,j}(n)$$

Table 3.1: Notation for Local Optimization algorithm

Notation	Meaning
$\{1,\ldots,J\}$	Set of wireless terminals
$\{1,\ldots,S\}$	Set of subcarriers
$g_{j,s}$	CNR of terminal j on subcarrier s
p_s	power assignment for subcarrier s
$F()$	Mapping of subcarrier SNR to applied modulation type
$c_{j,s}$	Assignment of subcarrier s to terminal j (= 0,1)
z_j	Subcarrier allocation for terminal j

where

$d_{i,j}(n)$ and $T_{i,j}(n)$ are defined as before and

$I_i(n) = 1$ if backlog of user i is non-empty and 0 otherwise

The rationale behind adding the weight is to ensure that subcarriers are given to users who have data to send. Also, the data rate factor is tracked into the smoothed throughput for non-zero backlog users only.

3.5 Local optimization algorithms

The optimization class of algorithms that were implemented using the *lpsolve* tool([65]) is:

3.5.1 Local optimization

In this scheduling scheme, subcarrier assignment problem is formulated as an integer program and solved. The formulation based on [15] is presented below:

With the above notation, the subcarrier assignment problem can be formulated as an optimization problem as follows:

$$max \sum_{\forall j,s} c_{j,s}(t) \cdot F(p_s(t) \cdot g_{j,s}(t))$$

subject to:

$$\forall j : \sum_{\forall s} c_{j,s}(t) \leq z_j(t)$$
$$\forall s : \sum_{\forall j} c_{j,s}(t) = 1$$

3.5.2 Local optimization without subcarrier allocation

In this scheduling scheme, we solve the linear optimization problem formulated in [15] for subcarrier assignment. The difference with the previous algorithm is that we remove the constraints for subcarrier allocation. In other words, the step of allotting subcarriers to MSs based on the queue length is skipped and instead, we try to obtain the maximum system throughput.

3.6 Other approaches

In this section, we discuss a few approaches that are applicable at an algorithm's level to all the three classes of algorithms discussed above.

3.6.1 Channel diversity

In this algorithm, we perform double transmission of each packet on sufficiently separated subcarriers to achieve reliability. This is an extension of the MIMO principle to MAC layer and capitalizes on the fact that with frequency selective fading, often adjacent subcarriers go bad and by transmitting on sufficiently spaced subcarriers, we nullify this fading effect. From a preliminary investigation of this algorithm, it was observed that TCP performance was poor. A possible explanation is that plain duplication of data results in significant loss of goodput, which is due to the reduction in effective bandwidth. A possible enhancement that was not studied as part of this work is probabilistic duplication based on channel condition, over sufficiently spaced subcarriers to ensure reliability.

3.6.2 Cross layer strategies

We explored pure cross layer strategies, for example, using the congestion window as a measure of backlog instead of queue length during the subcarrier allocation and assignment at BS. The rationale behind this experiment is that the congestion window actually represents that amount of outstanding data for a TCP sender and the BS scheduler may get a better estimate of the backlog using the congestion window over the node queue length at BS.

3.7 MAC design highlights

A few highlights of the MAC resource algorithms studied in our work:

- Focus of our work is to study the subcarrier allocation and assignment strategies and not power and bit loading. Hence, we assume power is distributed equally for each subcarrier.

- Table. 3.2 summarizes the algorithms studied considering the complexity, memory consumption, fairness and various other parameters.

- An important performance metric that is essential for evaluation of a MAC algorithm from TCP congestion control standpoint is *Packet Loss Rate*(PLR). TCP performance starts dropping when the PLR is around 3 to 4% and significantly degrades when it reached 10% [3]. Hence, a MAC layer algorithm design strategy of keeping the PLR below 3-4% keeps the TCP performance in control.

Table 3.2: Comparison of the different MAC algorithms

	Maximization Objective	**Fairness**	**Computational Complexity**	**Memory Usage**
Best Subcarrier	$d_{i,j}(n)$	Low	Low	Low
Throughput Fairness	$D_i(n)/D_{tot}(n)$	High	Medium	Low
Time Fraction Fairness	$B_i(n)/B_{tot}(n)$	High	Medium	Low
Channel-backlog balance	$\alpha * r_i(n) +$ $(1-\alpha) * d_{i,j}(n)$	Low	Medium	Medium
Local Optimization	$\sum_{\forall j,s} c_{j,s}(t) \cdot$ $F(p_s(t) \cdot g_{j,s}(t))$	Medium	High	High
Local optimization no alloc	same as above (no alloc constraints)	Low	High	High
Max-min fairness	max-min criterion	High	Medium	Medium
Maximize Throughput	$r_i(n) * d_{i,j}(n)$	Medium	Medium	Low
Proportionally Fair	$d_{i,j}(n)/T_{i,j}(n)$	Medium	Medium	Low
Proportionally Fair with queue	$I_i(n) * d_{i,j}(n)/T_{i,j}(n)$	High	Medium	Low

