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Opportunistic Cooperative Retransmission Enhancements for the IEEE 802.11 Wireless MAC

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I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

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TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

Table Number Page

LIST OF ALGORITHMS

LIST OF ABBREVIATIONS

AaF	Amplify and Forward
ACK	ACKnowledgement (MAC layer frame)
ARQ	Automatic Repeat reQuest
BO	Back Off
CBR	Constant Bit Rate
CDMA	Code Division Multiple Access
CFC	Call For Cooperation (custom MAC layer frame)
CSI	Channel State Information
CSMA/CA	Carrier Sense Multiple Access - Collision Avoidance
CTS	Clear To Send (MAC layer frame)
DaF	Decode and Forward
DAFMAC	Decode And Forward MAC (protocol)
DCF	Distributed Coordination Function
FDD	Frequency Division Duplexing
FDMA	Frequency Division Multiple Access
FCS	Frame Check Sequence
i.i.d.	independent and identically distributed
MAC	Medium Access Controller
MIMO	Multiple-Input Multiple-Output
MRC	Maximal Ratio Combining
NAK	Negative AcKnowledgement
PRO	Protocol for Retransmitting Opportunistically (MAC protocol)
QoS	Quality of Service
RTS	Request To Send (MAC layer frame)
TDMA	Time Division Multiple Access

LIST OF PARAMETERS

$d_{a,b}$	distance between points a and b
N_b	the *best* relay node as identified using the relay selection algorithm
N_d	the destination node
N_i	the ith node, used to refer to any node
N_s	the source node
$\mathcal{N}_c$	the set of relays contending for retransmission, $\mathcal{N}_c \subseteq \mathcal{N}_p$
$\mathcal{N}_n$	the total set of nodes that are neighbours to both N_s and N_d
$\mathcal{N}_p$	the set of relays participating in the retransmission process, $\mathcal{N}_p \subseteq \mathcal{N}_n$
ρ_n	(average) number of neighbours of each node
$RSS_{a,b}$	received signal strength at node N_b for transmission sent by node N_a, typically represented in dBm
SNR_{off}	minimum link quality offset (used only in proof of concept relay selection algorithm)
SNR_{rng}	range of expected SNR values between the lowest and highest path loss
t_i	contention delay generated by node N_i
T_{difs}	distributed inter-frame space
T_{phy}	duration of physical layer training sequence
T_{sifs}	short inter-frame space
T_{slot}	slot time for the MAC CSMA/CA back off sequence

ABSTRACT

Cooperative retransmission protocols improve wireless transmission reliability by providing distributed channel diversity. Unfortunately, this diversity comes at the cost of increased protocol complexity and processing overhead, which limits the scalability of cooperative protocols in large networks.

This Thesis introduces DAFMAC, an opportunistic retransmission protocol which operates without any explicit control messaging. DAFMAC uses passive transmission observations to select a suitable opportunistic relay using a distributed algorithm. The immediate benefit of reducing overhead is to enable a greater proportion of channel time available for data transmissions. The DAFMAC retransmission algorithm is compared to contemporary protocols through extensive simulations to evaluate network performance. The key result is that DAFMAC is able to meet or exceed the performance improvements of "coordinated" retransmission algorithms such as PRO and Δ-MAC, for metrics which include total network throughput, individual link fairness, energy efficiency, end-to-end transmission time and jitter. A proof-of-concept implementation of DAFMAC was deployed in a physical test-bed and was shown to significantly improve throughput in high path-loss links.

This Thesis also derives a general retransmission model which is applicable to many distributed cooperative algorithms. Due to the complexity of implementing cooperative protocols in simulators, algorithms are typically only compared to traditional non-cooperative ARQ retransmissions. Further, analytic models typically include naïve simplifications that makes meaningful comparisons between algorithms impossible. The analytic model presented in this Thesis calculates the opportunistic retransmission outcome probability and includes detailed failure-mode results which may be used to rapidly compare algorithm performance with different configuration parameters in addition to comparing different protocols. Using the straightforward design principles of a retrans-

mission algorithm, the model is able to accurately reproduce the cooperative performance results of a full state-based simulation. The retransmission model is independent of the channel model to facilitate performance analysis in different scenarios.

