Exploiting Multiuser Diversity with Capture in Wireless Networks

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Abstract

In a wireless network, owing to the time-varying nature of wireless channels, different mobile users typically experience peaks and troughs in channel quality at different times. This diversity in channel quality is known as multiuser diversity. With the aid of rate adaptation, multiuser diversity can be exploited by allowing the mobile user with the best channel to use the channel resource. However, in order to achieve this in most practical systems, the mobile users in the network must feed back their channel state information (CSI) to the transmitting user. In large networks, this feedback overhead can outweigh the multiuser diversity gain.

In this thesis dissertation, a centralised wireless medium access control (MAC) scheme, namely Multiuser Diversity with Capture (MDC), is discussed as a solution to obviate the overhead problem. MDC explicitly employs the capture effect in radio receivers to reduce network overhead by allowing multiple mobile stations (MSs) with channels better than a nominal response threshold to simultaneously compete for the wireless channel. Owing to the capture effect, the base station (BS) can determine which MS has the best channel. In comparison with the Medium Access Diversity (MAD) scheme in the literature, the proposed MDC possesses the strong merit that the feedback overhead is independent of the number of MSs in the network.

Several aspects of the MDC scheme are investigated in detail. An application of the MDC scheme based on the physical layer and parts of the MAC layer of the IEEE 802.11a standard is considered. A general analytical framework for the goodput performance of MDC is derived. Using this framework, the exact closed form solution for the expected goodput of MDC with rate adaptation over Rayleigh fading channels is calculated.

The fairness performance of MDC in networks where some MSs experience better average channel conditions than others is also addressed. MSs with low average channel states tend to use the channel less often in MDC than MSs with high average channel states. This issue is tackled with Fairer Multiuser Diversity with Capture (FMDC), a variant of the MDC scheme designed to share the channel resource more equitably across all of the MSs in the network. In FMDC, instead of using the network-wide response threshold to decide whether to compete for the channel, each MS only competes for the channel when their channel state is greater than a threshold factor multiplied by their average channel state.

Finally, the problem of adaptive optimisation of the response threshold for MDC and the threshold factor for FMDC is also considered. In the proposed solution, the response threshold and the threshold factor are adapted heuristically according to the estimated goodput performance of the system. The adaptive heuristic has importance in practical systems because the BS usually does not know the characteristics of the time varying channels of the MSs in the network.

List of Publications

[1] J. Foo, D. Huang and G. Mercankosk, "Exploiting Multiuser Diversity with Capture in Wireless Communication Networks," in *Proc. IEEE WCNC'07*, Mar. 2007, pp. 1931-1935.

[2] J. Foo and D. Huang, "Performance Analysis of Multiuser Diversity with Capture for Wireless Networks," in *Proc. IEEE ICC'08*, May 2008, pp. 4569-4574.

[3] J. Foo and D. Huang, "Multiuser Diversity with Capture for Wireless Networks: Protocol and Performance Analysis," in *IEEE J. Sel. Areas Commun.*, vol 26, no. 8, pp. 1386-1396, Oct. 2008.

[4] J. Foo, D. Huang and H. Li, "Improving Fairness in Multiuser Diversity with Capture," in *Proc. ICICS'09*, submitted for publication.

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List of Acronyms

ACK Acknowledgement

BS Base Station

CA Channel Allocation

cdf Cumulative Distribution Function

CP Channel Probe

CSI Channel State Information

CSIF Channel State Information Feedback

CTS Clear to Send

CSMA/CA Carrier Sense Multiple Access with Collision Avoidance

FMDC Fairer Multiuser Diversity with Capture

LAN Local Area Network

i.i.d. Independent and Identically Distributed

MAC Medium Access Control Layer

MAD Medium Access Diversity

MDC Multiuser Diversity with Capture

MPDU MAC Protocol Data Unit

MS Mobile Station

OFDM Orthogonal Frequency Division Multiplexing

pdf Probability Distribution Function

PHY Physical Layer

PLCP Physical Layer Convergence Procedure

PMD Physical Medium Dependent

PPDU PLCP Protocol Data Unit

PR Probe Response

RTS Request to Send

SIFS Short Inter-Frame Space

SMUD Selective Multiuser Diversity

SNR Signal to Noise Ratio

WLAN Wireless Local Area Network

Chapter 1

Introduction

1.1 Wireless Networks and Multiuser Diversity

Wireless communication technologies are the prevailing topic of interest in modern telecommunications. This interest is mainly due to the high demand for wireless communication technologies in the consumer market, as end users enjoy the convenience of mobility that is not achievable in wired communication. With the widespread adoption of mobile phones, cellular network technology is continually advancing as researchers strive towards the goal of ubiquitous computing. Currently, local area networks (LANs) using wireless communication hardware enable laptop computer users to connect to the Internet with considerably greater mobility than in wired LANs. Another emerging application of wireless communication technology is in wireless sensor networks, whereby a wireless network of autonomous sensing devices monitors some kind of physical environment.

Traditionally, research in wireless communication technology has focused on ensuring the reliability of point-to-point links for voice communications in cellular networks. In the modern setting of data communications, where network throughput is one of the major performance metrics, multiuser communication has recently drawn significant attention [1, 2]. In contrast with single user communication, multiuser communication views communication in a wireless network holistically, focusing on overall network performance rather than the performance of a single wireless link.

One of the most important revelations in multiuser communication was the discovery of *multiuser diversity*. Multiuser diversity is the inherent diversity in channel quality exhibited in time-varying wireless channels across different users at different times [3, 4]. The potential to exploit multiuser diversity was discovered by Knopp and Humblet [5], who demonstrated that the sum-rate capacity of the uplink channel of a wireless network is maximised by scheduling the user with the best channel to transmit at any given instant. This channel-aware scheduling policy achieves much better network throughput performance than round robin scheduling, since data is always transmitted at the peak data rate instead of the average data rate.

The specifications in the current IEEE 802.11 standards for wireless LANs [6, 7] mandate the capability of transmission at multiple data rates using different modulation and coding schemes. The purpose of this feature is to allow the transmitting user to adaptively select the highest transmission rate attainable during the current channel conditions. However, the IEEE 802.11 specifications do not mention how the adaptive modulation and coding mechanism (also known as rate adaptation or link adaptation) should be implemented. Ideally, if the transmitting user has perfect channel state information (CSI), then the best transmission rate can always be chosen provided that channel quality does not vary significantly over the duration of a transmission.

In order to exploit multiuser diversity with rate adaptation in a wireless network, it is necessary for the transmitting user to obtain the CSI of the user in the network with the best channel. The amount of system overhead required to obtain instantaneous CSI from every user in the network prior to each data transmission can have a detrimental effect on network goodput performance, particularly when the number of users in the network is large. Consequently, the major challenge in designing wireless communication systems that exploit multiuser diversity is the development of low overhead techniques for obtaining the CSI of the user with the best channel.

In a major class of solutions to this problem, known as limited feedback systems, the mobile users feed back quantised CSI (also called imperfect CSI) to the transmitting user using a small number of information bits [8–12]. The quantised CSI feedback is then used by the transmitting user for rate adaptation. Many researchers have shown that well designed quantised feedback schemes can achieve throughput performance benefits almost as good as ideal systems with perfect CSI knowledge [13–15].

However, using limited feedback systems is not the only approach to mitigating feedback CSI overhead. In Selective Multiuser Diversity (SMUD) scheduling [16], the amount of bandwidth required for the CSI feedback channel was reduced by enforcing that users would only access the feedback channel if their channel quality exceeded a particular threshold. The philosophy behind this scheduling method is that only users with good channels have reasonable chances of having the best channel, hence the CSI of the users with bad channels do not need to be fed back.

In the Medium Access Diversity (MAD) [17] scheme, only a small subset of the users in the network are queried prior to data transmission for their CSI, thereby reducing the system overhead. However, in querying the CSI of only a small subset of users, there is a potential loss of throughput since the MS with the best channel may not be in the chosen subset. Nonetheless, the results in [17] based on the free space path loss and Rayleigh fading propagation models showed a significant throughput improvement over earlier rate adaptation techniques such as Auto Rate

Fallback [18] and Opportunistic Auto Rate [19].

In [20], the user identification scheme for Orthogonal Frequency Division Multiplexing (OFDM) systems reduces the overhead by allowing multiple mobile users transmit their CSI to the network access point (AP) simultaneously, instead of one at a time. In [21], the capture effect was exploited to reduce system overhead and achieve a multiuser diversity gain in random reservation access systems.

1.2 Capture

In wireless communications, the capture effect is the ability of a radio receiver to receive a signal from one transmitter in the presence of interference from one or more other transmitters. The capture effect is an inherently complex phenomenon that depends on the specific implementation of the transceiver system. Several mathematical models have been proposed in the literature to characterise the capture effect [22, 23], although the capture ratio model remains the most popular.

The implications of the capture effect have been studied in Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) systems and in variants of the ALOHA protocol. With the inclusion of the capture effect in theoretical analysis, it has been demonstrated that wireless slotted ALOHA networks achieve significantly higher throughput than when the capture effect is not considered [24–27]. In [28], Kim and Lee analysed the effects of capture on CSMA/CA protocols and found that the network throughput performance is sensitive to the capture ratio, multipath fading and shadowing effects.

1.3 Thesis Contributions

The main contribution of this thesis dissertation is a centralised wireless medium access control scheme called Multiuser Diversity with Capture (MDC) to address the CSI feedback overhead problem. In MDC, the capture effect in radio receivers is *explicitly employed* to reduce overhead by allowing multiple stations (MSs) to simultaneously feed back their CSI to the base station (BS). With this opportunistic approach used in MDC, the overhead is independent of the number of MSs in the network.

In the discourse on MDC, the following aspects are considered:

- An application of MDC for wireless LANs (WLANs) using existing infrastructure from the IEEE 802.11a [6, 7] specifications.
- Theoretical analysis of the goodput performance of MDC.
- The fairness performance of MDC and the measurement of fairness in general for systems that exploit multiuser diversity.
- Adaptive optimisation of MDC goodput performance.

1.4 Thesis Structure

The rest of this thesis is organised as follows. In Chapter 2, the network model and the MDC scheme is described in detail. MDC is applied to the IEEE 802.11a framework and simulation results are presented. Chapter 3 is dedicated to the theoretical analysis of the goodput performance of MDC. Using this framework, the exact closed form solution for the expected goodput of MDC with rate adaptation over Rayleigh fading channels is calculated and the MDC scheme is studied. In

Chapter 4, the fairness performance of MDC is discussed and the Fairer Multiuser Diversity with Capture (FMDC) scheme is proposed. Applying the gain fairness measure, the goodput and fairness performances of MDC and FMDC are discussed. In Chapter 5, an adaptive heuristic to optimise the goodput performance of the MDC and FMDC is considered and simulation results are presented. Finally, Chapter 6 concludes this thesis.

Chapter 2

Multiuser Diversity with Capture

In this chapter, the details of the Multiuser Diversity with Capture (MDC) scheme are presented. An application of MDC scheme for the IEEE 802.11a system is then described. Finally, the goodput performance of MDC is evaluated via simulations over a typical WLAN channel.

2.1 MDC System Description

Consider a wireless network with one BS and N MSs, indexed from 1 to N. A constant transmission power P_T is used for all packet transmissions and the uplink and downlink channels are reciprocal. Whenever exactly one MS in the network transmits a packet, that packet is always received successfully. Channel quality is measured by the instantaneous signal to noise ratio (SNR) between an MS and the BS and will be referred to as the *channel state* of the MS. The total duration required to transmit a data packet, including the transmission time of the control packets that setup the data transmission, is assumed to be less than the channel coherence time. Consequently, the channel state of an MS is constant over the total duration required to transmit a data packet and the channel state of MS i is denoted by Γ_i.

Channel estimation is assumed to be perfect, hence Γ_i and its estimate will not be differentiated in the following discussion.

Note that there will be two types of "channels" discussed for MDC. The first type of channel is the wireless communication channel that exists between each MS and the BS. The second type of channel is the network channel, the network-wide communication resource that is shared between all of the MSs in the network and the BS. These two types of channels will be discerned by context. The first type of channel will always be associated with one MS or a group of MSs (e.g., "the channel states of the replying MSs") and in the absence of any association with a particular MS or a group of MSs, the second type of channel is the one being referred to (e.g., "the channel").

In downlink data transmission for MDC, each data packet transmission takes place as part of a *transmission cycle.* Each transmission cycle in MDC consists of the following six steps:

Step 1. Channel Probing

At the start of the transmission cycle, the BS broadcasts a channel probe (CP) packet, prompting the MSs to respond.

Step 2. Channel Competition

Each MS uses the CP packet to estimate its channel state. For MS i, if the SNR $\Gamma_i > \gamma$, then MS i responds to the BS with a probe response (PR) packet. The system parameter γ is called the *response threshold.*

Step 3. Channel Allocation

Based on the received PR packets, the BS seeks to identify the MS with the best channel and allocates it the rest of the transmission cycle so that it may perform data transmission. However, the BS will only be able to correctly identify the MS with the best channel if (i) there is exactly one responding MS, or (ii) the strongest PR signal can be captured from multiple responding MSs. When the MS with the best channel is identified, that MS is allocated the channel. Otherwise, the BS has not gained any information about which MS has the best channel and it allocates the channel to a randomly chosen MS instead. Specifically, the index of the MS is a uniformly distributed discrete random variable from 1 to N. After the BS has decided which MS will be allocated the channel, it then sends a channel allocation (CA) packet to that MS. The selected MS is called the *winning MS*, which will indexed by w.