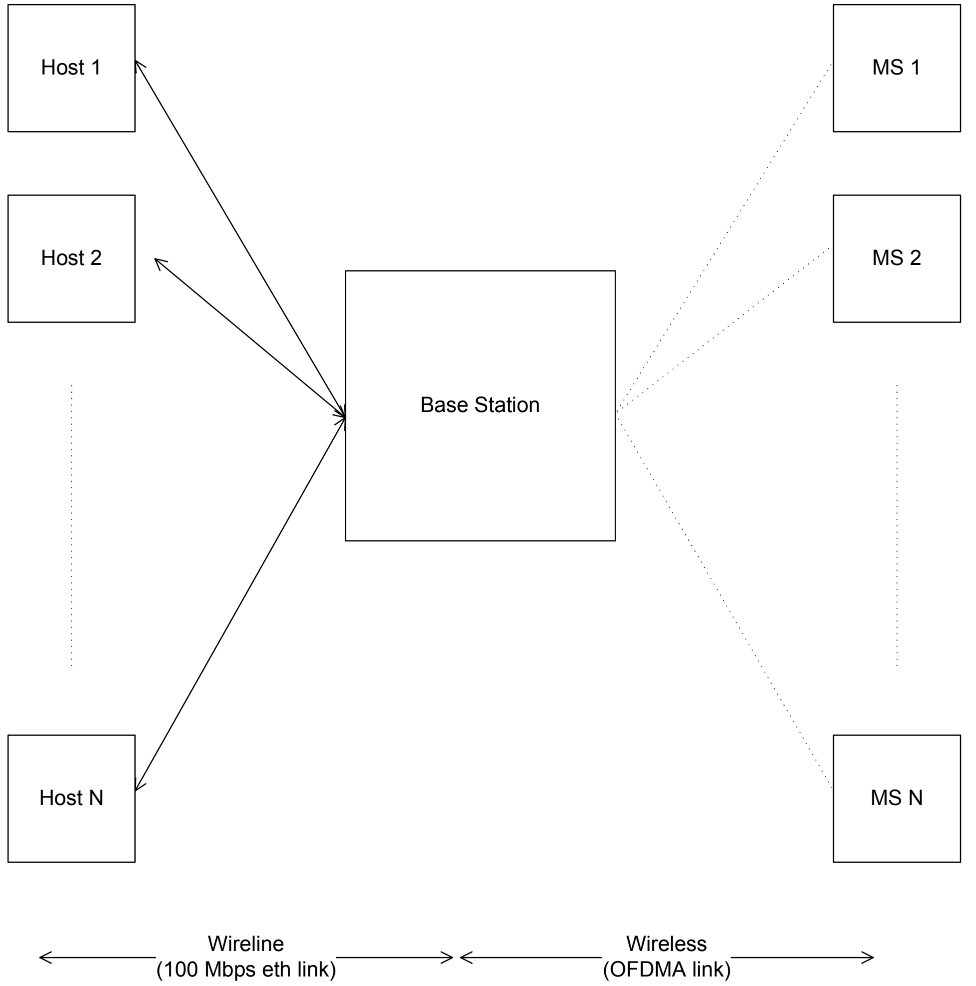

Figure 3.1: Simulation Environment

3.8 Results and Discussions

3.8.1 Simulation Environment

We used Omnet++ ([66]) discrete event simulator with INET framework for simulation. Channel models and MAC algorithms described in the previous were implemented as a separate module after adding host, base-station and mobile station nodes into the simulation environment. As shown in Fig. 3.1, the simulation environment has 8 mobile users, each running a FTP application to a server connected to the base-station. Using the channel model in 3.1, we generate the received SNR. If the received SNR is above the acceptable threshold (15dB), then the channel is taken to be good, else it is bad. We do not model adaptive modulation and coding. Instead, all subcarriers provide the same data rate i.e. 625Kbps when in good state and no data can be transferred on a bad subcarrier. The data rate chosen per good subcarrier is similar to that offered by wireless system like WiMaX [67].

Performance analysis of TCP using the TCP-Reno version was done for the following scenarios with different user characteristics:

- Scenario I: All users are pedestrian and experience channel quality that follows the model from 3.1 with identical parameters. The average SNR is 15 dB and the Nakagami-m parameter is 0.7 (for obtaining correlation in frequency domain).
- Scenario II: The eight users experience different channel quality (again from the model in 3.1), but the difference is that MS0 has best channel condition and MS7 has the worst channel condition.
- Scenario III: Variant of scenario I, with the exception that all the MAC algorithms detailed previously had cross layer enabled. In other words, TCP congestion window was used instead of the backlog at BS during subcarrier allocation and assignment.

3.8.2 Analysis of results for Scenario I

Table 3.3 and 3.4 present the TCP goodput for the various MAC algorithms and the summary of statistics. The system throughput as seen at the BS is in Fig. 3.2. Fig. 3.3 depicts the TCP goodput for different MSs, compared algorithm-wise and different visualization of this is seen in 3.4.

From the standard deviation and range metrics in the table, it is evident that the variation in algorithms that include a fairness metric and consider queue length like *max-min fairness, maximize throughput* is significantly lesser than their counterparts like *best subcarrier, channel backlog balance* algorithms. The next section summarizes the behavior of the different MAC algorithms using the information from table and bar charts.