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Chapter 1

INTRODUCTION

Wireless communications systems are an integral component of contemporary human civilisation. Society is increasingly dependent on universal access to communications services - for people, devices, and increasingly for infrastructure. Exponential growth in the use of such services has created the demand for ever-greater capacity, reliability, flexibility, and energy efficiency in the underlying networks.

One promising approach for improving the capacity and reliability of wireless networks is *cooperative communications*, in which nodes other than the source and destination can participate in a given MAC-layer frame delivery. Like MIMO, this is essentially a means of exploiting spatial diversity in the network; however, cooperative communications systems do so in a *distributed* manner. MAC-layer cooperative communication is quite distinct from (but complementary to) a network layer ad hoc routing protocol, in which a packet may be relayed from node to node before reaching its destination. Ad hoc routing protocols either require a reactive route discovery process (which delays delivery of the first packet) or proactive routing table maintenance (which uses a portion of the network capacity and consumes energy even when idle). By contrast, a MAC-layer cooperative communications system only aims to increase the reliability of one-hop transmissions with the aid of intermediate nodes. This is particularly beneficial in lightly loaded but relatively sparse networks.

1.1 Opportunistic Retransmissions

In the traditional source-coordinated *relay* model, the source node detects the presence of a weak direct link between the itself and destination. It then selects a relay to provide an alternate path to the destination with a lower latency or higher data rate. The term "relaying" is generally used to denote when the transmission path is determined *prior* to the initial transmission. An example of traditional relaying is shown in

Figure 1.1: The traditional source-coordinated relay model finds an alternate path around a poor link by sending frames via a relay

Figure 1.1. However, source-based selection of an optimal alternate path introduces a significant coordination overhead (for example, dissemination of neighbour node location and neighbour link quality information) which consumes both channel capacity and node computational resources.

Opportunistic retransmissions take a different philosophical approach. Initially, a given source attempts to transmit its data frame to the destination directly, even in situations with significant source-destination path loss and hence a non-negligible probability of failure. Neighbouring nodes overhear and retain a copy of this transmission, and, if they determine that the original transmission is unsuccessful, opportunistically attempt to retransmit the lost frames. The term "opportunistic retransmission" (or "opportunistic relaying") denotes the final path of the data frame is not known prior to transmission. An example of opportunistic retransmission is shown in Figure 1.2. The benefits of opportunistic user cooperation include a generally higher throughput and lower latency, since transmission over the direct link will frequently succeed (obviating the need for relaying) and a reduced retransmission overhead because source-directed coordination is not required. Therefore, the traditional source-directed relay strategy is most appropriate when the successful direct transmission probability becomes very small, whereas opportunistic retransmissions can offer significant performance advantages in cases where the direct transmission decoding probability is significantly greater than zero. This case applies to many sparse or irregularly-distributed networks, such as sensor and mobile ad hoc networks, in which the channel quality of direct links may vary between excellent and marginal.

This Thesis will therefore examine the problem of designing, optimising, and evaluating an effective opportunistic retransmission scheme for low-density ad hoc networks. The popular IEEE 802.11 wireless protocol is selected as the reference protocol in this work

Figure 1.2: The opportunistic relay model attempts a direct transmission (possibly over a poor link) where neighbours overhear the failed frame and cooperatively retransmit on behalf of the source

as it has been thoroughly analysed in the literature, is well documented and has been implemented in many simulators and open source operating systems. Generally, this Thesis will use 802.11b and 802.11g as the platform to evaluate the retransmission performance because they are widely available in simulators and are commonly used in society. However, many concepts of this work may carry over to newer protocol versions, such as 802.11n and 802.11ac.