Step 4. CSI Feedback

The winning MS, MS w, sends a channel state information feedback (CSIF) packet to the BS so that the exact CSI can be obtained by the BS.

Step 5. Data Packet Transmission

Based on the channel state estimate Γ_w, the most suitable data rate is selected by the BS and a data packet is transmitted from the BS to MS w.

Step 6. Data Packet Acknowledgement

Upon the successful reception of the data packet, MS w replies with an acknowledgement (ACK) packet.

In this thesis, the capture ratio model is used to model the effect of the simultaneous transmissions from the responding MSs in the channel competition step. According to this model, a signal is considered to be captured (i.e., decoded correctly by the receiver) when the ratio of the received signal power to the total interference power is greater than a nominal threshold factor, known as the *capture ratio*.

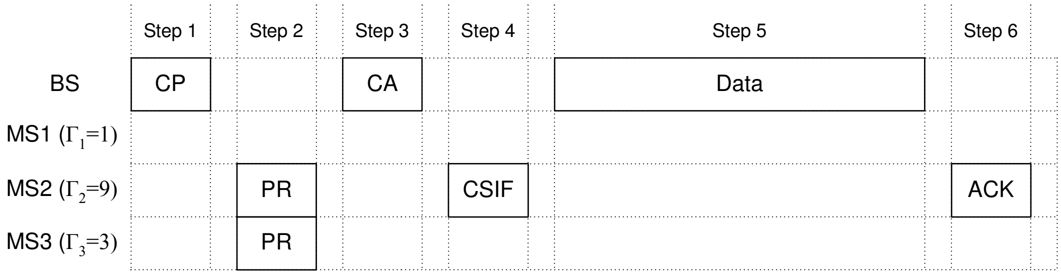

Figure 2.1: Example MDC transmission cycle for $\gamma = 2$ and $z = 2.5$.

In terms of MDC, let $n > 1$ be the number of responding MSs and let the indices of the responding MSs be $v_1, v_2, \ldots, v_n$. Without loss of generality, let v_1 be the index of the MS with the strongest signal. Then the PR packet from MS v_1 will be captured if and only if:

$$\Gamma_{v_1} > z \sum_{i=2}^{n} \Gamma_{v_i} \tag{2.1}$$

where z is the capture ratio. (2.1) will be referred to as the capture condition and it is assumed in the remainder of this thesis that $z \geq 1$.

It is further assumed that the PR packets do not explicitly carry CSI, since only the *identity* of the best MS is required to be extracted by the BS. Note that if CSI is explicitly carried in the PR packets, Steps 3 and 4 are not required when the best MS is captured by the BS at the channel competition step. However, when no MS is captured by the BS, Steps 3 and 4 are still needed. Furthermore, when CSI is explicitly carried, a good receiver is required to capture and decode the PR packet of the best MS to extract both its identity and its CSI. Nonetheless, the analysis in Chapter 3 can still be applied in this scenario, by proper redefinition of the rate adaptation function $g(x)$ for the cases where Steps 3 and 4 are used and not used.

Fig. 2.1 shows a simple example of the operation of MDC in a network consisting of three MSs. In the first step, the BS broadcasts a CP packet to all MSs. In the second step, MSs 2 and 3 will both reply with a PR packet and MS 1 will not reply since $\Gamma_1 < \gamma$. In the third step, the BS is able to capture the PR packet from MS 2 since $\Gamma_2 > z\Gamma_3$. In the fourth step, MS 2 sends a CSIF packet to the BS, which allows the BS to obtain the channel state of MS 2. In the fifth step, the BS selects a suitable data rate based on the channel state of MS 2 and transmits the data packet. Finally, in the sixth step, MS 2 transmits an ACK packet to indicate successful reception of the data packet.

For uplink data transmission, the operation of MDC is similar, but the CSIF packet is not needed. After MS w receives the CA packet in Step 3, it has an estimate of its own channel state Γ_w. Consequently, MS w can immediately select the most suitable data rate and transmit a data packet directly to the BS. In the final step of the uplink data transmission cycle, when the BS successfully receives the data packet, it replies to the winner MS w with an ACK packet. Since the CSIF packet is not needed in uplink data transmission, less overhead is required than in downlink data transmission and higher goodput is manifested. In this remainder of this thesis, the focus is on downlink data transmission only.

2.2 An MDC Application Example

2.2.1 Physical Layer and Medium Access Control Layer of IEEE 802.11a

The PHY of IEEE 802.11a [7] employs Orthogonal Frequency Division Multiplexing (OFDM) technology. There are 52 data subcarriers in each OFDM symbol. Adaptive coding and modulation with eight PHY modes is employed in IEEE 802.11a, which enables rate adaptation. Table 2.1 shows the modulation scheme, coding rate (CR), data rate and number of data bits per OFDM symbol (N_{DBPS}) for each IEEE

802.11a PHY mode.

Mode	Modulation	CR	Data Rate	N_{DBPS}
1	BPSK	1/2	6 Mbps	24
2	BPSK	3/4	9 Mbps	36
3	QPSK	1/2	12 Mbps	48
4	QPSK	3/4	18 Mbps	72
5	16-QAM	1/2	24 Mbps	96
6	16-QAM	3/4	36 Mbps	144
7	64-QAM	2/3	48 Mbps	192
8	64-QAM	3/4	54 Mbps	216

Table 2.1: IEEE 802.11a PHY Modes

The IEEE 802.11a PHY is composed of a Physical Medium Dependent (PMD) sublayer and a Physical Layer Convergence Procedure (PLCP) sublayer. The PLCP sublayer provides the interface of services to the medium access control (MAC) layer from the PMD through the service access point (SAP). Wireless stations communicate at the PHY level through PLCP protocol data unit (PPDU) frames. The transmission time of any packet is precisely the transmission time of a PPDU frame in an IEEE 802.11a system.

The PPDU frame format is shown in Fig. 2.2. It is composed of a training sequence of 10 short training symbols followed by 2 long training symbols. The duration of the training sequence is 16 μs. The training sequence is succeeded by the SIGNAL field, which fits exactly within a PHY mode 1 OFDM symbol. The remaining part of the PPDU frame, the DATA field, contains a SERVICE field, the MAC Protocol Data Unit (MPDU), tail bits and pad bits.

The number of data bits per OFDM symbol for each IEEE 802.11a PHY mode is shown in Table 2.2. An OFDM symbol duration is 4 μs. For a PHY mode m with $b(m)$ data bits per OFDM symbol (i.e., N_{DBPS} in Table 2.1), the transmission time

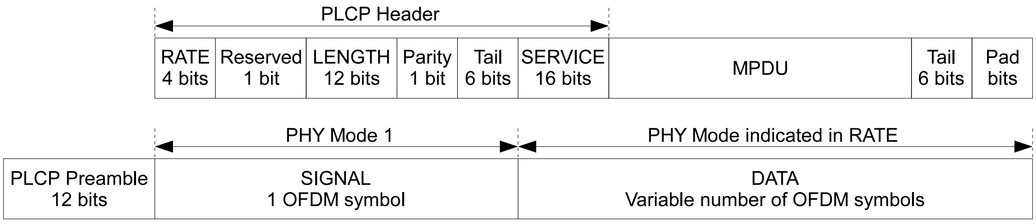

Figure 2.2: IEEE 802.11a PPDU frame format.

t in μs of an MPDU frame of size l octets is:

$$\begin{aligned} t(m,l) &= 16 + 4 + 4\left\lceil \frac{16 + 8l + 6}{b(m)} \right\rceil \\ &= 4\left\lceil \frac{8l + 22}{b(m)} + 5 \right\rceil \end{aligned} \tag{2.2}$$

where $\lceil\cdot\rceil$ is the ceiling function.

2.2.2 MDC as Applied in IEEE 802.11a

In this section, an application of MDC using the existing infrastructure from the IEEE 802.11a system is presented. The IEEE 802.11a system has been modified as little as possible in order to compare the proposed MDC with the MAD [17] scheme in the literature. As such, the transmission times of the control packets used for this application of MDC can be significantly reduced since the BS only needs to determine the identity of a transmitting MS. Fig. 2.3 shows the IEEE 802.11 [6] MAC frame formats (i.e., the MPDUs) used in MDC, which include Request to Send (RTS) frames, Clear to Send (CTS) frames, data frames and acknowledgement (ACK) frames. The RTS and CTS frames are short control frames used as part of the optional RTS/CTS mechanism in IEEE 802.11 for channel reservation in its CSMA/CA MAC protocol.

In MDC, the CP and CA packets are implemented as RTS frames, and the PR

Octets:	2	2	6	6	4
	Frame Control	Duration	Receiver Address	Transmitter Address	Frame Check Sequence

(a) RTS frame format

Octets:	2	6	6	4
	Frame Control	Duration	Receiver Address	Frame Check Sequence

(b) CTS frame format

Octets:	2	2	6	6	6	2	0-2304	2
	Frame Control	Duration/ID	Address 1	Address 2	Address 3	Sequence Control	MSDU	Frame Check Sequence

(c) Data frame format

Octets:	2	2	6	4
	Frame Control	Duration	Receiver Address	Frame Check Sequence

(d) ACK frame format

Figure 2.3: IEEE 802.11 MAC frame formats used in MDC.

and CSIF packets are implemented as CTS frames. The RTS and CTS frames from the IEEE 802.11 standard require some small modifications to accommodate the proposed MDC. For the CP packet, the pad bits in the PPDU frame can be used to carry command information. For the PR packet, the Receiver Address field in the CTS frame should be replaced with the Transmitter Address, so that the BS can distinguish which MS has the best channel. For the CSIF packet, the Receiver Address field in the CTS frame can be modified to carry CSI.

Following the IEEE 802.11 standard, RTS and CTS frames are always transmitted using PHY mode 1. Hence, using (2.2), their transmission times can be calculated to be $t_{\mathrm{RTS}} = 52\ \mu$s and $t_{\mathrm{CTS}} = 44\ \mu$s, respectively.

In the MDC system, PHY mode 2 is not used because the goodput analysis results in [29] have shown that the effective goodput using PHY mode 3 exceeds that of PHY mode 2 at all SNRs for both 200-byte and 2000-byte payloads. The mode thresholds for each PHY mode have been adjusted upwards by a 5 dB implementation margin from the theoretical mode thresholds in [29].

According to the IEEE 802.11a standard, all control frames must be transmitted at one of the rates in the mandatory rate set {6 Mbps, 12 Mbps, 24 Mbps}. In the

Data Mode	Payload (bytes)	t_{data} (μs)	ACK Mode	t_{ACK} (μs)	Mode Threshold (dB)
1	218	336	1	44	9
3	485	348	3	32	12
4	743	348	3	32	15
5	1013	352	4	28	18
6	1535	352	4	28	21
7	2057	352	4	28	26
8	2304	352	4	28	28

Table 2.2: MDC data transmission parameters

MDC system, an ACK packet is transmitted at the highest rate in the mandatory rate set that does not exceed the transmission rate of the associated data packet. Additionally, the largest possible payload of 2304 bytes [29] is transmitted using PHY mode 8, and the sum of the data packet transmission duration (t_{data}) and the ACK packet transmission duration (t_{ACK}) is made constant across all PHY modes. Table 2.2 shows the payload size, t_{data}, ACK PHY mode, t_{ACK} and mode threshold for each PHY mode in the MDC system.

Following each step in the MDC transmission cycle, the IEEE 802.11a Short Inter-Frame Space (SIFS), which is 16μs in duration, is used to provide the PHY and MAC the necessary time to respond to a received transmission. Hence, the resultant MDC transmission cycle duration t_{cycle} (in μs) is:

$$\begin{aligned} t_{\text{cycle}} &= 2t_{\text{RTS}} + 2t_{\text{CTS}} + t_{\text{data}} + t_{\text{ACK}} + 6 \times 16 \\ &= 668. \end{aligned} \tag{2.3}$$

Note that in Step 1 of MDC, the CP packet can carry control information to explicitly enforce that all MSs with a channel state greater than the response threshold to send PR packets after a delay of SIFS duration. As a result, MDC is different from the CSMS/CA mechanism used in IEEE 802.11 systems. On the other hand, at the end of each transmission cycle, the BS may opt to release the channel by not sending the CP packet. In this manner, conventional CSMA/CA can be still applied in the proposed application example.

2.2.3 Channel Model

The fluctuations in the channel quality across the WLAN are modelled by path loss, shadowing and multipath fading [30–32]. The Γ_is are assumed to be independent and identically distributed (i.i.d.) random variables and the Γ_is of different transmission cycles are assumed to be statistically independent.

The instantaneous SNR Γ of a transmitted radio signal is given by

$$\Gamma = \frac{P_T K_L K_S K_F}{P_N} \tag{2.4}$$

where P_T is the constant network-wide transmission power, K_L is the scalar factor that represents path loss, K_S is the scalar factor that represents shadowing, K_F is the scalar factor that represents multipath fading and P_N is the noise power.