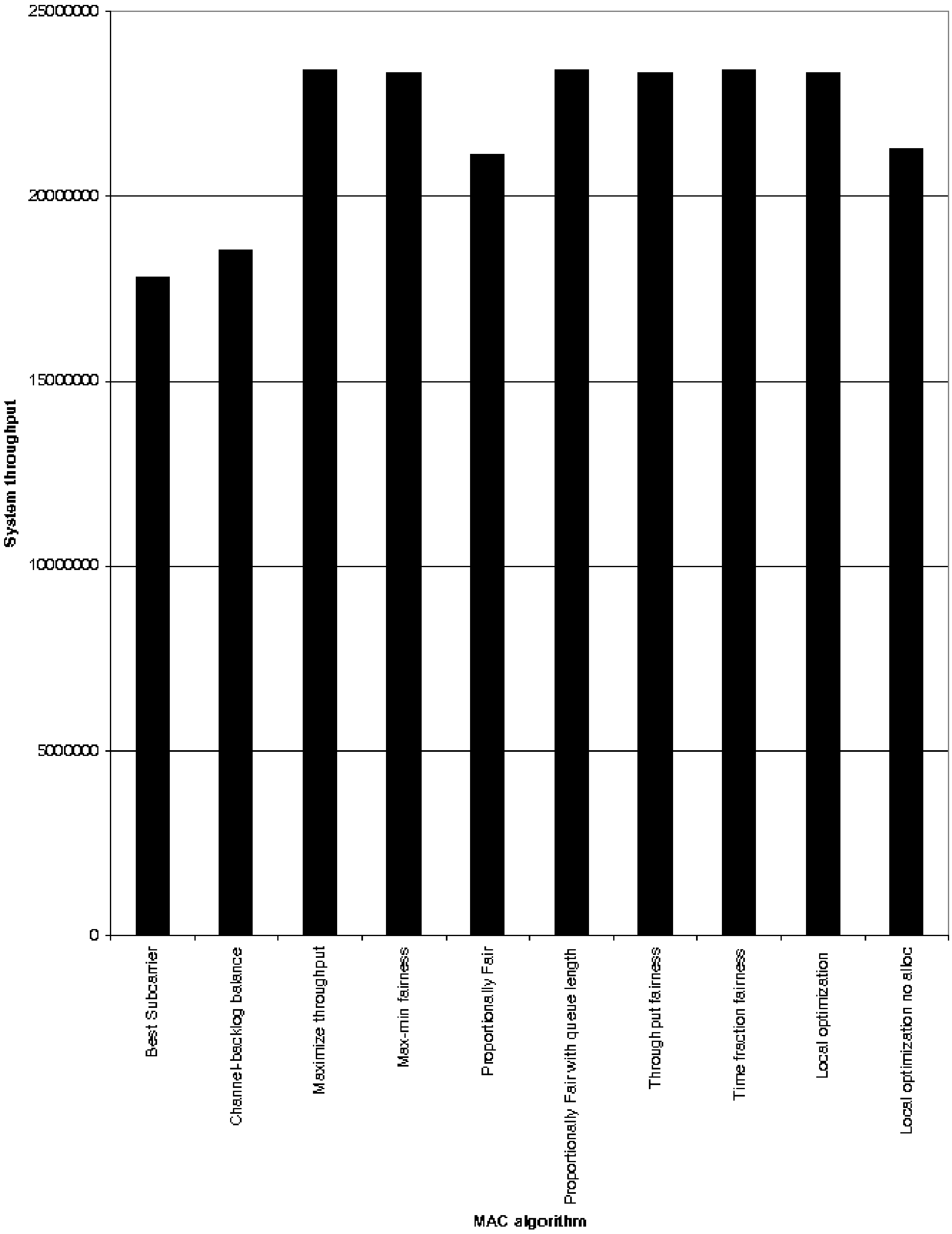

Figure 3.2: Net throughput at the BS

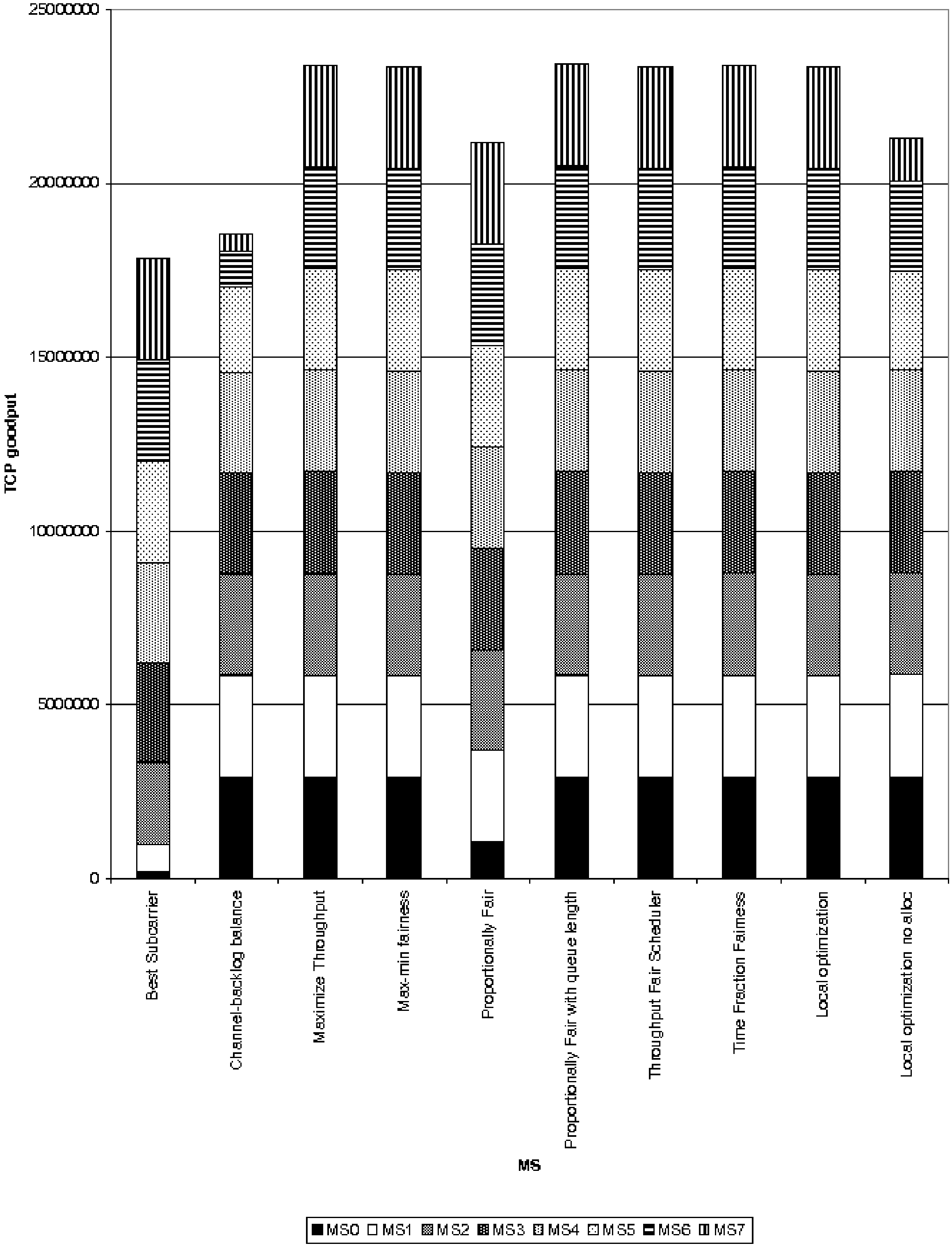

Figure 3.3: TCP goodput for each MS, algorithm-wise comparison

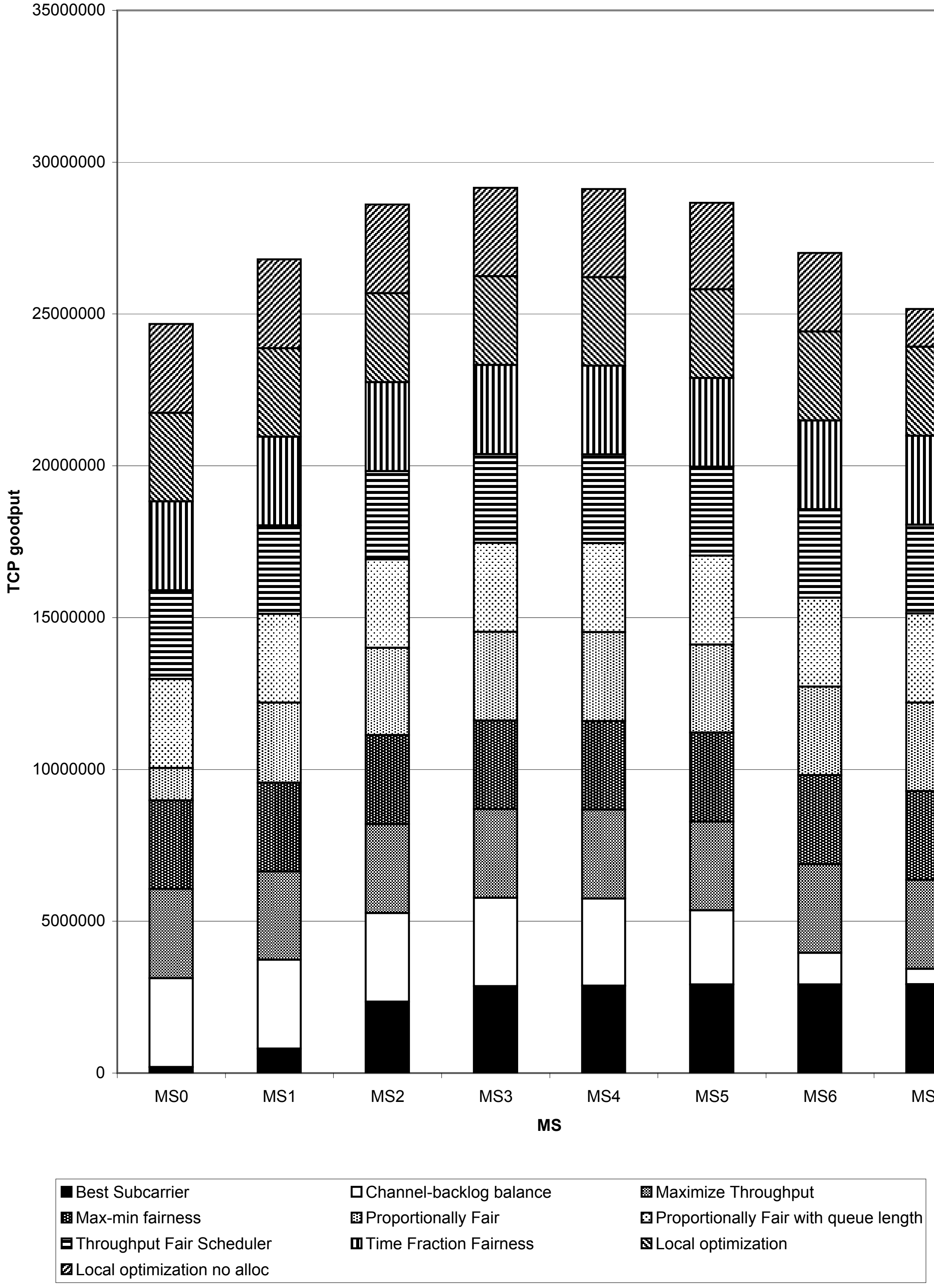

Figure 3.4: TCP goodput for each algorithm, MS-wise comparison

Table 3.3: TCP goodput comparisons for different MSes, MAC algorithm-wise - part I

	Best Subcarrier	**Throughput fairness**	**Time fraction fairness**	**Channel-backlog balance**	**Local optimization**
MS0	197120	2920960	2926592	2931200	2915840
MS1	802304	2915840	2921472	2928640	2908672
MS2	2349056	2903552	2933760	2917888	2927616
MS3	2860544	2928128	2933760	2908160	2920448
MS4	2871296	2926592	2921984	2874880	2915840
MS5	2912256	2928128	2921472	2443264	2919936
MS6	2913280	2915840	2921984	1042432	2928128
MS7	2921472	2926592	2930688	509440	2928128
Mean	2228416	2920704	2926464	2319488	2920576
Stdev	1095731.71	8628.38	5533.05	976934.09	7077.30
CoV	0.492	0.003	0.002	0.421	0.002

Table 3.4: TCP goodput comparisons for different MSes, MAC algorithm-wise - part II

	Local optimization no alloc	**Max-min fairness**	**Maximize throughput**	**PF**	**PF with backlog**
MS0	2933760	2915840	2933248	263680	2934784
MS1	2935808	2915840	2910208	961024	2924544
MS2	2923520	2926080	2934272	2565120	2912256
MS3	2919424	2915840	2921984	2882048	2928128
MS4	2905600	2917888	2928640	2911232	2930688
MS5	2849792	2928128	2926592	2894848	2928128
MS6	2593792	2925568	2926592	2906624	2931712
MS7	1246720	2921984	2928128	2914816	2936320
Mean	2663552	2920896	2926208	2287424	2928320
Stdev	583798.09	5181.35	7543.47	1056997	7514.56
CoV	0.219	0.002	0.003	0.462	0.003

3.8.3 Inferences from Scenario I results

- The class of MAC algorithms that do not consider the queue length of the individual MSs perform poorly as compared to the ones which consider the backlog. This is evident in the performance of *best subcarrier* and *Local optimization without subcarrier allocation* algorithms. Also, the proportionally fair algorithm that considered queue length weight performed better than the one which did not.

- The BS throughput and the individual MS's TCP goodput achieved by *max-min fairness, throughput fairness, time fraction fairness and proportional fairness with queue length* are similar. In essence, this leads us to conclude that the various fairness metrics lead to similar TCP and system performance.