1.1.1 MAC Protocol Design

The primary functions of the *medium access control* (MAC) layer include framing, addressing, error and one-hop flow control, and (particularly in wireless networks) arbitration between nodes seeking to access the channel. In IEEE 802.11, arbitration is achieved using carrier sense multiple access with collision avoidance (CSMA/CA); devices sense when the channel is idle before attempting to transmit; if the channel is not idle or if a transmission fails, the sender waits for a random number of back-off time slots before retransmitting to avoid colliding with other transmissions. Cooperative relaying (as distinct from network-layer ad hoc routing) is a logical extension to error control functions and is therefore implemented at the MAC-layer.

The challenge with opportunistic cooperative MAC protocols is in selecting the single best relay to retransmit a failed frame. The optimal relay is ideally chosen using a distributed scheme, without significantly increasing latency while keeping coordination overhead to a minimum. To ensure minimal retransmission latency, most cooperative protocols retransmit data frames within the 802.11 ARQ period, which allows insufficient time for an explicit election process to be conducted between candidate relays.

Therefore, several relay arbitration mechanisms have been proposed in the literature to autonomously select a relay to forward the failed frame.

There are two essential components to an opportunistic cooperative MAC protocol: firstly, the transmission and signalling protocol itself; and secondly, the distributed relay selection algorithm.

Existing transmission and signalling protocols have adopted a variety of retransmission approaches, including: pre-selection of a relay for a given link before retransmission is required; nominating a relay as part of the data frame transmission sequence; negotiating between relays using a brief flag signalling exchange; and selecting relay(s) using a distributed algorithm with two-hop link state information. Additionally, retransmissions may be triggered by an explicit cooperation request or by detecting the absence of an acknowledgement. The benefits and limitations of each of these approaches are discussed in depth in Chapter 2.

The relay selection component of cooperative MAC protocols is a computational process used to determine if and when a contending node should attempt to cooperatively retransmit a frame. A variety of approaches have been proposed, including: random contention back-off based on the CSMA/CA access protocol; fixed channel access delays based on the measured link quality; restricting contention to a subset of available devices; immediate retransmission by a pre-selected relay; and simultaneous mutually orthogonal OFDMA or CDMA retransmissions. Again, each method has its own benefits and limitations, and all widely used techniques are also reviewed in Chapter 2.

A significant research opportunity exists to design an effective opportunistic decode and forward retransmission scheme which introduces minimal coordination overhead and can operate using the partial channel state information available to contending nodes with existing commodity 802.11 hardware.

1.1.2 Analysis and Comparison of Protocols

A direct performance comparison between cooperative algorithms is challenging - each protocol is complex and non-trivial to implement in network simulators, while the analytic models presented with published protocol descriptions are typically limited to specific channel models, receiver architectures, and network configurations. Because of this, many published retransmission schemes only evaluate cooperative performance against non-cooperative ARQ retransmission schemes and offer no relative performance comparison to other cooperative protocols. Analytic protocol evaluations typically use naïve assumptions to reduce the complexity of analysis, such as assuming that all relays in the network have the same link quality to the source and destination nodes. Furthermore, such evaluations frequently omit a detailed failure mode analysis or even assume that simultaneous cooperative retransmissions do not collide but combine to increase the decoding probability at the destination.

Therefore, there is also a significant opportunity to improve the method of relative performance evaluation and comparison for cooperative retransmission protocols.

1.2 Thesis Statement

Opportunistic user cooperation is an effective and resource efficient method of reducing the link outage rate in wireless networks. Although the predominant research efforts in cooperative MAC protocols focus on coordinating information between contending devices to reduce or avoid retransmission collisions, an effective relay selection algorithm produces a lower total cooperative overhead and outage loss and therefore retains a greater share of the channel capacity for general use.

1.3 Objectives and Overview of this Thesis

The objective of this thesis is to develop a novel opportunistic retransmission-based MAC protocol based on a series of extensions to 802.11 MAC. The protocol, entitled DAFMAC (Decode And Forward MAC), aims to offer high retransmission efficacy and fair channel access to users without introducing explicit relay coordination overhead. Furthermore, DAFMAC is relatively straightforward to implement with commercial off-the-shelf 802.11 hardware. DAFMAC introduces several novel features, including a hybrid distributed relay time algorithm with both link quality and random delay components, and a zero-overhead preferred relay scheme to minimise retransmission collisions. DAFMAC is developed and exhaustively evaluated via analysis and simulation under diverse network conditions (both realistic and pathological) throughout the remainder of this Thesis. It is conclusively demonstrated that DAFMAC achieves the stated design objectives and does so more effectively than the alternative protocols with which it is compared.