The path loss scalar factor K_L is modelled according to the following:

$$K_L(d) = K_L(d_0)\left(\frac{d}{d_0}\right)^{-\eta} \quad d \geq d_0 \tag{2.5}$$

where d is the transmitter-receiver separation distance, η is the path loss exponent and d_0 is the close-in reference distance. The scalar factor $K_L(d_0)$ in (2.5) is determined from the free space path loss model:

$$K_L(d_0) = \frac{G_T G_R \lambda^2}{(4\pi d_0)^2} \tag{2.6}$$

where G_T is the transmitter antenna gain, G_R is the receiver antenna gain and λ is the wavelength of the carrier. It is assumed that the network covers a circular cell with the BS at its centre and MSs are uniformly distributed over a punctured disk with inner radius d_0 and outer radius R. Hence, the probability density function (pdf) of the distance d between the BS and each MS is

$$f_d(x) = \frac{2x}{R^2 - {d_0}^2}, \quad d_0 \leq x \leq R. \tag{2.7}$$

The shadowing scalar factor K_S is modelled by a log-normal random variable with mean of 0 dB and a standard deviation of σ_s dB. Thus, the pdf of K_S is

$$f_{K_S}(x) = \frac{1}{\sigma x \sqrt{2\pi}} e^{-((\ln x)/\sigma)^2}, \quad x > 0 \tag{2.8}$$

where $\sigma = 0.1\sigma_s \ln 10$.

Multipath fading is modeled by the Rayleigh fading model and the pdf of the fading scalar factor K_F is given by (3.18) with $\mu = 1$. The source of the wireless channel noise is assumed to be thermal noise and the noise power P_N is modelled by

$$P_N = kTB \times 10^{0.1NF} \tag{2.9}$$

where k is the Boltzmann constant, T is the equivalent noise temperature of the wireless environment, B is the bandwidth of the channel and NF is the noise figure of the wireless system.

2.3 Simulation Results

In this section, the simulation results using the system described in Section 2.2 are presented. Table 2.3 shows the values of the parameters for the wireless channel model used in the simulations. The predicted SNR at the outer radius R due to path loss was chosen to be equal to the mode threshold for PHY mode 3. That is,

$$10\log_{10}\left(\frac{P_T K_L(R)}{P_N}\right) = 12 \text{ dB}. \tag{2.10}$$

Following [33], a standard deviation of 3.8 dB is used as the shadowing factor K_S for the IEEE 802.11a PHY at a carrier frequency of 5.2 GHz in residential environments. The other values in Table 2.3 are consistent with those employed in [34].

Parameter	**Value**
P_T	10 dBm
d_0	1 m
G_R	0 dBi
G_T	0 dBi
λ	0.0577 m
η	3
R	25.5 m
σ_s	3.8 dB
T	290 K
B	20 MHz
NF	10 dB

Table 2.3: Values of Wireless Channel Model Parameters

Fig. 2.4 shows the effect of the value of γ on the goodput performance of MDC for a network with 8 MSs, based the channel model parameters in Table 2.3. It can be seen from Fig. 2.4 that the optimisation of γ is important in MDC, as the goodput for MDC is adversely affected by a poor choice of γ.

However, it can also be seen from Fig. 2.4 that the goodput is not sensitive to

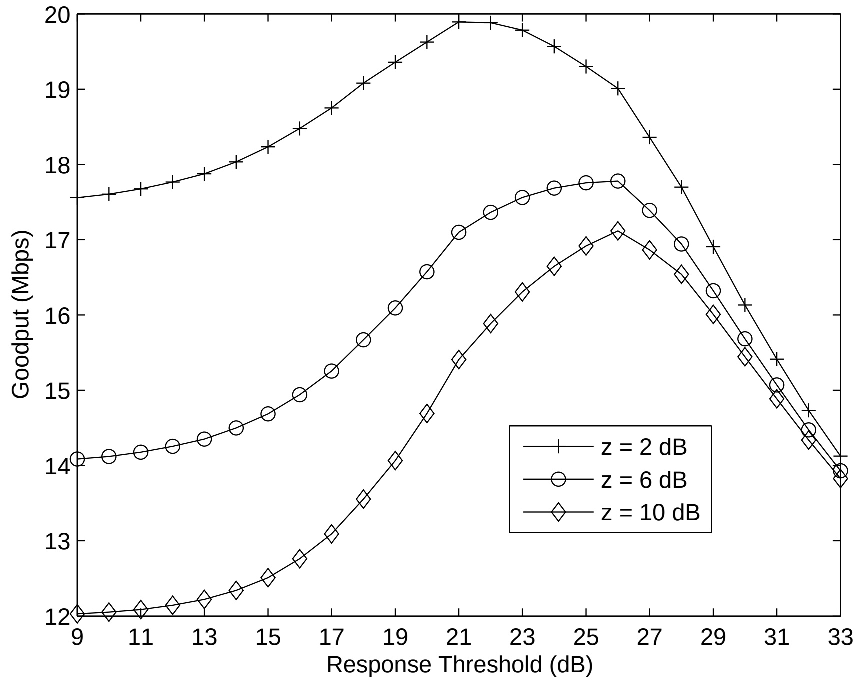

Figure 2.4: MDC goodput performance versus γ in a network with 8 MSs

the value of γ when γ is near the optimal value. For example, at $z = 10$ dB, the optimal value of γ is 26 dB, with a goodput of 17.1 Mbps. However, for $\gamma = 24$ dB, the goodput is 16.7 Mbps and for $\gamma = 28$ dB, the goodput is 16.5 Mbps, which is only a 3% decrease.

Table 2.4 shows the optimal values of γ that maximise the goodput for MDC for the wireless channel described in Table 2.3 over various values of N and z, obtained through extensive simulations. From Table 2.4, it can be seen that the optimal value of γ is a non-decreasing function of N and z.

To understand relationship between the optimal value of γ and N and z, consider the effect of γ on the operation of MDC. The response threshold γ serves to limit the number of interfering MSs in the channel competition step, where "interference" refers to PR packets sent by the MSs that do not have the best channel. This thresholding concept, used to limit the amount of feedback overhead in SMUD [16],

N	$z = 2$ dB	$z = 6$ dB	$z = 10$ dB
2	9 dB	12 dB	15 dB
3	15 dB	18 dB	21 dB
4	17 dB	21 dB	21 dB
5	18 dB	21 dB	22 dB
6	21 dB	21 dB	24 dB
7	21 dB	24 dB	26 dB
8	21 dB	26 dB	26 dB
9	22 dB	26 dB	26 dB
10	23 dB	26 dB	26 dB
11	24 dB	26 dB	27 dB
12	26 dB	27 dB	28 dB
13	26 dB	27 dB	28 dB
14	26 dB	28 dB	28 dB
15	26 dB	28 dB	28 dB
16	26 dB	28 dB	29 dB

Table 2.4: Optimal response thresholds γ for MDC based on the wireless channel in Table 2.3

is based on the assumption that only users with good channels have reasonable chances of having the best channel in any particular transmission cycle. If γ is too small, then too many MSs compete and the BS captures the best signal less often. If γ is too large, then a significant proportion of the time, none of the MSs will have a reasonable chance to compete for the channel. When γ is chosen judiciously, the amount of interference from bad channels is restricted while the MSs with good channels compete for the channel (in an averaged probabilistic sense).

The multiuser diversity gain in MDC arises from the times when the BS is able to determine which MS has the best channel. Consider the effect of increasing N and z while holding γ constant in MDC. If N increases while γ is kept constant, more MSs are likely to interfere during the channel competition step. Therefore, the BS will capture the MS with the best channel less often and system goodput decreases. Similarly, if z increases while γ is kept constant, the capture condition is satisfied less often and system goodput again decreases. As a result, the optimal value of γ

is a non-decreasing function of both N and z, since the rate adaptation function is non-decreasing. If it were possible with rate adaptation to transmit at the Shannon capacity instead of a discrete rate set, then γ would be a strictly increasing function of both N and z.

Fig. 2.5 shows the expected goodput performance for MDC using the optimal response thresholds from Table 2.4. The solid curve shows the expected goodput performance for MAD when all of the MSs in the network are queried. The dashed line shows the expected goodput for MAD when the optimal number of MSs are queried ($N = 4$). In simulating the MAD scheme, the CTS and ACK packet formats described in the IEEE 802.11 standard have been used rather than the modified versions described in [17], since the channel model that has been used in this thesis assumes channel reciprocity and packet concatenation has not been used. The modified CTS packet in [17] contains an extra field that carries CSI and the modified ACK packet contains an extra field that enables acknowledgement of multiple packets within a superframe. Unlike MDC, a broadcast packet is insufficient for the channel probing step in MAD because the MSs must know in which order the reply messages are to be sent. Therefore, the format of the Group Request to Send (GRTS) frame in [17] for MAD has been maintained in the simulations. As in MDC, the total duration for data transmission and acknowledgement is maintained constant for MAD, based on the data transmission parameters from Table 2.2. The SIFS is also used between each MAD packet transmission. Thus, the cycle time for MAD is $(68N + 472)$ μs.

From Fig. 2.5, it can be seen that by employing the capture effect, MDC enjoys reduced overhead while exploiting multiuser diversity. Since the overhead in MDC is constant and independent of N, the expected goodput for MDC increases with N in Fig. 2.5. On the other hand, the overhead for MAD outweighs the multiuser

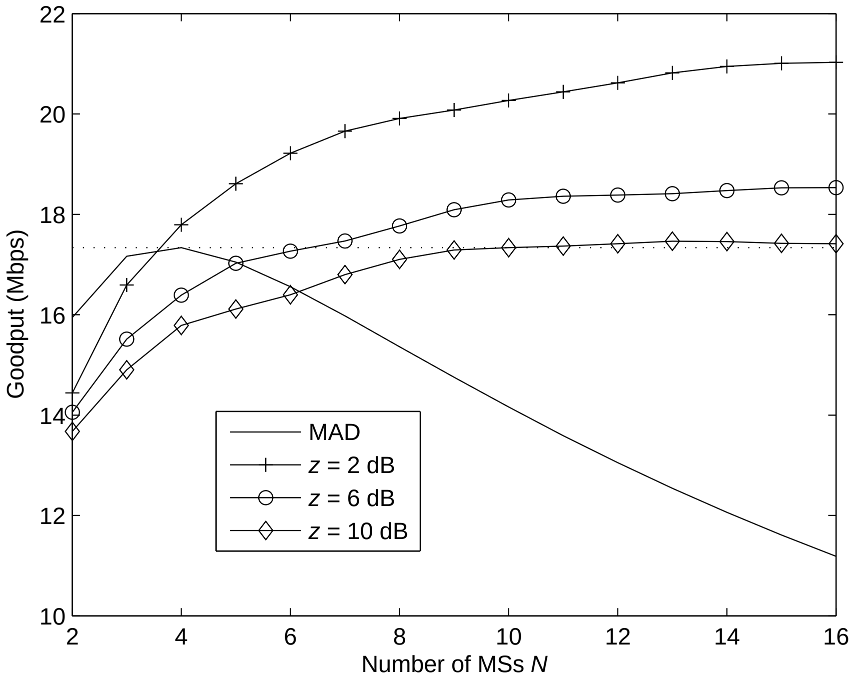

Figure 2.5: MAD goodput performance and MDC goodput performance with optimal response thresholds

diversity gain as the N increases and more MSs are queried.

The expected MDC goodput curves for $z = 2$ dB and $z = 6$ dB show an appreciable performance improvement over the optimal MAD goodput. Even for $z = 10$ dB, if N is large enough, the expected goodput for MDC is higher than the goodput when the optimal number of MSs are queried. It is also noteworthy that the expected goodput for MDC becomes less sensitive to z as z increases. As a result, the $z = 10$ dB curve approximately represents the worst case goodput performance of MDC even as z increases towards very high values.

Chapter 3

Goodput Performance Analysis of MDC

In this chapter, the goodput performance of the MDC scheme is analysed in detail and the various factors which affect the goodput performance of MDC are closely examined. In the following discourse, the expected goodput of the MDC system is derived under very general conditions, after which Rayleigh fading channels are given special attention. For Rayleigh fading channels, it transpires that the expected goodput of MDC has a closed form expression. The relationship between the expected goodput and the probability of capture is then discussed, followed by a discussion of numerical results. In the following analysis, it is assumed that the channel states of the MSs in the networks (i.e., the Γ_is) are i.i.d. random variables.