- The class of MAC algorithms that has no fairness metric incorporated result in unfairness w.r.t. MSs, as expected. This is clear in the case of the *best subcarrier*, *channel backlog balance* and *Local optimization without subcarrier allocation* algorithms, as some of MSs show very poor goodput results as compared to others with these algorithms.

- The performance of the algorithms adopting a fairness metric was close to the *Local optimization algorithm with subcarrier allocation* algorithm's performance.

- The *maximize throughput* algorithm showed results on par with local optimization and fair algorithms. Very small variation was seen in the TCP performance of the individual MSs. This can be attributed to the fact that this algorithm uses not only the subcarrier quality, but also the queue length of the MSs effectively to decide the subcarrier assignment.

- The TCP PLR for fairness oriented algorithms remained under 3-4%, keeping the TCP performance under control. For the efficiency oriented schemes that showed unfair results, the PLR was not the same for all MSs and as expected, was high for penalized MSs (i.e., MSs having very low TCP goodput).

3.8.4 Discussion of Scenario II results

We present only the TCP goodput results for the MSs, compared algorithm-wise in Fig. 3.5. Extensive TCP performance plots - goodput, packet delay, congestion window evolutions and packet loss ratios (PLR) for various algorithms - are available in [68]. From the chart, it can be seen that the inferences drawn from Scenario I are still applicable. For example, poor performance is observed for algorithms which do not include any fairness metric like *channel-backlog balance*, *local optimization without subcarrier allocation*. The fair algorithms and maximizing throughput algorithm show good performance for all users in this scenario as well.

3.8.5 Cross layer strategies evaluation

Fig. 3.6 depicts the TCP goodput for different MSs in Scenario III setting (i.e. using TCP sender's congestion window for MAC resource allocation). It is observed that no significant performance gains as compared to the setting of Scenario I and II where no explicit cross layer feedback was present. Additionally, the congestion window parameter has to be passed to the BS from the TCP host: mostly an overhead if the TCP/IP header is used and also means a change to TCP/IP stack present in the wireline systems. Also, this approach makes BS complex as it has to work with TCP sender explicitly or implicitly to get the congestion window.