A second major objective is to develop a new analytic model to predict the outcome probability for retransmission attempts using *any* cooperative retransmission-based relaying protocol. This is a significant research contribution because no existing analytic model includes a full failure mode analysis with independent link parameters across such a wide range of protocols. The proposed model offers a significant benefit by allowing researchers to quickly and accurately compare the retransmission performance of cooperative protocols in various scenarios. The value of this model is demonstrated by using it to predict the performance of a variety of protocols under realistic network scenarios.

The structure of the remainder of this Thesis is as follows:

- Chapter 2 presents a critical review of relevant literature, including a detailed discussion of current protocol designs and relay selection methods. This chapter summarises the key features for a successful cooperative protocol, and also identifies opportunities to improve the retransmission performance.

- Chapter 3 introduces the DAFMAC opportunistic cooperative MAC protocol. A primitive but functional relay selection algorithm is incorporated into the DAFMAC protocol to evaluate its potential retransmission performance. The design philosophy of DAFMAC is that a useful relay can be selected using only the partial channel state information already available to the MAC without introducing further signalling overhead. DAFMAC is analytically shown to meet or exceed the performance of two of the most promising cooperative protocols, PRO and Δ-MAC.

- The DAFMAC relay selection algorithm is explored in greater detail in Chapter 4. A general algorithm is presented and the optimal parameter values (or range of values) are analytically and/or empirically derived to minimise the retransmission collision probability. A zero-overhead preferred relay scheme is also introduced which further reduces the retransmission collision probability by approximately half. The performance of DAFMAC is comprehensively evaluated against the traditional 802.11 MAC ARQ and the PRO cooperative MAC using a state-based simulator. DAFMAC is shown to offer a higher total network throughput, superior fairness between individual data flows, and a lower energy consumption per successfully transmitted frame, both for 802.11b and 802.11g.

- Chapter 5 presents a general cooperative retransmission outcome probability model. The retransmission model utilises knowledge of the slot-based mechanism for cooperative contentions and therefore evaluates the cooperative protocol and relay selection algorithm behaviour without implementing the full protocol in a simulator. The model is shown to accurately reproduce the retransmission performance of a series of QualNet simulations using only a fraction of the development and computational resources. Furthermore, the model includes a full breakdown of the failure mode for analysis and algorithm refinement.

- Chapter 6 shows that cooperative MAC protocols offer a significant reliability benefit to network layer ad hoc routing protocols compared with simple ARQ schemes. Simulations demonstrate that DAFMAC significantly improves the total network throughput, link fairness, energy efficiency, end-to-end transmission time, and jitter for a variety of common routing protocols.

- Finally, Chapter 7 summarises the contributions and key results presented in this Thesis. Opportunities for further research based on this Thesis are also presented.

1.4 Related Publications

The publications directly related to the contribution of this Thesis are as follows:

- Proof-of-concept high-level simulation of DAFMAC, showing that cooperative retransmission with no control messaging potentially offers lower rates of packet loss compared to cooperative protocols with explicit messaging (Chapter 3):
  Brett Hagelstein, Mehran Abolhasan, Daniel Franklin and Farzad Safaei, "An Efficient Opportunistic Cooperative Diversity Protocol for 802.11 Networks", in *Proceedings of the ACM International Conference on Communications and Mobile Computing (IWCMC)*, July 2010, pages 417–421 [46].

- Implementation of a simplified form of the DAFMAC algorithm in a commercial off-the-shelf 802.11 transceiver. Initial experimental results also validate the initial simulation work (Chapter 3):

  Craig S. Cooper, Brett Hagelstein and Daniel Franklin, "Implementation of Opportunistic Cooperative Diversity in an Ad-Hoc Network using Commodity Hardware", in *Proceedings of the IEEE International Conference on Communications and Mobile Computing (IWCMC)*, August 2012, pages 165–168 [34].