3.1 Goodput Analysis of MDC over General Channels

Let the random variable G represent the goodput of the MDC system and let $g(x)$ be the amount of payload transmitted per unit time in a transmission cycle for the winning MS with channel state x. $g(x)$ will be referred to as the rate adaptation function. The amount of payload transmitted per unit time in any given transmission cycle is a realisation of G, hence the goodput of the MDC system is given by

$$G = g(\Gamma_w), \tag{3.1}$$

where the random variable Γ_w is the channel state of the winning MS. Using the continuous form of the law of total expectation [35], the expected goodput of the MDC system is given by

$$E(G) = \int_0^\infty g(x)\, dP(\Gamma_w \le x). \tag{3.2}$$

Let R_n denote the event that n of the MSs in the network compete for the channel by responding to the BS with a PR packet. Applying the law of total probability,

$$P(\Gamma_w \le x) = \sum_{n=0}^{N} P(\Gamma_w \le x | R_n) P(R_n). \tag{3.3}$$

Let C denote the event that the BS is able to capture the MS with the best channel during the channel competition step. With a second application of the law of total probability, it follows that for $n \ge 2$,

$$P(\Gamma_w \le x \mid R_n) = P(\Gamma_w \le x | C \cap R_n) P(C|R_n) + P(\Gamma_w \le x | \bar{C} \cap R_n) P(\bar{C}|R_n) \tag{3.4}$$

where the bar notation $\bar{C}$ has been used to denote the set complement of C.

In order to derive expressions for $P(R_n)$, $P(C|R_n)$, $P(\bar{C}|R_n)$, $P(\Gamma_w \leq x|R_0)$, $P(\Gamma_w \leq x|R_1)$, $P(\Gamma_w \leq x|C \cap R_n)$ and $P(\Gamma_w \leq x|\bar{C} \cap R_n)$, the following definitions have been made. For each MS, Γ_i is distributed with pdf $f_\Gamma(\cdot)$ and cumulative distribution function (cdf) $F_\Gamma(\cdot)$.

For the channel competition step, let the indices of the MSs that do not send a PR packet to the BS be $u_1, u_2, \ldots, u_{N-n}$ and note that the indices of the MSs that do send PR packets to the BS are $v_1, v_2, \ldots, v_n$. Since the Γ_is are i.i.d., it follows that the Γ_{u_j}s are i.i.d. and that the Γ_{v_k}s are also i.i.d.. Denote the pdfs of Γ_{u_j} and Γ_{v_k} by $f_U(\cdot)$ and $f_V(\cdot)$, and their cdfs by $F_U(\cdot)$ and $F_V(\cdot)$, respectively. It is easily shown that

$$f_U(x) = \frac{f_\Gamma(x)}{F_\Gamma(\gamma)}, \quad 0 \leq x < \gamma, \tag{3.5}$$

$$F_U(x) = \frac{F_\Gamma(x)}{F_\Gamma(\gamma)}, \quad 0 \leq x < \gamma, \tag{3.6}$$

$$f_V(x) = \frac{f_\Gamma(x)}{1 - F_\Gamma(\gamma)}, \quad x \geq \gamma, \tag{3.7}$$

$$F_V(x) = \frac{F_\Gamma(x) - F_\Gamma(\gamma)}{1 - F_\Gamma(\gamma)}, \quad x \geq \gamma. \tag{3.8}$$

Further, let the pdf and cdf of the sum of n independent random variables with pdf $f_V(\cdot)$ be $f_{V,n}(\cdot)$ and $F_{V,n}(\cdot)$, respectively. It follows from probability theory that $f_{V,n}(\cdot)$ is the n-fold convolution of $f_V(\cdot)$ [35]. Note that by definition, $f_{V,0}(x) = \delta(x)$, where $\delta(\cdot)$ is the Dirac delta function and $f_{V,1}(x) = f_V(x)$.

As demonstrated in the Appendix,

$$P(R_n) = \binom{N}{n}(1 - F_\Gamma(\gamma))^n F_\Gamma(\gamma)^{N-n}, \tag{3.9}$$

$$P(C|R_n) = n\int_{(n-1)\gamma}^{\infty} (1 - F_V(zx)) f_{V,n-1}(x)\, dx, \quad n \geq 2, \tag{3.10}$$

$$P(\bar{C}|R_n) = 1 - P(C|R_n), \quad n \geq 2, \tag{3.11}$$

$$P(\Gamma_w \leq x|R_0) = f_U(x), \tag{3.12}$$

$$P(\Gamma_w \leq x|R_1) = f_V(x), \tag{3.13}$$

$$P(\Gamma_w \leq x|C \cap R_n) = \frac{n\alpha_n(x)}{P(C \mid R_n)}, \quad n \geq 2, \tag{3.14}$$

where

$$\alpha_n(x) = \int_{z(n-1)\gamma}^{x} F_{V,n-1}\left(\frac{y}{z}\right) f_V(y)\, dy \tag{3.15}$$

and

$$P(\Gamma_w \leq x|\bar{C} \cap R_n) = \frac{N-n}{N} F_U(x) + \frac{n(F_V(x) - \alpha_n(x) - (n-1)\beta_n(x))}{NP(\bar{C} \mid R_n)}, \quad n \geq 2 \tag{3.16}$$

where

$$\beta_n(x) = \int_{\gamma}^{x}\int_{(n-2)\gamma}^{\infty} f_V(u)(1 - F_V(z(u+y))) f_{V,n-2}(y)\, dy\, du. \tag{3.17}$$

From (3.2)-(3.4) and (3.9)-(3.16), it can be seen that the expected goodput for MDC is completely described by:

- the number of MSs in the network, N;
- the capture ratio, z;
- the response threshold, γ;
- the pdf of the SNR of a received signal, $f_\Gamma(\cdot)$, which is determined by the wireless channel and the transmit power P_T; and
- the rate adaptation function, represented by $g(\cdot)$

In general, $E[G]$ is not closed form because it is usually not possible to derive a closed form expression for $f_{V,n}(\cdot)$. In the next section, the Rayleigh fading channel is analysed, which possesses the nice property that $f_{V,n}(\cdot)$ has a closed form expression.

3.2 Goodput Analysis of MDC over Rayleigh Fading Channels

For Rayleigh fading channels, the received signal amplitudes at the BS are Rayleigh distributed, thus Γ_i is exponentially distributed for all i. Hence,

$$f_\Gamma(x) = \mu e^{-\mu x}, \quad x > 0 \tag{3.18}$$

and

$$F_\Gamma(x) = 1 - e^{-\mu x}, \quad x > 0 \tag{3.19}$$

where μ is a constant that is inversely proportional to the transmit power P_T.

The physical layer (PHY) is assumed to be capable of rate adaptation and selects the highest feasible data rate given the channel state of the winning MS. Specifically,

$$g(x) = \begin{cases} 0, & x < m_1 \\ g_i, & m_i \leq x < m_{i+1}, \forall i < M \\ g_M, & x \geq m_M \end{cases} \tag{3.20}$$

where for $1 \leq i \leq M$, g_i is the amount of payload transmitted per unit time over the transmission cycle for PHY mode i, M is the number of PHY modes and m_i is the minimum SNR required to transmit at PHY mode i. We will refer to m_i as the *mode threshold* for PHY mode i.

Define $m_0 = -\infty$, $m_{M+1} = \infty$ and the function

$$\zeta(x) = \underset{1 \le i \le M}{\text{argmax}}\{m_i \mid m_i \le x\}. \tag{3.21}$$

Then, since (3.20) represents a step function, it follows that

$$\begin{aligned}\int_a^b g(x) dP(\Gamma_w \le x) = g_{\zeta(a)} \left(P(\Gamma_w \le m_{\zeta(a)+1}) - P(\Gamma_w \le a) \right) \\ + g_{\zeta(b)} \left(P(\Gamma_w \le b) - P(\Gamma_w \le m_{\zeta(b)}) \right) \\ + \sum_{i=\zeta(a)+1}^{\zeta(b)-1} g_i \left(P(\Gamma_w \le m_{i+1}) - P(\Gamma_w \le m_i) \right). \end{aligned} \tag{3.22}$$

By substituting (3.19) into (3.9), it can be shown that

$$P(R_n) = \binom{N}{n} e^{-n\mu\gamma} (1 - e^{-\mu\gamma})^{N-n}. \tag{3.23}$$

To find the expressions for $P(C|R_n)$, $P(\Gamma_w \le x|C \cap R_n)$ and $P(\Gamma_w \le x|\bar{C} \cap R_n)$, the computation of $f_{V,n}(\cdot)$ is required. Using (3.18) and (3.7), it can be shown by induction that

$$f_{V,n}(x) = \frac{(\mu(x - n\gamma))^{n-1}}{(n-1)!} \mu e^{-\mu(x-n\gamma)}, \quad x \ge n\gamma. \tag{3.24}$$

By putting (3.19), (3.8) and (3.24) into (3.10), it can be shown after some algebraic manipulations that for $n \ge 2$,

$$P(C|R_n) = \frac{n e^{-\mu\gamma(z(n-1)-1)}}{(z+1)^{n-1}}. \tag{3.25}$$

To compute $P(\Gamma_w \le x|C \cap R_n)$ and $P(\Gamma_w \le x|\bar{C} \cap R_n)$ for $n \ge 2$, it suffices to compute $\alpha_n(x)$ and $\beta_n(x)$. After some lengthy algebraic manipulations, it can be demonstrated that

$$\alpha_n(x) = \sum_{k=0}^{n-2}\sum_{j=0}^{k} \frac{(\mu(x - z(n-1)\gamma))^j}{(z+1)^{k-j+1} z^{j-1} j!} e^{-\mu\left(\left(1+\frac{1}{z}\right)x - n\gamma\right)} + \frac{e^{-\mu\gamma(z(n-1)-1)}}{(z+1)^{n-1}} - e^{\mu(x-\gamma)} \tag{3.26}$$

and

$$\beta_n(x) = \frac{e^{-\mu\gamma(z(n-1)-1)}}{(z+1)^{n-1}}(1 - e^{-\mu(z+1)(x-\gamma)}). \tag{3.27}$$

From (3.23)-(3.27), it can be seen that an exact closed-form expression for the goodput of the MDC system over Rayleigh fading channels has been obtained.

3.3 Probability of Capture

Define the probability of capture $P(C)$ to be probability that the BS is able to determine the MS with the best signal during the channel competition step:

$$P(C) = P(R_1) + \sum_{n=2}^{N} P(C|R_n)P(R_n). \tag{3.28}$$

Recall the assertion from Section 2.3 that the multiuser diversity gain in MDC stems from the BS's ability to determine which MS has the best channel. In other words, the optimal value of γ should be approximately equal to the value of γ that optimises $P(C)$. Applying (3.28), this assertion can be supported by the following argument. The expected goodput of the MDC system can be expressed in an alternative form:

$$\begin{aligned} E[G] &= P(C)E[G|C] + (1 - P(C))E[G|\bar{C}] \\ &= P(C)\left(E[G|C] - E[G|\bar{C}]\right) + E[G|\bar{C}] \end{aligned} \tag{3.29}$$

where

$$E[G|C] = \int_0^\infty g(x)\, dP(\Gamma_w \leq x|C) \tag{3.30}$$

and

$$E[G|\bar{C}] = \int_0^\infty g(x)\, dP(\Gamma_w \leq x|\bar{C}). \tag{3.31}$$

Since the BS allocates the channel to a randomly chosen MS when it cannot determine which MS has the best channel, it follows that

$$P(\Gamma_w \leq x|\bar{C}) \approx F_\Gamma(x). \tag{3.32}$$

Thus, $E[G|\bar{C}]$ is approximately constant for all values of γ, and it can be seen from (3.29) that $E[G]$ is maximised when $P(C)E[G|C]$ is maximised. As a result, under the conjecture that $P(C)$ fluctuates faster with respect to γ than $E[G|C]$, the value of γ that maximises $P(C)$ should be very close to optimal value of γ.

For Rayleigh fading channels, by substituting (3.10) and (3.25) into (3.28), it can be shown that

$$P(C) = N\left(\left(\frac{e^{-\mu\gamma(z+1)}}{z+1} + 1 - e^{-\mu\gamma}\right)^{N-1} - \left(1 - e^{-\mu\gamma}\right)^N\right). \tag{3.33}$$

Note that in (3.33), $P(C)$ is a function of $\mu\gamma$, z and N. Consequently, there is an optimal value of $\mu\gamma$ that maximises $P(C)$ for given values of N and z. Therefore, if N and z are kept constant, it can be found that every 1 dB of increase in the average SNR (i.e., $1/\mu$) corresponds to 1 dB of increase in the response threshold that maximises $P(C)$.

Using (3.33), the value of γ that maximises $P(C)$ can be computed exactly for Rayleigh fading channels. In particular, since it is possible to calculate the first and second derivatives of $P(C)$ with respect to γ, Newton's method may be used to maximise $P(C)$ with respect to γ. Table 3.1 shows the response thresholds which maximise $P(C)$ over Rayleigh fading channels with $\mu = 0.02$ (i.e., an average SNR of 16.99 dB).

N	$z = 2$ dB		$z = 6$ dB		$z = 10$ dB	
	γ (dB)	$P(C)$	γ (dB)	$P(C)$	γ (dB)	$P(C)$
2	0.00	0.774	14.83	0.516	15.39	0.500
3	15.43	0.581	17.30	0.448	17.39	0.444
4	17.31	0.520	18.37	0.423	18.41	0.422
5	18.28	0.489	19.04	0.410	19.06	0.410
6	18.92	0.469	19.51	0.402	19.52	0.402
7	19.39	0.456	19.88	0.397	19.88	0.397
8	19.75	0.446	20.17	0.393	20.17	0.393
9	20.04	0.438	20.41	0.390	20.41	0.390
10	20.28	0.432	20.61	0.387	20.61	0.387
11	20.49	0.428	20.79	0.386	20.79	0.386
12	20.67	0.423	20.94	0.384	20.94	0.384
13	20.83	0.420	21.08	0.383	21.08	0.383
14	20.97	0.417	21.20	0.382	21.20	0.382
15	21.10	0.414	21.32	0.381	21.32	0.381
16	21.22	0.412	21.42	0.380	21.42	0.380

Table 3.1: Response thresholds to maximise $P(C)$ over Rayleigh fading channels with $\mu = 0.02$.