We propose using the backlog-based MAC protocols instead of the cross layered strategy, due to the closely matching performance of both approaches and the practical implementation concerns of the latter.

3.8.6 Validation of the Simulation Framework

One-way ANOVA (Analysis Of Variance) was performed on the data collected from the simulation framework using different random seeds. The random number generator used in Omnet++ was Mersenne Twister RNG, which has an extremely long overlapping sequence (See [69]). The one-way Anova tests were performed for the

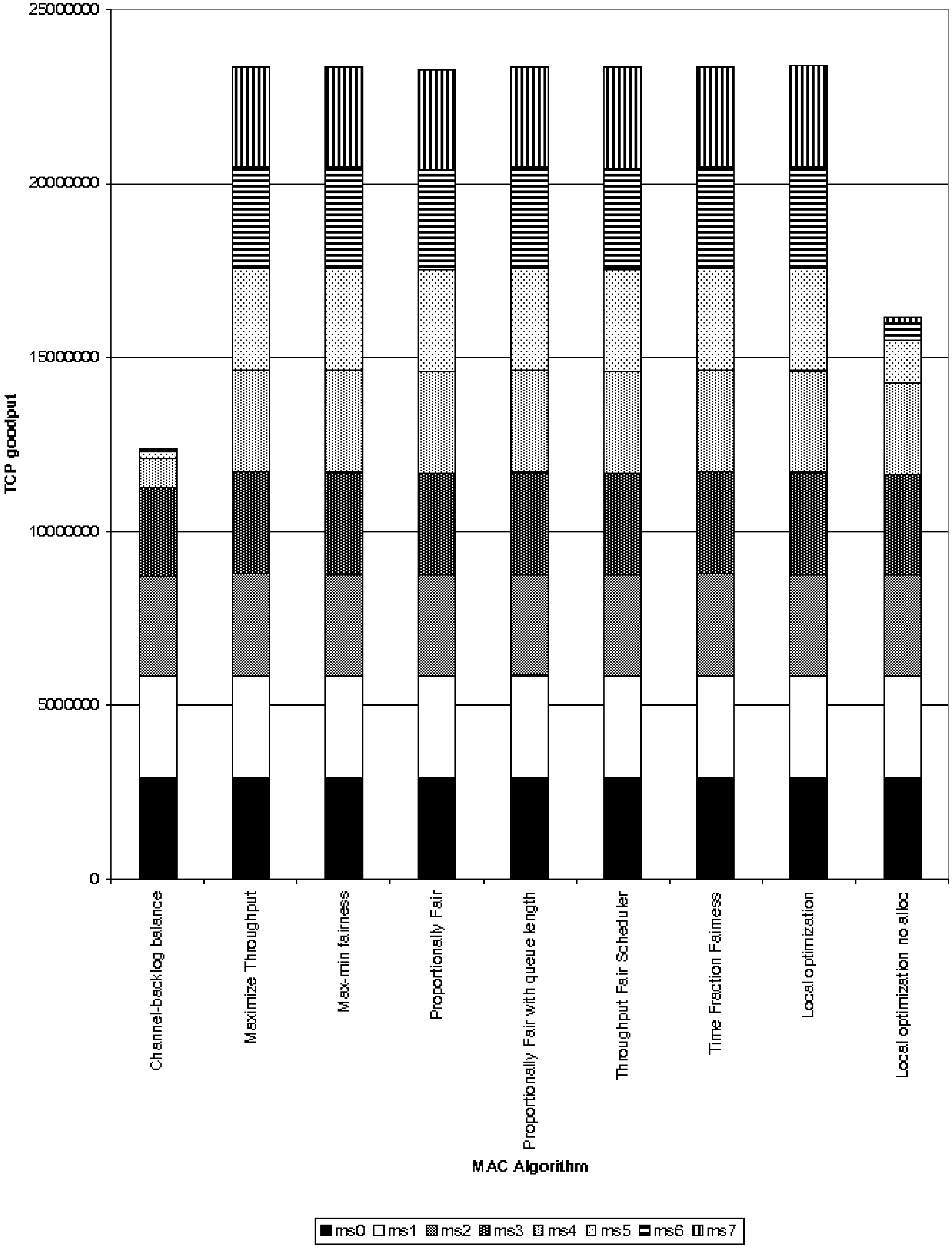

Figure 3.5: TCP goodput for each MS in scenario II, algorithm-wise comparison

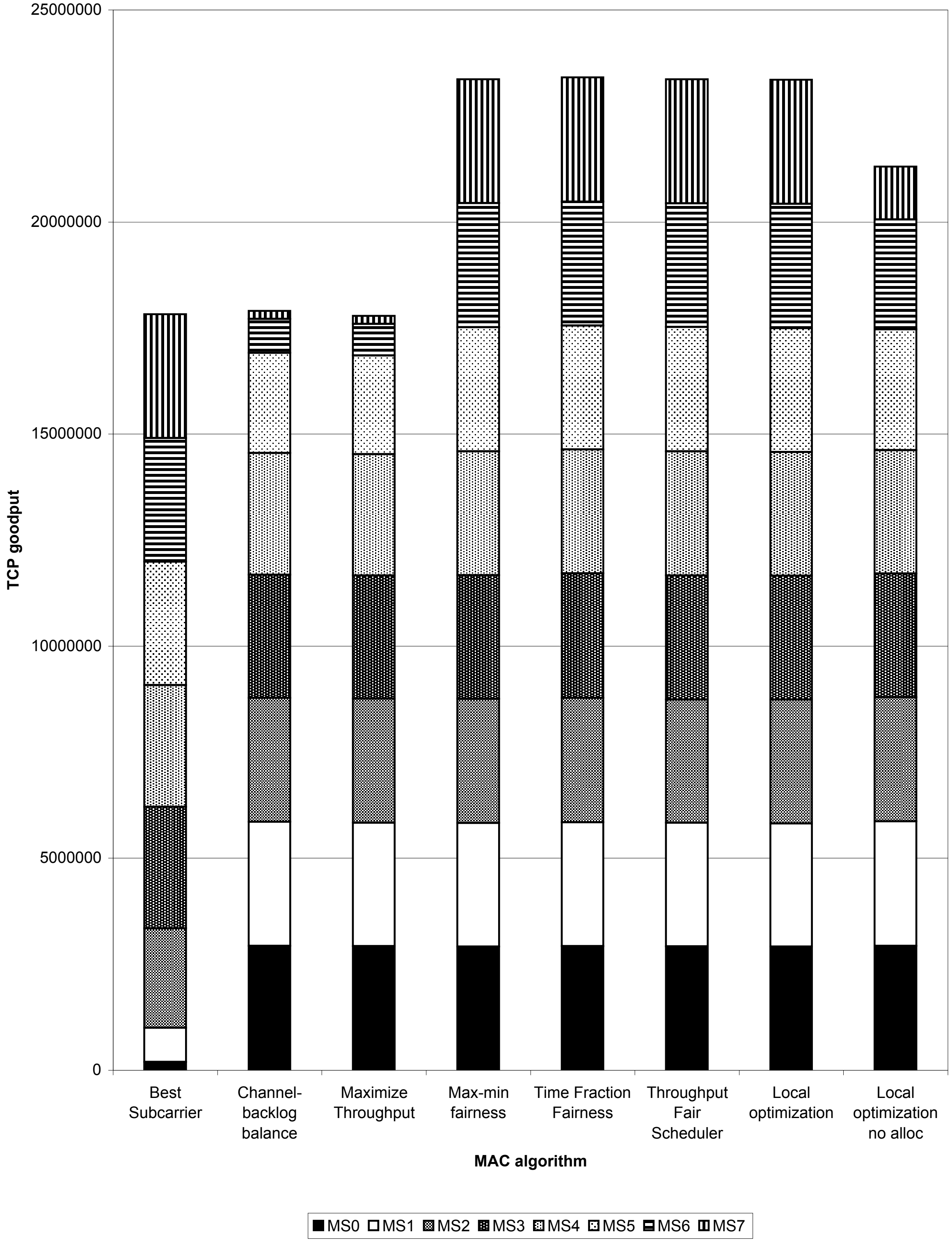

Figure 3.6: TCP goodput for each MS in scenario III, algorithm-wise comparison

Table 3.5: Anova test input data - TCP goodput from Best subcarrier MAC algorithm

MS/Seed	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
MS1	192000	204288	185344	211968	201216	194048	186880	203264	183808	200704
MS2	768512	795136	765952	766976	759808	756736	784896	763904	795136	749568
MS3	2375680	2345472	2358784	2349056	2349056	2375168	2347008	2363392	2365440	2356736
MS4	2853888	2863616	2860544	2866176	2865664	2863616	2861568	2857472	2872320	2863104
MS5	2914816	2915328	2908160	2904064	2909184	2912256	2911744	2905600	2905600	2910208
MS6	2921984	2910208	2923520	2919936	2911232	2912256	2919424	2909184	2919424	2924544
MS7	2906624	2921472	2917376	2917888	2923008	2910720	2922496	2909184	2916864	2921984
MS8	2911232	2915840	2921984	2915328	2912768	2922496	2918912	2915328	2914304	2913280

Table 3.6: Anova results for Best subcarrier MAC algorithm

ANOVA						
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F crit**
Between Groups	2.5E+08	9	27773065	2.27E-05	1	2.016601
Within Groups	8.56E+13	70	1.22E+12			
Total	8.56E+13	79				

system throughput as well as the TCP throughput from the various MAC algorithms. The complete summary of the tests carried out for various algorithms is available in [68].

The results of Anova single factor tests, with TCP goodput from *Best subcarrier* MAC algorithm as input data (See Table. 3.5), are presented in Table. 3.6. Observing that the F-statistic observed is lesser than the F critical value and also that the p-value is larger than 0.05 (95% confidence), we accept that there is no significant difference between the simulation runs with different random seeds.

3.8.7 Summary

We designed and evaluated a good mix of resource allocation schemes at MAC layer that included both efficiency and fairness oriented approaches. From the TCP performance results, it is observed that the queue length considering fair algorithms outperform the greedy channel diversity exploiting schemes. This serves to reinforce the idea that fairness oriented resource scheduling schemes is suitable for elastic traffic sources and a combination of TCP congestion control with queue length considering scheduling algorithms ensures fair resource allocation and queue length stability ([70],[71]). It was also seen that a cross layer scheme of using the congestion window as input to the MAC algorithm is unnecessary, as a smoothed queue length of a node at BS is a good indicator of the unacknowledged data and MAC algorithms that considered this queue length clearly produced good results.

3.9 Extensions to support heterogeneous service needs

3.9.1 OFDM-MAC design for heterogeneous traffic