- Enhancing the DAFMAC retransmission algorithm to reduce repeated cooperative collisions and identifying the impact of opportunistic retransmission algorithms on transmission fairness; a detailed simulation campaign is also presented which compares throughput, jitter, fairness, and energy consumption with competing protocols under a wide variety of conditions (Chapter 4):

  Brett Hagelstein, Mehran Abolhasan, Daniel Franklin and Farzad Safaei, "Improving Fairness in IEEE 802.11 Networks Using MAC Layer Opportunistic Retransmission", *accepted for publication in Elsevier Computer Networks*, 2013 [47].

- Development of an analytic model for predicting both the probability of success and each of the possible failure modes for cooperative retransmission attempts performed using a variety of MAC protocols and relay selection algorithms (Chapter 5):

  Brett Hagelstein, Mehran Abolhasan, Daniel Franklin and Farzad Safaei, "A General Performance Model for MAC Layer Cooperative Retransmission Contention Protocols", *accepted for publication in the IEEE Global Communications Conference (GLOBECOM)*, 2013, [48].

- Extensions to the above analytic retransmission outcome model to include more MAC protocols, in particular, those incorporating a state-based contention delay mechanism (Chapter 5):

  Brett Hagelstein, Mehran Abolhasan, Daniel Franklin and Farzad Safaei, "A General Performance Model for State-Based MAC Layer Cooperative Retransmission Contention Protocols", *submitted to IEEE Transactions on Mobile Communications*, 2013, [49].

- Exploring the performance benefits of increased link stability from the use of co-operative MACs in combination with ad hoc routing protocols in multi-hop mesh networks (Chapter 6):
  Brett Hagelstein, Mehran Abolhasan, Daniel Franklin and Farzad Safaei, "Increasing Mesh Network Performance Using A Cooperative MAC-Layer Retransmission Protocol", *(in preparation for submission to) IEEE International Conference on Communications (ICC)*, 2014, [50].

Chapter 2

LITERATURE REVIEW

2.1 Introduction

This Thesis explores the performance gains available by extending the IEEE 802.11 MAC layer using cooperative retransmissions. This chapter begins with a general discussion of the foundation work in MAC-layer cooperation, including:

- user cooperation diversity;
- techniques of retransmission orthogonality; and
- on-demand retransmissions.

It then critically analyses the related work in greater detail, where the key topics include:

- relay selection methods;
- distributed selection protocol signalling schemes;
- opportunistic routing for maximum throughput;
- cooperative retransmission protocols to reduce outages;
- the influence of the wireless MAC in routing schemes; and
- performance evaluation methods for cooperative protocols.

2.2 Cooperative Diversity Foundation Work

Spatial diversity via multiple antennas is an effective method to mitigate localised severe channel fading [84]. Furthermore, it is an attractive technique because it is readily combined with both temporal and frequency diversity [69]. However, the continued miniaturisation of devices means it is not possible to achieve the required antenna separation required to provide sufficiently independent paths [7].

Instead, *user cooperation diversity* proposed by Sendonaris, Erkip, and Aazhang enables terminals to share their resources to create a virtual antenna array [89]. Data transmitted from the source to the destination (either a symbol or a whole frame) is also overheard by the partner node by virtue of the broadcast nature of radio transmissions. The partner node then cooperatively retransmits the data to the destination via its own independent channel. This creates a cooperative form of spatial diversity which provides robustness to transitory channel fading.

Cooperative diversity relays are fundamentally different from the classical relay channel model [36]; user cooperation provides outage resilience to both users. Furthermore, both the direct- and relayed transmissions are combined at the destination, using a technique such as maximal-ratio combining (MRC), to improve the probability of decoding the frame [66]. User cooperative diversity significantly reduces the outage rate compared to both non-cooperative retransmissions and the classical relay model [90].