It can be seen from Table 3.1 that the response threshold that maximises $P(C)$ over Rayleigh fading channels is a non-decreasing function of both N and z. This relationship is similar to the one observed between the optimal value of γ and N and z over the general WLAN channel in Table 2.3 in Section 2.3. The justification for the observed trend is the same as before: to optimise MDC performance, γ must increase as either N or z increases in order to limit the amount of interference in the channel competition step, so that the BS can capture the PR packet from the MS with the best channel sufficiently often.

3.4 Numerical Results for MDC over Rayleigh Fading Channels

In this section, the relationship between the expected goodput for MDC over Rayleigh fading channels and the system parameters N, z and γ is studied. For the numerical results in this section, the average SNR is 17 dB (i.e., $\mu = 0.02$). The rate adaptation policy follows the IEEE 802.11a system applied in MDC described in Section 2.2 and is summarised in Table 3.2.

PHY	m_i	g_i
1	$10^{0.9}$	$\frac{436}{167}$
3	$10^{1.2}$	$\frac{970}{167}$
4	$10^{1.5}$	$\frac{1486}{167}$
5	$10^{1.8}$	$\frac{2026}{167}$
6	$10^{2.1}$	$\frac{3070}{167}$
7	$10^{2.6}$	$\frac{4114}{167}$
8	$10^{2.8}$	$\frac{4608}{167}$

Table 3.2: The MDC rate adaptation policy in the applied IEEE 802.11a system: mode thresholds and goodput values for each PHY mode.

Fig. 3.1 shows the numerical results for the expected goodput for MDC and MAD over a Rayleigh fading channel. In the goodput analysis for MAD, Γ_w is the largest order statistic of the Γ_is, while (3.2) still applies. Therefore, the expected goodput for MAD is given by

$$E(G_{\text{MAD}}) = \int_0^\infty g(x)\, dP(\Gamma_{w,\text{MAD}} \leq x). \tag{3.34}$$

where

$$P(\Gamma_{w,\mathrm{MAD}} \leq x) = P\left(\max_i(\Gamma_i) \leq x\right) \tag{3.35}$$

$$= F_\Gamma(x)^N \tag{3.36}$$

In Fig 3.1, γ has been numerically optimised so that the goodput is maximised for each value of N and z. As can be seen from Fig. 3.1, the numerical results match the simulation results.

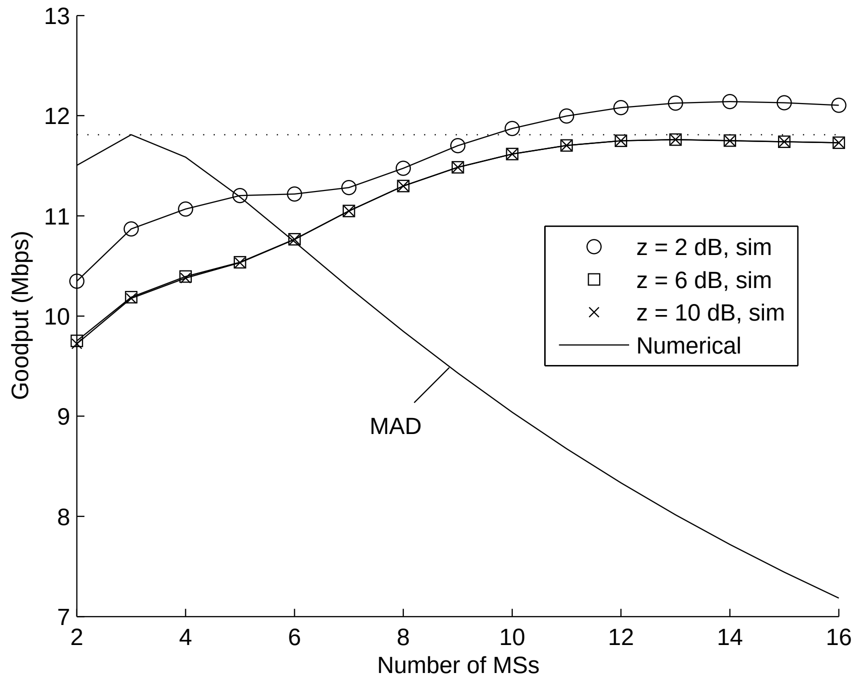

Figure 3.1: Expected goodput for MDC over Rayleigh fading channels at an average SNR of 17 dB.

It is apparent from Fig. 3.1 that the results observed for Rayleigh fading channels are similar to the results observed for the general WLAN channel observed in Section 2.3. When the number of MSs is reasonably large, the goodput performance of MDC over Rayleigh fading channels, even for z = 10 dB, is comparable to the goodput performance of MAD when the optimal number of MSs are queried. It can also be seen that the expected goodput for MDC becomes less sensitive to z as z increases. In particular, there appears to be no difference in goodput performance between $z = 6$ dB and $z = 10$ dB in Fig. 3.1. Hence the goodput curve for $z = 10$ dB can be considered to approximately represent the lower bound on the goodput performance of MDC.

Table 3.3 shows the optimal values of γ to the nearest 0.01 dB, used for plotting Fig. 3.1. Except for optimal value of γ at $N = 2$ and $z = 2$ dB, these entries are quite close to the values in Table 3.1, whose entries are the values of γ that optimise $P(C)$.

N	$z = 2$ dB	$z = 6$ dB	$z = 10$ dB
2	9.00 dB	15.00 dB	15.00 dB
3	15.00 dB	18.00 dB	18.00 dB
4	18.00 dB	18.20 dB	18.30 dB
5	18.00 dB	19.51 dB	19.53 dB
6	18.84 dB	20.41 dB	20.42 dB
7	19.86 dB	21.00 dB	21.00 dB
8	20.97 dB	21.00 dB	21.00 dB
9	21.00 dB	21.00 dB	21.00 dB
10	21.00 dB	21.00 dB	21.00 dB
11	21.00 dB	21.00 dB	21.00 dB
12	21.00 dB	21.00 dB	21.00 dB
13	21.00 dB	21.08 dB	21.08 dB
14	21.00 dB	21.21 dB	21.21 dB
15	21.11 dB	21.32 dB	21.32 dB
16	21.22 dB	21.42 dB	21.42 dB

Table 3.3: Optimal values of γ for MDC over Rayleigh fading channels with $\mu = 0.02$.

The small differences between the entries in these two tables can be attributed to the rate adaptation policy. In Table 3.3, there are a significant number of entries whose values correspond exactly to the mode threshold of some PHY mode. The reason for this phenomenon is that when the value of γ that maximises $P(C)$ is slightly below the mode threshold for some PHY mode, the goodput gained from increasing the probability that the BS will capture an MS capable of transmitting at that PHY mode outweighs the goodput lost from the BS being unable to capture the MS with the best channel.

Chapter 4

Fairer Multiuser Diversity with Capture

In this chapter, the Fairer Multiuser Diversity with Capture (FMDC) scheme is presented. FMDC is a variant of MDC that addresses the issue of the poor fairness performance of MDC in networks where some MSs experience better average channel conditions than others. In such networks, system unfairness emerges in MDC because of the operation of the channel competition step. During the channel competition step, each MS with a channel state exceeding the response threshold competes for use of the channel. Consequently, the MSs with high average channel states typically respond during the channel competition step with high probabilities in MDC. MDC clearly exhibits unfairness in this scenario, since MSs with high average channels states use the channel more often than MSs with low average channel states.

4.1 FMDC Operation

The fairness performance of MDC can be improved by requiring that each MS has its own individual response threshold. However, solving the optimisation problem of finding the individual response thresholds that enable perfect fairness while maximising the expected goodput is a difficult non-linear programming problem for general wireless channels. Instead, a simpler solution is to use an individual response threshold for each MS that is an increasing function of its average channel state. In FMDC, during the channel competition step, MS i competes for the use of the channel if and only if

$$\Gamma_i > \kappa A_i \tag{4.1}$$

where A_i denotes the average SNR of MS i and the system parameter κ is called the *threshold factor*.

Accordingly, for downlink data transmission in FMDC, all of the steps in the transmission cycle are the same as for MDC except for channel competition step:

Step 2. Channel Competition

Each MS uses the CP packet to estimate its channel state. For MS i, if the SNR $\Gamma_i > \kappa A_i$, then MS i responds to the BS with a probe response (PR) packet.

In FMDC, the global response threshold γ used in MDC has been replaced with a threshold factor κ, so that MS i uses a response threshold that is directly proportional to its average SNR A_i. Thus, the relative frequency at which the MS with the largest A_i competes in the channel competition step is reduced, providing the other MSs greater chances of being captured by the BS. As a result, users with lower average channel states obtain a more appropriate share of the channel in FMDC than in MDC.

The FMDC scheme described above possesses particular properties that deliver insight into its relationship with MDC and how it exploits multiuser diversity while maintaining a high degree of fairness. An important relationship between FMDC and MDC manifests in networks where every MS has the same average channel state (i.e., $A_i = A$ for $1 \leq i \leq N$). In this special case, FMDC and MDC are equivalent, because each MS in the system uses the same response threshold. In particular, when $\gamma = \kappa A$ for this scenario, FMDC and MDC operate in exactly the same manner.

In the general case, however, not every MS has the same average channel state. Consequently, the two schemes behave differently and their goodput and fairness performances are different. In MDC, the MSs with higher average channel states compete for the channel and use the channel more often than MSs with lower average channel states. FMDC tends to allow MSs with lower average channel states to compete for the channel and use the channel more often than MDC will. As a result, MDC manifests better goodput performance than FMDC.

In FMDC, each MS is equally likely to compete in the channel competition step over Rayleigh fading channels. This fact arises because Γ_i is exponentially distributed for Rayleigh fading channels, which implies that

$$\begin{aligned} P(\Gamma_i > \kappa A_i) &= e^{-\frac{\kappa A_i}{A_i}} \\ &= e^{-\kappa}. \end{aligned} \tag{4.2}$$

It follows that for Rayleigh fading channels, any unfairness in FMDC can be isolated as being a consequence of the channel allocation step, where the BS tries to capture the MS with the best channel. Thus, the study of Rayleigh fading channels is very important for assessing the fairness performance of FMDC, and it is studied later in Section 4.3.

4.2 Gain Fairness

Fairness is an important performance consideration in the design of medium access control (MAC) protocols. A MAC protocol is considered to be fair if it does not manifest preference to any particular user when multiple users attempt to access the channel. Fairness has been studied extensively in wired networks, which has led to max-min fairness and proportional fairness as being the predominant notions of fairness in the literature.

Traditionally, max-min fairness has been the model for perfect fairness [36]. A rate allocation is max-min fair if increasing the data rate for one MS necessitates decreasing the data rate for another MS that has a smaller data rate. Consequently, the MS that requests the lowest data rate receives the lesser of the rate it requested and its fair share of the total channel capacity. The MS that requests the next lowest data rate receives the lesser of the rate it requested and its fair share of the remaining channel capacity, and so on. In the wireless network context, where one considers the long term data rate of each MS, the max-min fair allocation manipulates the channel occupancy time of each MS so that all of the MSs have equal data rates.

Proportional fairness is a compromise between maximising throughput and achieving max-min fairness. If the utility of MS i being allocated the data rate x_i is $\log x_i$, then the allocation of data rates for the system is proportionally fair if and only if it maximises the aggregate utility $\sum_i \log x_i$ [37]. This fairness notion led to the design of proportional fair scheduling (PFS) techniques, used in the CDMA2000 1xEVDO [38] and High Speed Downlink Packet Access (HSDPA) [39] systems, by selecting the MS with the highest ratio of its instantaneous throughput to its average throughput for transmission. The maximum relative gain scheduling ideas discussed in MAD is also a form of PFS. However, based on the definition of proportional fairness, it is not apparent how a wireless system's deviation from proportional fairness can be measured.

In time-based fairness, also known as temporal fairness, each user receives an equal time share of the channel occupancy time. It has been demonstrated in the literature that proportional fairness implies time-based fairness [40]. However, time-based fairness does not accurately reflect how evenly multiuser diversity is exploited across all users in the network. A wireless system where all users receive an equal time share of the channel could potentially exploit better than average channel conditions for some users more than others.