Following the evaluation of MAC algorithms from a TCP performance standpoint, we incorporate real-time traffic into the problem space and attempt to address the problem of scheduling data transmission for heterogeneous traffic over an OFDM wireless link. We design novel extensions to some of the MAC resource allocation algorithms designed previously to support heterogeneous service needs (both real and non real-time traffic). Satisfying the QoS requirements of both real time and non real time users, while simultaneously exploiting the channel diversity are the goals behind optimizing the interactions between the various protocol layers. In the context of a TCP based application, QoS relates to latency (average delay), throughput, packet losses, while in VoIP context, it is worst-case delay bounds, delay jitter, etc. Performance evaluation of these algorithms is not performed due to the lack of availability of the VoIP protocol stack modules to support real-time traffic applications in the simulation framework we adopted above for TCP performance analysis.

Design Contributions

The design objectives for MAC algorithms are:

- exploit multi-user diversity gain to maximize system utility
- provide ”temporal” fairness
- satisfy the QoS expectations of both real-time and non real-time users.

To handle the QoS requirements related to delay of real time traffic, we use following model of user i: $P(W_i > T_i) \leq \delta$ where W_i is the delay encountered HoL packed in user i's queue and T_i is the deterministic QoS deadline.
We assume that the downlink scheduler at Base Station (BS) is aware of the channel conditions for all users and subcarriers at the beginning of each time slot. The channel-aware algorithms that were designed to cater to heterogeneous service needs are described below:

Credit based scheduling

The credit-based fair queueing scheduling algorithm proposed in [72] for wireline network achieves the fairness of the SCFQ algorithm ([73]), but at a much lower complexity. This is achieved by maintaining a credit value per flow and service the backlogged flow based on the number of credits accumulated, the size of HOL packet and the guaranteed rates. With each packet transmission, the corresponding flow's credit counter is zeroed while all the other waiting flows accumulate credits.
Background:
The WCFQ algorithm proposed in [74] adapts the credit-based fair queueing algorithm to a CDMA based wireless network. The WCFQ algorithm retains the credit counters per flow and enhances the CBFQ algorithm by incorporating the wireless channel conditions in a cost function. Using the credit counters and cost functions the algorithm balance between efficiency and fairness i.e. tradeoff opportunistic exploitation of the channel to maximize throughput v.s. provision of temporal fairness to different users. The WCFQ algorithm works as follows:

- Un-backlogged flows have zero credits.
- Flow selected for transmission reduces its credits by HoL packet length or zero, whichever is higher.
- All the un-scheduled flows perform a weighted share increase of their credits. The increase amount is the difference between HoL packet length and credits of the

Table 3.7: Notation

Notation	Meaning
n	TTI number
ϕ_i	weight of user i
$K_{i,j}(n)$	credit counter of user i for subcarrier j at TTI n
$B(n)$	the set of active or backlogged users at TTI n
$L_{i,j}(n)$	User i's HoL packet portion transferable in TTI n
$U_{i,j}(n)$	estimated transmission cost for user i on subcarrier j
$f_j(n)$	user that is scheduled to transmit on subcarrier j in TTI n

selected flow, provided it is non-negative. Otherwise, the increase amount is zero.