There are three key cooperative diversity relaying schemes: amplify-and-forward (AaF), decode-and-forward (DaF), and coded-cooperation [52, 65]. The AaF relay amplifies the received signal by the estimated inverse of the channel gain to restore the signal to the original transmission power. However, this technique also amplifies any interference or receiver noise and retransmits it to the destination. Conversely, frames are only relayed by the decode-and-forward technique if the data is successfully decoded at the relay. While this avoids retransmitting errors at the relay, it also imposes a minimum link quality on the inter-user channel. Coded-cooperation also requires the relay to successfully decode the frame. However, instead of repeating the data frame, the coded-cooperation technique calculates and transmits additional redundancy information which is combined with the direct frame at the destination to improve the decoding probability [52].

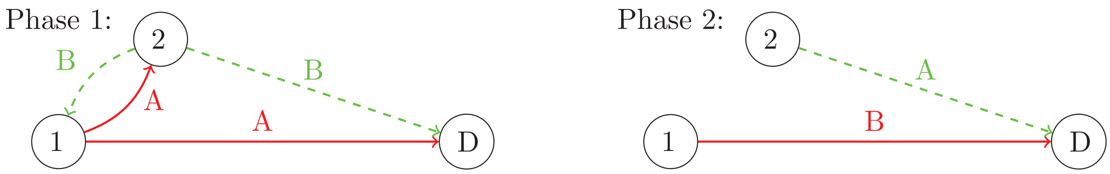

Figure 2.1: User 1 transmits frame 'A' and user 2 transmits frame 'B' in the first slot, then retransmit each other's frame in the second slot

Cooperative diversity reduces the outage rate primarily because of the reduced probability that *both* direct and relay channel exhibit deep fading. Although AaF also amplifies any receiver noise, this is typically resolved using a suitable MRC at the destination [66]. Conversely, a DaF relay will detect the error and not retransmit at all, leading to AaF enjoying a lower outage rate than DaF for channels with higher inter-relay path loss. If the inter-user channel is sufficient for the relay to decode the frame correctly, DaF performance improves and marginally exceeds AaF. The coded-cooperation technique also requires a good inter-relay channel, but once this threshold is met, provides a 1-2 dB gain over DaF and AaF relaying [31, 53].

2.3 Transmission Orthogonality

Traditional user cooperation scenarios consist of a three node network; two user nodes, which act as both sources and relays, and one destination node. Transmissions from the two source nodes must be orthogonal to be successfully decoded at the destination. This can be via different carrier frequencies (FDMA), time slots (TDMA), or codes (CDMA). Wireless interfaces are limited to half-duplex communication. Therefore, nodes require two such interfaces to concurrently transmit their frame while receiving their partner's frame in order to maximise the cooperative throughput.

Sendonaris, Erkip, and Aazhang employ scheduled CDMA transmissions in a cellular communication environment to improve the user up-link channel [89]. The direct and cooperative transmissions occur in a two-slot system; users transmit their own data in the first slot (concurrently receiving the other user's data on a second wireless interface), and transmit each other's data in the second slot using the appropriate CDMA code. This is illustrated in Figure 2.1.

Laneman, Wornell, and Tse use FDMA to achieve a similar result using two sub-channels [69]. Nodes transmit their own data in the first slot, while simultaneously receiving a data frame from its partner on another interface on another FDD frequency band [67]. Users retransmit their partner's frame to the destination in the second slot over their own channel.

A subsequent model by Laneman and Wornell uses a cluster of cooperative relays [68]. This protocol has two implementations, depending on the hardware available. For n users in a cluster, each user has $n + 1$ half-duplex interfaces [25]. Each user transmits their own data in the first time slot and concurrently receives data from other users on the remaining interfaces. Using a *repetition* scheme, each user subsequently forwards data to the destination on one of its interfaces in each slot such that only one user is transmitting on each interface frequency. The total transmission and retransmission process takes n time slots for a single data frame. An extension to this model employs space-time coding (STC) to allow *simultaneous* transmissions from all relays, on all interfaces, during a single time slot. This method compresses the entire transmission and retransmission process into a two slot cycle and therefore offers a significantly higher spectral efficiency. However, there are a number of technical challenges to overcome before a distributed STC scheme is possible with an arbitrary (and varying) number of users [23].