In this thesis, a different fairness concept, called *gain fairness*, is used to evaluate the fairness performance of multiuser diversity systems. A multiuser diversity system is fair in the sense of gain fairness if every MS experiences the same proportional increase in goodput when compared to a corresponding round robin system. Let x_i be the expected goodput for MS i in the multiuser diversity system. Let y_i be the expected goodput for MS i for the corresponding round robin system that has the same overhead as the multiuser diversity system. Then the gain fairness measure for the multiuser diversity system is given by

$$f_g = 1 - \frac{\sigma_N}{\mu_N \sqrt{N-1}} \tag{4.3}$$

where

$$\mu_N = \frac{1}{n} \sum_{i=1}^{N} \frac{x_i}{y_i} \tag{4.4}$$

is the mean of $\frac{x_i}{y_i}$ and

$$\sigma_N = \sqrt{\frac{1}{n}\sum_{i=1}^{N}\left(\frac{x_i}{y_i}\right)^2 - {\mu_N}^2} \tag{4.5}$$

is the standard deviation of $\frac{x_i}{y_i}$.

The proposed method for calculating fairness has several useful advantages, similar to the popular Jain's fairness measure [41]. Firstly, f_g is dimensionless, because it is defined in terms of the coefficient of variation $\frac{\sigma_N}{\mu_N}$, which is a dimensionless quantity commonly used for measuring dispersion in statistics. Secondly, $0 \leq f_g \leq 1$. In particular, if the $\frac{x_i}{y_i}$ values are all the same, representing perfect gain fairness, then $f_g = 1$. If $x_i = 0$ for every MS except one, representing the case where one MS monopolises the channel, then $f_g = 0$. As a result, f_g represents the percentage fairness exhibited by a multiuser diversity system.

Note that it is possible to convert between Jain's fairness measure and the gain fairness measure. If f_j is Jain's fairness measure for $\frac{x_i}{y_i}$, then

$$f_g = 1 - \sqrt{\frac{\frac{1}{f_j} - 1}{N - 1}} \tag{4.6}$$

Despite using different performance metrics to measure fairness, time-based fairness and gain fairness possess many similarities. The common link between the two fairness concepts is that they both use round robin as the referential fair system. While time-based fairness emphasises the equity in channel occupancy time, gain fairness emphasises the equity in goodput gain. Hence, for most multiuser diversity systems, the two fairness measures should yield fairly similar results.

To understand the difference between gain fairness and time-based fairness, consider a simplified numerical example. Consider a network with two MSs and one BS, with $\Gamma_1 \sim U(2, 6)$ and $\Gamma_2 \sim U(10, 14)$ where $X \sim U(a, b)$ means that X is a uniformly distributed random variable from a to b. There are two physical layer modes and the rate adaptation function (i.e., the goodput function for a given SNR) is:

$$g(x) = \begin{cases} 0, & x < 1 \\ 2, & 1 \leq x < 4 \\ 4, & x \geq 4 \end{cases} \tag{4.7}$$

Consider a multiuser diversity system whereby MS 1 is chosen to transmit if its channel state is better than average (i.e., $\Gamma_1 > 4$) while the channel state of MS 2 is not better than average (i.e., $\Gamma_2 \leq 12$), and vice versa. In the case of a tie (i.e., either $\Gamma_1 > 4$ and $\Gamma_2 > 12$ or $\Gamma_1 \leq 4$ and $\Gamma_2 \leq 12$), the BS randomly chooses between MS 1 and MS 2 for data transmission with equal probability. Fig. 4.1 highlights the relevant rate adaptation regions for the multiuser diversity system described above.

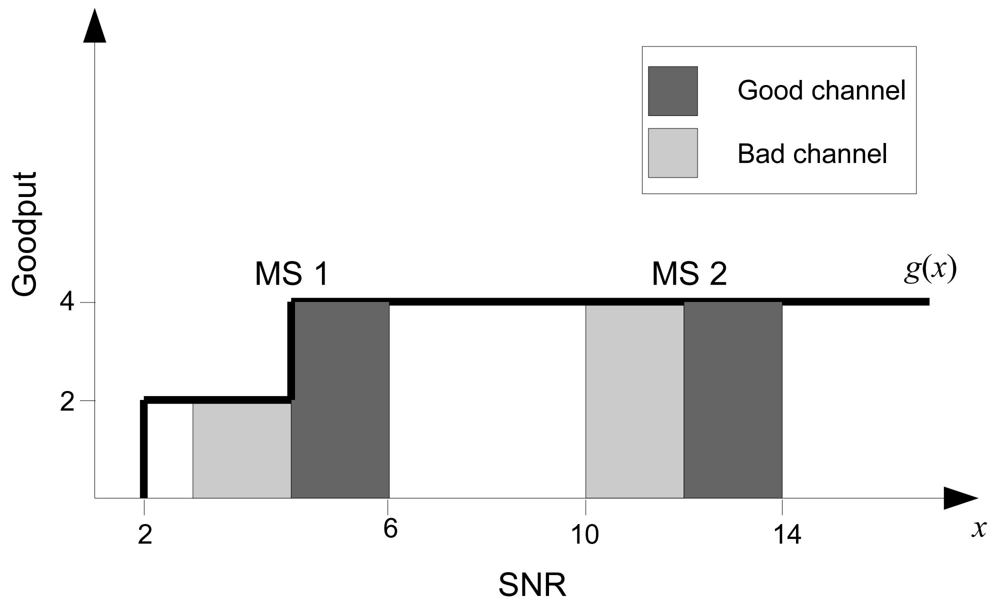

Figure 4.1: Rate adaptation regions for an example multiuser diversity system.

Using time-based fairness to judge the fairness performance of this multiuser diversity system, it would be considered to be completely fair, since both MS 1 and

MS 2 use the channel half of the time. Thus, using a fairness measure similar to (4.3) for time-based fairness, the fairness measure for this system would be equal to 1. However, it is obvious from this example that this system manages to exploit multiuser diversity for MS 1, but not for MS 2. When MS 2 experiences better than average channel conditions, it is not able to transmit more data than during worse than average channel conditions. Thus, as this example shows, time-based fairness does not accurately reflect how evenly multiuser diversity is exploited across all the MSs in the network.

However, using gain fairness as the fairness performance metric, this system can be shown to manifest some degree of unfairness. For this multiuser diversity system, $x_1 = \frac{7}{4}$ and $x_2 = 2$. For the corresponding round robin system, $y_1 = \frac{3}{2}$ and $y_2 = 2$. Therefore, using (4.3), the gain fairness index for this multiuser diversity system is $f_g = \frac{12}{13}$, which indicates that this system exhibits some small degree of unfairness.

4.3 Simulation Results

In this section, the simulation results on the goodput and fairness performances for FMDC, MDC and MAD are compared. In the simulations for MAD, the k-set round robin implementation with $k = 4$ (optimal) was used. Once again, the rate adaptation policy follows the IEEE 802.11a system applied in MDC, summarised in Table 3.2 in Section 3.4.

In the network simulations, a quasi-static Rayleigh fading channel where each MS has an average SNR that is in the set $\{10 \text{ dB}, 15 \text{ dB}, 20 \text{ dB}\}$ is considered. Let n_{10}, n_{15} and n_{20} be the number of MSs with an average SNR of 10 dB, 15 dB and 20 dB respectively, so that $N = n_{10} + n_{15} + n_{20}$. Table 4.1 shows how the distribution of average SNR values for $N = 2$ up to $N = 16$ has been assigned.

N	n_{10}	n_{15}	n_{20}
2	1	1	0
3	1	1	1
4	2	1	1
5	2	2	1
6	2	2	2
7	3	2	2
8	3	2	2
9	3	3	3
10	4	3	3
11	4	4	3
12	4	4	4
13	5	4	4
14	5	5	4
15	5	5	5
16	6	5	5

Table 4.1: Distribution of average SNR values

Fig. 4.2 shows the expected goodput performance of FMDC when the threshold factor κ has been optimised to the nearest 0.1 dB. Similarly, the response threshold for MDC has been optimised to the nearest 0.1 dB. The optimised values for κ and γ used in Fig. 4.2 for $z = 2$ dB, $z = 6$ dB and $z = 10$ dB are shown in Table 4.2. The general trend that is apparent from Table 4.2 is that κ increases with N and also increases as z increases. In Chapter 2, where independently and identically distributed channel states for the MSs were studied, similar properties in the global response threshold γ were observed.

From Fig. 4.2, it can be seen that MDC exhibits better goodput performance than FMDC, which in turn exhibits much better goodput performance than MAD. This result is noticeably different from the results in Section 2.3 and Section 3.4. The difference occurs because of the way in which k-set round robin scheduling [17] enforces time-based fairness, which reduces some of the potential for the MAD scheme to exploit multiuser diversity.

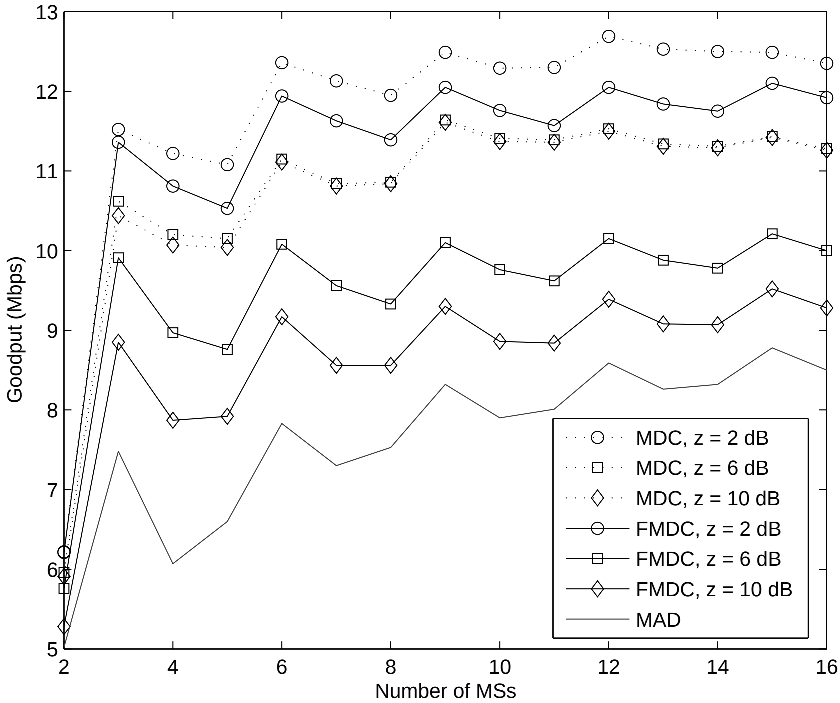

Figure 4.2: Goodput performance of FMDC, MDC and MAD

In k-set round robin scheduling, there is a queue of MSs with backlogged data to send and queue of serviced MSs. In each iteration of the service loop, the first k MSs are queried and the BS allocates the channel to the best MS in the queried subset. After data transmission, the selected MS is dequeued from the backlogged queue and enqueued into the serviced queue. Eventually, when there are less than k MSs in the backlogged queue, the BS only queries the remaining MSs in the backlogged queue, thereby enforcing time-based fairness. Once the backlogged queue is empty, the backlogged queue and the serviced queue are swapped. As a result, the average number of MSs queried per transmission cycle in MAD with k-set round robin scheduling is less than k, thereby reducing the multiuser diversity gain.

Fig. 4.3 shows the fairness performance of FMDC using the same values of κ as in Fig. 4.2. Similarly, the fairness performance for MDC is based on the same

N	$z = 2$ dB		$z = 6$ dB		$z = 10$ dB	
	κ_{dB}	γ_{dB}	κ_{dB}	γ_{dB}	κ_{dB}	γ_{dB}
2	-6.0	9.0	-6.0	12.0	-3.0	12.0
3	-5.6	12.1	-2.4	15.0	0.0	12.0
4	-3.0	14.8	-0.9	16.4	1.0	17.6
5	-0.8	15.3	1.0	18.0	2.0	18.0
6	0.9	18.0	1.3	20.3	2.2	20.5
7	1.0	18.0	2.0	20.3	2.7	20.5
8	1.0	18.5	2.4	20.6	3.0	20.8
9	1.6	21.0	2.8	21.0	3.2	21.0
10	1.9	21.0	3.0	21.0	3.5	21.0
11	2.2	21.0	3.1	21.0	3.8	21.0
12	2.6	21.0	3.4	21.5	4.0	21.5
13	2.7	21.0	3.5	21.5	4.1	21.5
14	3.0	21.0	3.8	21.5	4.3	21.6
15	3.1	21.5	3.9	22.1	4.5	22.2
16	3.2	21.5	4.0	22.1	4.6	22.2

Table 4.2: Optimised threshold factors for FMDC and optimised respond thresholds for MDC over Rayleigh fading channels with average SNR values shown in Table II 4.1

response thresholds used in Fig. 4.2. From Fig. 4.3, it is immediately apparent that the fairness performance of FMDC is far superior to that of MDC. It can also be seen that except for $z = 2$ dB, the fairness performance of FMDC and MAD are quite similar. Nonetheless, the fairness performance for $z = 2$ dB increases as the number of MSs in the network increases. Additionally, it is noteworthy that the threshold factor κ has specifically been chosen so that the goodput is optimised. As a result, for the $z = 2$ dB case, the fairness performance could be improved significantly at the cost of some goodput performance.