We provide three adaptations of the WCFQ algorithm ([74]) in multi-carrier systems. While we retain the credit abstraction and transmission cost functions, the difference w.r.t. WCFQ is that the algorithm works at a periodic time slot (TTI) and not at a packet transmission interval.

Algorithm 1:

Each user maintains a vector of credits, one per subcarrier. Each subcarrier assignment follows the WCFQ algorithm. While the credits ensure system fairness, the channel diversity is exploited using the cost function per user.

A summary of notation similar to [74] is presented in Table. 3.7

The scheduling decision for subcarrier j at TTI n is defined as follows:

$$f_j(n+1) = \min_{i \in B(n)} (L_{i,j}(n) - K_{i,j}(n) + U_{i,j}(n))/\phi_i$$

The rationale behind the above scheduling decision is to allow low transmission cost users to use the resources (subcarriers), while the "poor" channel users eventually catch up by accumulating enough credits. The algorithm pseudo-code for updating the credits is as follows:

Table 3.8: Credit update algorithm - Algorithm 1

```
for($i$=1 to N)
{
  for($j$=1 to S)
  {
    if( $i \in B(n+1)$ and $i \neq f_j(n+1)$ )
      $K_{i,j}(n+1) = K_{i,j}(n) + \max(L_{f_j,j}(n) - K_{f_j,j}(n)/\phi_{f_j}, 0)/\phi_i$
    else if ( $i \notin B(n+1)$ )
      $K_{i,j}(n+1) = 0$
  }
}
for($j$=1 to S)
{
  if( $f_j(n+1) \in B(n+1)$ )
    $K_{f_j,j}(n+1) = \max(K_{f_j,j}(n) - L_{f_j,j}(n), 0)$
  else if ( $f_j(n+1) \notin B(n+1)$ )
    $K_{f_j,j}(n+1) = 0$
}
```

This extension of the WCFQ algorithm to multi-carrier systems is high on space and time complexity due to the maintenance of user credits per subcarrier and the algorithm execution for each subcarrier. An alternate algorithm presented in the next section reduces the space and time complexity vis-a-vis this algorithm, while still ensuring statistical fairness guarantees w.r.t. number of subcarriers.

Algorithm 2:

The salient features of this algorithm are that it remains computationally inexpensive and attempts to balance the efficiency and fairness objectives. A single "credit" counter is maintained per user and this is used to reflect the resource access times of the user. As argued before, we attempt to normalize the resource access times and not throughput of each user. The resource considered here is the subcarrier count and over a long time duration, the objective is to have each user allotted with the same proportion of the subcarriers.

The scheduling loop iterates through the backlogged users in order of a parameter that is a function of credits, backlog and transmission cost. The scheduling parameter is

Table 3.9: Notation

Notation	Meaning
n	TTI number
ϕ_i	weight of user i
$K_i(n)$	credit counter of user i at TTI n
$B(n)$	the set of active or backlogged users at TTI n
$U_i(n)$	estimated transmission cost for user i
$L_i(n)$	HoL packet length for user i

defined below

$$\min_{i \in B(n)} (L_i(n) - K_i(n) + U_i(n))/\phi_i$$

At the end of each time slot, the excess credits accumulated by each user are redistributed among the active users, in a manner similar to the previous algorithm. As illustrated in [74] the transmission cost function $U_i(n)$ can be used to balance efficiency and fairness. The main difference w.r.t. the previous algorithm is that fairness is ensured not at a subcarrier level, but at the subcarrier count level. This reduces the space and time complexity as credits are maintained per user and the update algorithm iterates the users alone.

Algorithm 3:

This algorithm is similar to the previous, except that the cost functions are not the same for each user. Higher priority to real-time users is achieved by assigning a higher transmission cost and lower weight to the non-real time users in the scheduling decision.

Opportunistic scheduling with fairness

In [75], the authors formulate several optimization problems with a general system utility objective function and several QoS constraints. The formulations are for both single and multiple interfaces, with different processor sharing and data rate constraints.

We formulate the resource assignment problem in a multi-carrier OFDM setting, considering QoS needs of heterogeneous applications. Data rate constraints for real time applications and fairness or time share constraints to non-real time applications are included in the formulation. Solving this optimization problem gives us insight into the achievable performance of the system that caters to heterogeneous applications.

Optimization Problem Formulation

We follow the notation similar to [75].

- $\mathcal{N}$: set of users or mobile stations (MSs), from 1 to N
- $\mathcal{S}$: set of subcarriers, from 1 to S
- d_i^j: the data rate of user i over subcarrier j
- z_i: denotes the subcarrier allocation for user i
- f_i: denotes the system utility function for user i
- g_i: the QoS constraint function for user i
- c_i^j is the scheduling decision for user i w.r.t. subcarrier j (= 0,1)

The opportunistic scheduling problem for a multi-carrier OFDM setting can be defined as follows:

$$\max_{c} \sum_{i\in\mathcal{N}} \sum_{j\in\mathcal{S}} E\{f_i(d_i^j) I_{c_i^j=1}\}$$

such that

$$\begin{aligned} \forall i, \sum_{j\in\mathcal{S}} \{g_i(d_i^j) I_{c_i^j=1}\} &\geq G_i \\ \forall i, \sum_{\forall j} I_{c_i^j=1} &\leq z_i(t) \\ \forall j, \sum_{\forall i} I_{c_i^j=1} &= 1 \end{aligned}$$

The objective of the optimization problem formulated above is to maximize the system utility subject to subcarrier allocation and assignment constraints and the user QoS constraints. The user QoS constraints can be either

- Time share constraints: Guarantee an expected share of the resources (subcarriers) for each user. These constraints suit the elastic or non-real time applications.
- Date rate constraints: Guarantee a minimum data rate. These constraints are more applicable to real-time applications.