Figure 2.2 illustrates the transmission and retransmission sequence using direct transmissions, a single relay (such as the aforementioned CDMA and FDMA models), repetition relaying, and simultaneous relaying from the perspective of a single source node.

Including more relay users into the retransmission process decreases the probability that all transmissions and retransmissions are subject to deep fading. Therefore, adding more users increases the diversity gain [20]. However, this comes at three significant costs:

- there are more retransmissions for each user data frame, which increases the energy consumption per data frame;

- either a simple device is used and requires multiple time slots during the retransmission process, or a complex device is required to implement a multi-user distributed space-time coding scheme; and

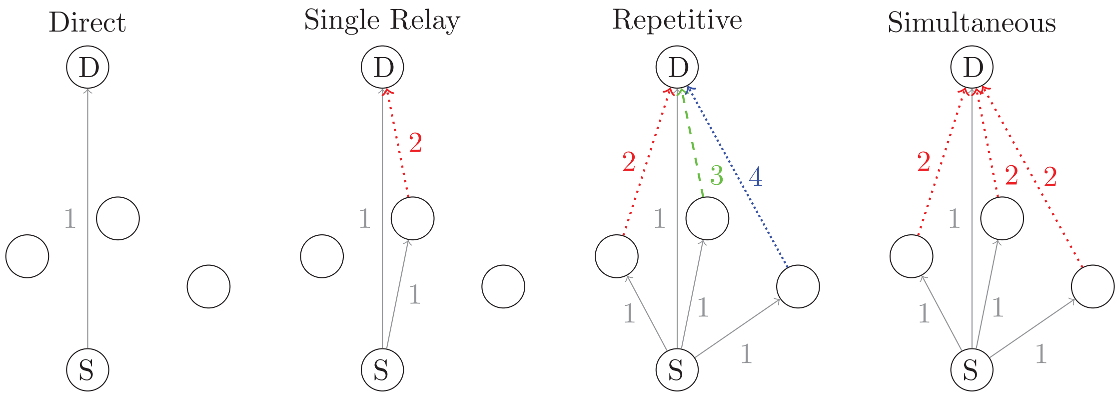

Figure 2.2: Cooperation timing sequence using different relay transmission techniques, where numbers correspond to the time slot in which the frame is sent, from the perspective of a single source node [19]

- each user is required to support multiple transmission interfaces which increases the per-device manufacturing cost.

Solutions, workarounds, and compromises for these costs are discussed in the following sections.

2.4 On-Demand Cooperation

A primary driver for user cooperation is to improve the channel usage efficiency. However, the simple repetition scheme (as shown in Figure 2.2) significantly increases the duration of the channel access required to transmit each frame. Furthermore, while Alamouti has provided a simple diversity scheme for a two antenna system on the same device [7], solutions for an unknown number of *distributed* users remain an open area of research [23]. Therefore, the only viable form of user cooperative diversity using commodity hardware is limited to the single relay model.

The single relay model does not detract from the general result of diversity gain. Bletsas, Shin, and Win analytically prove that selecting the best single relay provides the same diversity gain (and the corresponding reduction in outage rate) as using all available relays [23].

When relays retransmit every frame they receive, this consumes more energy at the relay. To compensate for this, the AaF and DaF cooperative diversity models by Bletsas, Khisti, and Win [20], among others, share the total transmission energy between the source and relay. Furthermore, the transmission rate is doubled, by means of reducing the number of redundant bits in the forward error correction (FEC) coding. This configuration maintains a constant total energy and total channel access duration for both the transmission with cooperative diversity and the traditional direct transmission. The cooperative diversity scheme is shown to reduce the outage rate over a traditional direct transmission in Rayleigh fading channels. However, this is not a general result that is applicable to all channel fading models. Bukhari and Khayam also show that the cooperative model has a higher outage rate than a higher powered direct transmission with additional FEC bits in non-fading channels [28].