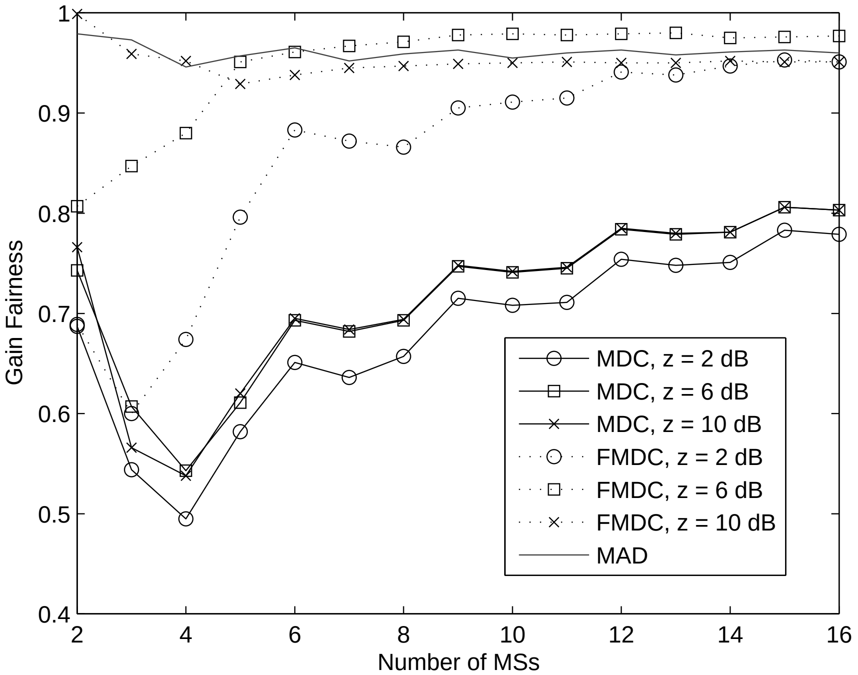

Figure 4.3: Fairness performance of FMDC, MDC and MAD

Chapter 5

Adaptive Optimisation of MDC Performance

In previous chapters, the optimal response threshold for MDC and FMDC over different types of wireless channels were found using extensive simulations. However, this method is computationally expensive and is unlikely to be feasible in a practical system. Additionally, the BS typically does not know the probability distribution of the channel state of each user and this distribution may change with time. In this chapter, the discussion revolves around an adaptive heuristic that adjusts the response threshold to optimise the goodput performance of MDC and FMDC.

5.1 Heuristic Threshold Optimisation

Consider the random variable G, the goodput of the MDC system (the following argument applies to FMDC as well). Recall from Section 3.1 that the amount of payload transmitted per unit time in any given transmission cycle is a realisation of G. The average value of a number of these realisations may be used to estimate $E[G]$, since according to the weak law of large numbers, this average value will approach

$E[G]$ arbitrarily closely for a sufficiently large number of realisations. While it is not feasible to estimate $E[G]$ to the degree of accuracy possible with extensive simulations in a practical system, it is possible to obtain a coarse estimate of $E[G]$ by computing the average goodput over a much smaller number of transmission cycles.

Because MDC is a centralised WMAC scheme, the goodput information in each transmission cycle is available at the BS. Consequently, for a given value of γ, the BS can observe the average goodput over a *batch* of transmission cycles and use it as an estimate for the expected goodput for the MDC system at that value of γ. By maintaining a history of estimated goodput values from previous batches, the system parameter γ can then be adjusted accordingly. Recall from Section 2.3 that $P(C)$ (and therefore $E[G]$) is not sensitive to the value of γ when γ is near the optimal value. This implies that for a sufficiently large batch size, this adaptive method should achieve near optimal performance if γ is adjusted judiciously. Essentially, the idea is that the BS "simulates" the MDC system over a small time scale and increases or decreases γ as required.

Let B denote the batch size and let γ_{new} be the response threshold in decibels used for the current batch. Let s be the constant step size (in dB) that is used to adjust γ_{dB} at the end of every batch. Let γ_{old} and G_{old} denote the response threshold used in the previous batch in decibels and the observed goodput in the previous batch, respectively. Let G_{new} denote the observed average goodput in the current batch. The proposed adaptive scheme for MDC is described in Algorithm 1 on the following page.

It is apparent that adaptive heuristic in Algorithm 1 is of low complexity, since a history buffer of just one goodput estimate to adjust γ for the successive batches. For FMDC, the corresponding algorithm is nearly identical, with $\gamma_{\text{db,new}}$ and $\gamma_{\text{dB,old}}$ replaced by $\kappa_{\text{db,new}}$ and $\kappa_{\text{dB,old}}$, respectively.

Initialise B and s;
$\gamma_{old} = 0$;
$\gamma_{new} = 18$;
$G_{\text{old}} = 0$;
$G_{\text{new}} = 0$;
while *TRUE* **do**
  Execute transmission cycle using γ_{new};
  Calculate G_{new} for the past B cycles;
  $g = \gamma_{\text{new}}$;
  if $(\gamma_{new} > \gamma_{old}$ **and** $G_{new} > G_{old})$ **or** $(\gamma_{new} < \gamma_{old}$ **and** $G_{new} < G_{old})$ **then**
    $\gamma_{\text{new}} += s$;
  end
  else
    $\gamma_{\text{new}} -= s$;
  end
  $\gamma_{\text{old}} = g$;
  $G_{\text{old}} = G_{\text{new}}$;
  $b = 0$;
end

Algorithm 1: Adaptive optimisation of γ for MDC

5.2 Simulation Results

In this section, simulation results on the goodput and fairness performances of the heuristics described in the previous section are presented. The goodput and fairness performances of the heuristics are evaluated with respect to the performances that are achieved when the optimal value of γ and κ are selected for MDC and FMDC, respectively. The versions of MDC and FMDC that use the heuristics will be referred to as MDC-A and FMDC-A, respectively. As before, the rate adaptation policy follows the IEEE 802.11a system applied in MDC, summarised in Table 3.2 in Section 3.4.

Fig. 5.1 shows the goodput performance of MDC-A with $B = 2000$ and $s = 0.1$ dB. The curve labelled MDC represents the goodput performance for MDC when γ is optimised. Since the transmission cycle duration of MDC is 668μs, the heuristic adjusts the value of γ approximately every 1.3s. It can be seen from Fig. 5.1 that

MDC-A achieves nearly optimal goodput performance. As a result, the goodput performance of MDC-A over Rayleigh fading channels is comparable to the goodput performance of MAD when the optimal number of MSs are queried.

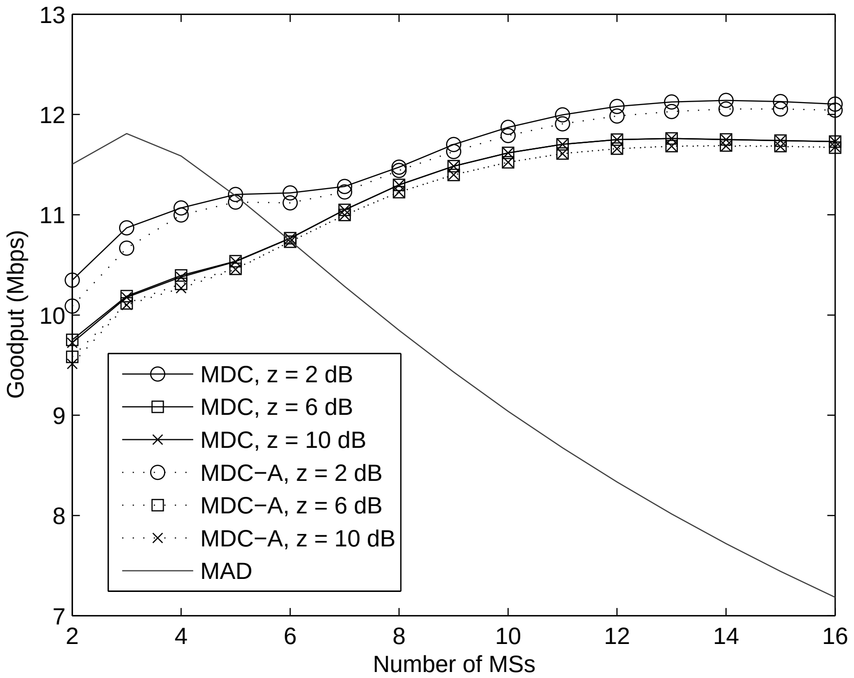

Figure 5.1: Goodput performance for MDC-A over an i.i.d. Rayleigh channel, with batch size $B = 2000$ and step size $s = 0.1$ dB.

Fig. 5.2 shows the goodput performance for FMDC-A for batch sizes of 500, 1000 and 2000 transmission cycles. In the time scale, these batch sizes correspond to the adjustment of κ approximately every 0.3s, 0.7s and 1.3s, respectively. The curve labelled FMDC represents the goodput performance of FMDC when κ is optimised. It can be seen from Fig. 5.2 that FMDC-A also achieves nearly optimal goodput performance.

Fig. 5.3 shows the fairness performance for FMDC-A from the same simulation setup as in Fig. 5.2. For $N > 5$, FMDC-A exhibits slightly better fairness performance than FMDC. This phenomenon occurs for the same reason that FMDC has

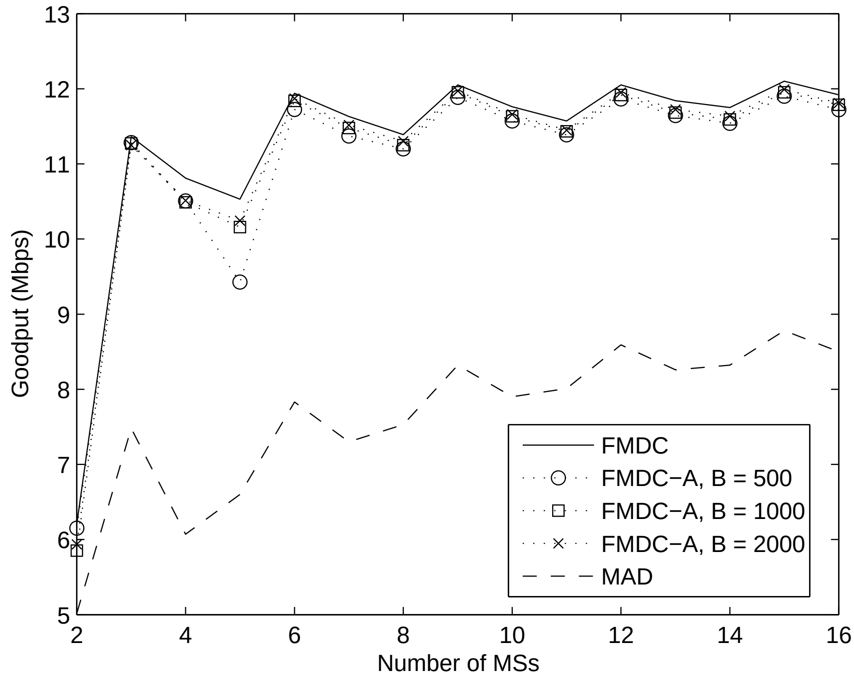

Figure 5.2: Goodput performance of FMDC-A over Type II channels with $z = 2$ dB and step size $s = 0.1$ dB.

better goodput performance than FMDC-A. Because FMDC-A adjusts κ every B transmission cycles using a coarse estimate of $E[G]$, the value of κ at any given time will usually not be optimal. When κ is not optimal, the BS captures the PR packet from the MS with the best channel less often and therefore allocates the channel to a randomly chosen MS more often. As a result, the BS allocates the channel to a randomly chosen MS more often in FMDC-A than in FMDC, and FMDC-A has better fairness performance.

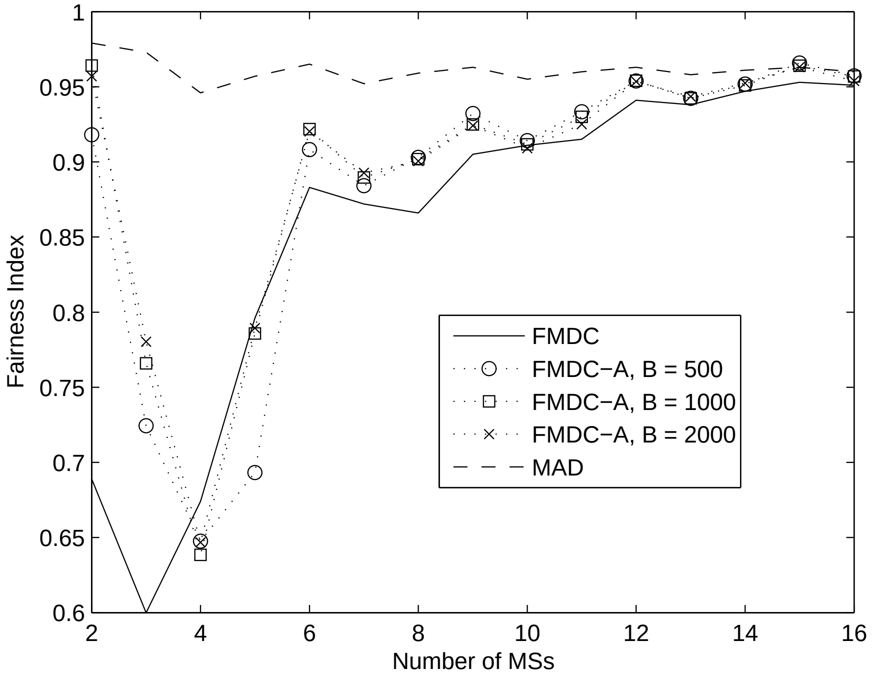

Figure 5.3: Fairness performance of FMDC-A over Type II channels with $z = 2$ dB and step size $s = 0.1$ dB.