The solution to the opportunistic scheduling problem with varying degree of fairness and rate constraints can be attempted by using the stochastic approximation algorithm as in [75, 14]. This approach has the advantage of converging to the optimal solution and also, is not computationally complex.

Weighted Max-min fairness

In this scheduling scheme, subcarrier allocation is performed following the max-min allocation criterion i.e., subcarriers are allotted in the order of increasing demand with no node getting more subcarriers than its demand. Also, nodes with unsatisfied demands get an equal share of the subcarriers. Following this allocation, the assignment of subcarriers is performed by picking the z_j best subcarriers, where z_j is the number of subcarriers allotted to node j. Flow differentiation is achieved by providing higher weights to real-time flows than non-real time flows.

Time fraction fairness with delay factor

In this scheduling scheme, we combine the time fraction fairness with delay factor to balance between long term fairness and real-time QoS requirement. Time fraction factor signifies the share of resources that each user has received and is the fraction of number of subcarrier allotted to a particular node to the total of subcarriers. The motivation behind normalizing the channel access time instead of flow throughputs is that different users experience different channel conditions and to normalize throughput, the worst channel user needs to be given a substantial fraction of the bandwidth.

Maximize Throughput

This is similar to the algorithm designed in 3.3. The attempt here is to achieve throughput optimality by weighting the data rates by the backlog queue length. To reiterate, the scheduling scheme works as follows: We create a matrix M for N users and S subcarriers

$$M_{i,j}(n) = r_i(n) * d_{i,j}(n)$$

where

$r_i(n)$ is the backlog or queue length for user i in TTI n

$d_{i,j}(n)$ is the instantaneous data rate of user i over subcarrier j With the above matrix, each subcarrier is assigned to the user with the highest matrix value for this particular subcarrier.

Delay Variant: This is similar to previous algorithm except that it incorporates delay requirements to suit real time traffic.

Specifically, subcarrier j is assigned to user i in TTI n if

$$i = \max_{j} Q_i(n) * d_{i,j}(n) * W_i(n)$$

where

W_i is the delay encountered by the HoL packet in user i's queue and

r_i and $d_{i,j}$ are defined as before.

Other algorithms

Algorithms like Largest weighted delay first ([76]), Earliest deadline due first (EDD), Minimum laxity threshold policy (MLT), exponential rule scheduling schemes that cater to real time traffic requirements can be effectively combined with maximize throughput, max-min fairness, proportional fairness, throughput fairness and time-fraction algorithms. This combination has the potential to achieve ”good” performance balancing the objectives of MAC algorithm design outlined before.

Analysis and Recommendations

While *Maximize Throughput* works effectively towards exploiting the multi-user diversity, it does not guard against misbehaving users . On the other hand, *Weighted max-min fairness* caters well to the fairness objective, but does not maximize system utility as most of the subcarriers will be consumed by users with bad channel conditions (to maximize the minimum bit rate). The algorithms *Credit based scheduling, Time fraction fairness with delay factor, Delay variant of maximize throughput and Opportunistic scheduling with fairness* offer a lot of promise due to three factors: they employ the fairness notion of providing nearly same channel access duration for each user, balance system utility vs. fairness and incorporate delay requirements to cater to real time traffic.

3.9.2 Summary

Designing OFDM-MAC that achieves close to optimal performance while providing long term fairness, is quite challenging. We proposed a few algorithms to solve the MAC resource allocation problem, considering heterogeneous service needs. The approach adopted was to balance three objectives: multi-user diversity gain, fairness provision over long time scale and support of real and non real-time traffic. From the design exercise, we speculate that the algorithm extensions: *Credit based scheduling, Time fraction fairness with delay factor, Delay variant of maximize throughput and Opportunistic scheduling with fairness* offer a lot of promise and are strong candidates for further investigation. The performance evaluation of these algorithms is beyond the scope of this work, as modules for real-time applications, protocols at transport, link and medium access layer are not available in the simulation framework we built previously for TCP performance analysis.

Chapter 4

Conclusions and Future Directions

In this thesis, we considered resource allocation and scheduling problems in the context of an OFDM based wireless network. We adopted a cross layer analysis approach that attempted to understand the interactions between control loops at transport and medium access layer from an error and flow control perspective. The main contributions of this thesis are summarized as follows:

We have designed and evaluated a good mix of channel-aware resource allocation schemes at MAC layer that balanced the efficiency and fairness objectives. The novel resource allocation schemes proposed were compared with each other and contrasted with local optimization schemes. From the TCP performance results obtained, it is observed that the queue length considering fair algorithms outperform the greedy channel diversity exploiting schemes. This analysis comes under the realm of cross layer design proposals, specifically under the *vertical calibration* method. This approach ensures that our proposals stay within the currently existing layered network architecture.

We have incorporated a pure cross layer strategy of using TCP sender's congestion window instead of the backlog for scheduling purposes at BS. Performing adaptive resource allocation and assessing it in true cross layer spirit requires explicit as well as implicit exchange of information between layers. This necessitated the exploration of a L4 (TCP) to L2(MAC) information sharing scheme. It was observed from the TCP performance results that the *congestion window* sharing strategy is unnecessary as the backlog using MAC algorithms produced commensurate results. A possible explanation is that the smoothed queue length of a node at BS is a good indicator of the unacknowledged data. This obviates the need for congestion window information for the scheduler at BS - an approach that possibly introduces performance overheads and adds to the complexity of the system.

We have extended the algorithms designed previously to cater to both real time and non real time application needs. While a full-fledged performance analysis was not performed, from the preliminary design and analysis effort, we recommended detailed performance evaluation of the credit based algorithms, opportunistic scheduler with fairness and weighted max-min and maximize throughput algorithm variants. These algorithms were designed to opportunistically exploit the channel conditions, tradeoff efficiency to fairness and support heterogeneous service needs.

4.1 Future directions

A number of avenues to extend this work are possible.

First, the MAC algorithms proposed for heterogeneous application support can be implemented and evaluated through performance simulations. This comparative evaluation would then provide valuable insight into the behavior of MAC algorithms and aid the network designer in selecting the MAC resource allocation scheme that suits his need best. An analytical study can be performed to understand the interactions of TCP and VoIP/RTP layers with the MAC resource allocation algorithms. This can be verified against performance results from simulation.

Second, it would be interesting to explore the cross layer interactions between transport layer congestion/rate control, link layer retransmissions, medium access resource scheduling, adaptive modulation and coding and transmission power/rate control at the physical layer from an optimization framework perspective.

Third, the proposals we studied under the realm of cross layer optimization were mostly lower layer design and its impact on upper layers (except the congestion window sharing to MAC). However, a full treatment of this problem using cross layer arguments would be interesting.

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