Chapter 6

Conclusions and Future Work

In this thesis, a wireless MAC scheme designed to mitigate the overhead problem in exploiting multiuser diversity has been presented and analysed in detail. The proposed solution, MDC, explicitly employs the capture effect to opportunistically determine the MS with the best channel at the BS. Since the MSs feed back CSI to the BS simultaneously, the overall system overhead is independent of the number of MSs in the network.

An application of the MDC scheme using the infrastructure defined in the IEEE 802.11a standard with some slight modifications has been considered. To simulate goodput performance of the MDC system, a WLAN channel model including path loss, shadowing and Rayleigh fading has been adopted. The results show that when the number of MSs in the network is reasonably large, MDC performs quite well in comparison with the MAD scheme in the literature, even when the optimal number of MSs are queried in the MAD scheme.

To study the MDC scheme in further detail, a general analytical framework for the analysis of the goodput performance of MDC has been derived. Using this framework, the goodput performance of MDC over Rayleigh fading channels has been investigated. An exact closed form solution for the expected goodput of MDC has been demonstrated in Rayleigh fading channels and the correctness of the analytical solution has been verified by simulation. It has been observed that MDC exhibits the same characteristics in the Rayleigh fading channel as in the previously simulated, more general WLAN channel model.

In networks where some MSs experience better average channel conditions than others, MSs with low average channel states use the channel less often in MDC than MSs with high average channel states. To address this problem in networks where fairness is an important issue, the FMDC variant of the MDC scheme has been proposed. In FMDC, instead of using a network-wide response threshold, each MS uses an individual response threshold that is a function of its own average channel state. The fairness performances of FMDC, MDC and MAD in Rayleigh fading channels where some MSs have better average channel conditions than others have been simulated and compared using the gain fairness measure. The results show that with a limited degradation in goodput performance FMDC manifests far better fairness performance than MDC, with comparable fairness performance to MAD. The results also show that both FMDC and MDC have much better goodput performance than MDC in this type of channel.

Finally, an adaptive heuristic to optimise the goodput performance of MDC and FMDC has been discussed. The adaptive heuristic is based on the idea that the BS can obtain a course estimate the expected goodput of MDC (or FMDC) for a given response threshold (or threshold factor) and use a history of expected goodput estimates to adjust the response threshold (or threshold factor) adaptively. The results show that with the adaptive heuristic, the goodput and fairness performances of MDC (and FMDC) are very close to those observed when the optimal response thresholds (and threshold factors) are used.

There are many possibilities for extending this dissertation work on MDC and FMDC. In this thesis, applications of the MDC and FMDC schemes were considered for the IEEE 802.11a system. However, the proposed MDC and FMDC schemes are of a general nature and can be applied in any wireless system where the possibility of exploiting the capture effect is reasonable. Additionally, it is possible to analyse more detailed capture models tailored to particular modulation and coding systems in order to maximise the multiuser diversity gain in MDC and FMDC.

Appendix A

Derivation of Terms for Calculating $P(\Gamma_w \leq x)$

When none of the MSs respond with a PR packet, the set of Γ_is is equal to the set of Γ_{u_j}s. Hence,

$$\begin{aligned} P(\Gamma_w \leq x | R_0) &= \sum_{i=1}^{N} P(\Gamma_w \leq x | R_0 \cap w = i) P(w = i | R_0) \\ &= \sum_{j=1}^{N} P(\Gamma_w \leq x | w = u_j) P(w = u_j) \\ &= N P(\Gamma_{u_1} \leq x) \frac{1}{N} \\ &= F_U(x) \end{aligned} \tag{A.1}$$

where in the third step, the fact that the Γ_{u_j}s are i.i.d. has been used.

When exactly one MS responds with a PR packet, the winning MS is the only replying MS. Therefore, $\Gamma_w = \Gamma_{v_1}$ and

$$\begin{aligned} P(\Gamma_w \leq x | R_1) &= P(\Gamma_{v_1} \leq x) \\ &= F_V(x). \end{aligned} \tag{A.2}$$

For $n \geq 2$, the event $C \cap R_n$ occurs when the channel state of one of the replying MSs exceeds z times the sum of the channel states of the other $(n-1)$ replying MSs. Define the event $E_{k,n}$ as

$$E_{k,n} = \left\{ \Gamma_{v_k} > z \sum_{i=1, i \neq k}^{n} \Gamma_{v_i} \right\}. \tag{A.3}$$

The event $E_{k,n}$ is the sufficient and necessary condition for MS v_k to be captured at the BS given that n MSs send a PR packet. Since $z \geq 1$ is assumed and $\Gamma_{v_k} \geq 0$ for $1 \leq k \leq n$, it transpires that

$$\begin{aligned} \Gamma_{v_k} > z \sum_{i=1, i \neq k}^{n} \Gamma_{v_i} &\Rightarrow \Gamma_{v_k} > \sum_{i=1, i \neq k}^{n} \Gamma_{v_i} \\ &\Rightarrow \Gamma_{v_k} > \Gamma_{v_i} \quad \forall i \neq k. \end{aligned} \tag{A.4}$$

which can only occur for at most one value of k. Therefore, the events $E_{1,n}, E_{2,n}, \ldots, E_{n,n}$ are mutually exclusive.

Further, since the Γ_{v_k}s are i.i.d., it follows from the symmetry in (A.3) that $P(E_{k,n})$ is independent of k. Hence, only one MS can be captured at the BS at the channel competition step and each MS has an equal probability of being captured.

Therefore, for $n \geq 2$,

$$\begin{aligned} P(C|R_n) &= P\left(\bigcup_{k=1}^{n} E_{k,n}\right) \\ &= \sum_{k=1}^{n} P(E_{k,n}) \\ &= nP(E_{1,n}) \\ &= n\int_{(n-1)\gamma}^{\infty}\int_{zx}^{\infty} f_V(y) f_{V,n-1}(x)\,dy\,dx \\ &= n\int_{(n-1)\gamma}^{\infty} (1 - F_V(zx)) f_{V,n-1}(x)\,dx. \end{aligned} \tag{A.5}$$

Because the Γ_{v_k}s are i.i.d., it follows that for $n \geq 2$

$$\begin{aligned} P(\Gamma_w \leq x|C \cap R_n) &= \sum_{k=1}^{n} P(\Gamma_w \leq x|C \cap R_n \cap w = v_k) P(w = v_k|C \cap R_n) \\ &= P(\Gamma_w \leq x|C \cap R_n \cap w = v_1) \\ &= P(\Gamma_{v_1} \leq x|E_{1,n}) \\ &= \frac{P(\Gamma_{v_1} \leq x \cap E_{1,n})}{P(E_{1,n})} \\ &= \frac{1}{P(E_{1,n})} P\left(z\sum_{i=2}^{n}\Gamma_{v_i} < \Gamma_{v_1} \leq x\right) \\ &= \frac{n}{P(C|R_n)}\int_{z(n-1)\gamma}^{x}\int_{(n-1)\gamma}^{y/z} f_{V,n-1}(u) f_V(y)\,du\,dy \\ &= \frac{n}{P(C|R_n)}\int_{z(n-1)\gamma}^{x} F_{V,n-1}\left(\frac{y}{z}\right) f_V(y)\,dy \end{aligned} \tag{A.6}$$

where in the second step, the facts that $P(w = v_k|C \cap R_n) = \frac{1}{n}$ and $P(\Gamma_{v_k} \leq x|C \cap R_n)$ is independent of k have been used.

When n MSs send a PR packet simultaneously and the BS is unable to identify the MS with the best channel, the BS will allocate the channel to a randomly chosen

MS. The index of the randomly chosen MS is either in $\{u_i\}$ or $\{v_i\}$. Thus for $n \geq 2$,

$$P(w = u_i|\bar{C} \cap R_n) = \frac{1}{N}, \quad 1 \leq i \leq N - n \tag{A.7}$$

and

$$P(w = v_j|\bar{C} \cap R_n) = \frac{1}{N}, \quad 1 \leq j \leq n. \tag{A.8}$$

Since the Γ_{u_i}s are i.i.d and the Γ_{v_j}s are also i.i.d,

$$\begin{aligned} P(\Gamma_w \leq x|\bar{C} \cap R_n) &= \sum_{i=1}^{N-n} P(\Gamma_w \leq x|\bar{C} \cap R_n \cap w = u_i) P(w = u_i|\bar{C} \cap R_n) \\ &\quad + \sum_{j=1}^{n} P(\Gamma_w \leq x|\bar{C} \cap R_n \cap w = v_j) P(w = v_j|\bar{C} \cap R_n) \\ &= \frac{N-n}{N} F_U(x) + \frac{n}{N} P(\Gamma_{v_1} \leq x|\bar{C} \cap R_n). \end{aligned} \tag{A.9}$$

Note that $P(\Gamma_{v_1} \leq x|\bar{C} \cap R_n)$ is the conditional cdf of Γ_{v_1} given that n MSs send a PR packet and the BS is unable to capture the strongest signal. Hence, for $n \geq 2$,

$$\begin{aligned} P(\Gamma_{v_1} \leq x|\bar{C} \cap R_n) &= \frac{P(\Gamma_{v_1} \leq x \cap \bar{C}|R_n)}{P(\bar{C}|R_n)} \\ &= \frac{1}{P(\bar{C}|R_n)} P\left(\Gamma_{v_1} \leq x \cap \left(\bigcap_{k=1}^{n} \bar{E}_{k,n}\right)\right) \\ &= \frac{1}{P(\bar{C}|R_n)} \left(P(\Gamma_{v_1} \leq x) - P\left(\Gamma_{v_1} \leq x \cap \left(\bigcup_{k=1}^{n} E_{k,n}\right)\right)\right) \\ &= \frac{1}{P(\bar{C}|R_n)} \left(P(\Gamma_{v_1} \leq x) - \sum_{k=1}^{n} P(\Gamma_{v_1} \leq x \cap E_{k,n})\right) \end{aligned} \tag{A.10}$$

where de Morgan's law has been used in the third step and the fact the $E_{k,n}$s are mutually exclusive has been used in the final step.

Now consider $P(\Gamma_{v_1} \leq x \cap E_{k,n})$. For $k = 1$, it has already been shown from the derivation of $P(\Gamma_w \leq x | C \cap R_n)$ that

$$P(\Gamma_{v_1} \leq x \cap E_{1,n}) = \int_{z(n-1)\gamma}^{x} F_{V,n-1}\left(\frac{y}{z}\right) f_V(y)\, dy. \qquad \text{(A.11)}$$

Since the Γ_{v_k}s are i.i.d., it follows that $P(\Gamma_{v_1} \leq x \cap E_{k,n}) = P(\Gamma_{v_1} \leq x \cap E_{2,n})$ for $2 \leq k \leq n$. Hence for $n \geq 2$,

$$\begin{aligned} \sum_{k=2}^{n} P(\Gamma_{v_1} \leq x \cap E_{k,n}) &= (n-1)\, P(\Gamma_{v_1} \leq x \cap E_{2,n}) \\ &= (n-1)\, P\left(\Gamma_{v_1} \leq x \cap \Gamma_{v_2} > z \sum_{i=1, i\neq 2}^{n} \Gamma_{v_i}\right). \qquad \text{(A.12)} \end{aligned}$$

For $n > 2$ in (A.12),

$$\begin{aligned} P(\Gamma_{v_1} \leq x \cap E_{2,n}) &= P\left(\Gamma_{v_1} \leq x \cap \left(\Gamma_{v_2} > z\left(\Gamma_{v_1} + \sum_{i=3}^{n} \Gamma_{v_i}\right)\right)\right) \\ &= \int_{\gamma}^{x}\int_{(n-2)\gamma}^{\infty}\int_{z(y+u)}^{\infty} f_V(t) f_{V,n-2}(u) f_V(y)\, dt\, du\, dy \\ &= \int_{\gamma}^{x}\int_{(n-2)\gamma}^{\infty} (1 - F_V(z(y+u))) f_{V,n-2}(u) f_V(y)\, du\, dy. \qquad \text{(A.13)} \end{aligned}$$

For $n = 2$ in (A.12),

$$\begin{aligned} P(\Gamma_{v_1} \leq x \cap E_{2,2}) &= P(\Gamma_{v_1} \leq x \cap \Gamma_{v_2} > z\Gamma_{v_1}) \\ &= \int_{\gamma}^{x}\int_{zy}^{\infty} f_V(u) f_V(y)\, du\, dy \\ &= \int_{\gamma}^{x} (1 - F_V(zy)) f_V(y)\, dy. \qquad \text{(A.14)} \end{aligned}$$

Substituting $n = 2$ in (A.13), it follows from the sifting property of the Dirac delta function that (A.14) is actually a special case of (A.13).

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