Therefore, the best solution is to provide diversity only when it is required [65]. This method is an extension of the traditional automatic repeat request (ARQ) mechanism, and is denoted as cooperative ARQ [38]. Using the same constraints of fixed energy and transmission time, Zimmermann, Herhold, and Fettweis developed a basic retransmission model which showed that cooperative hybrid-ARQ transmissions produce the lowest outage rate in mobile networks with independent fading [111].

2.5 Relay Selection Methods

This section explores key methods to autonomously select the cooperative relay. Aspects of relay selection include:

- nomination scheme;
- link evaluation metric;
- metric weighting;
- contending relay set;
- confirmation and handshaking; and,
- contention and selection.

2.5.1 Relay Nomination Scheme

Centralised Allocation. The foundation cooperative diversity protocols assume that a relay is allocated in a centralised scheme such as the *Optimal Relay Assignment* algorithm (ORA) by Shi *et al* [94]. The ORA algorithm initially allocates a random (but valid) relay for each data link and recursively substitutes relays to maximise the total network capacity. However, ORA requires immediate and accurate knowledge of all link states to ensure the relay selection is valid. This requires a significant overhead to funnel all channel information to the centralised algorithm and a similar overhead to disseminate the relay selection to individual nodes. Therefore, a distributed approach is preferable in real-world applications.

Simultaneous Retransmission. The relay nomination process is avoided by using all available relays. Transmission orthogonality is typically maintained using a coding scheme, traditionally with CDMA in cellular systems and more recently with STC in packet-based communications. However, a distributed STC scheme for an arbitrary number of links over fading channels remains an open research problem and is not a 'solution' to cooperative retransmission relay selection.

Control Signalling. The source node can nominate a relay node either in a custom RTS frame [81, 109] or as part of the actual data frame [61, 62] prior to the destination attempting to decode the frame. In the event of an outage, the relay is already selected and can immediately begin retransmission. However, in cases where the relay did not decode the data frame or is not idle and available for retransmission, the failed frame cannot be relayed. Similarly, the destination node can nominate a relay as part of a customised CTS frame or in a specific request for retransmission using feedback from the relays [9, 12].

Allocated Time Slots. The relay selection reliability can be improved by nominating an ordered set of relays instead of selecting a single relay. The source node defines the set of relay candidates, where each has an opportunity to retransmit the frame during an allocated time slot. This method requires two-hop neighbour knowledge for a source node to identify neighbours that also have a low relay-destination path loss.

Distributed Channel Access via Contention Windows. Finally, neighbours can take it upon themselves to relay frames without colliding with each other. The first protocols simply accessed the channel using the standard CSMA/CA access scheme using an identical contention window size. More recently protocols weight the contention window such that better ranked relays are allocated a higher transmission priority.

Distributed Channel Access via Cooperation Probability. In a similar approach, relays monitor whether another device has already transmitted. If not, contending relays randomly decide whether to retransmit or not at the beginning of each time slot [101]. The same principle can be applied to prioritise transmissions from better ranked relays using weighted retransmission probability values.

2.5.2 Link Quality Evaluation Metrics

Various link quality metrics are used by cooperative retransmission protocols to select a relay. These include relay location, transmission rate, packet delivery ratio (PDR), signal to interference and noise ratio (SINR), received power, and received signal strength indicator (RSSI).

Location. Zorzi and Rao proposed using the node location as the relay selection metric [112]. The principle is to examine the set of relays that decode the source frame and use the relay closest to the destination to forward the frame. The node location can be derived via a fixed table of known positions or via GPS devices on mobile nodes. Location-based relay ranking provides an abstraction for the average path loss that is independent of transitory fading. However, GPS interfaces increase the cost, complexity, and energy consumption of devices and do not provide an accurate location when indoors. Furthermore, even when the location is accurately known, it may not reflect the channel gain in scenarios with interfering objects (shadowing).

Transmission Rate. Some opportunistic routing protocols focus on the transmission rate to minimise the total transmission period in multi-rate scenarios [74, 110]. Nodes passively observe the transmission rate between all pairs of neighbouring nodes to maintain their own link quality table. However, the transmission rate selected by a node is at the discretion of the rate adaptation algorithm. Therefore, an inaccurate rate selection can compound effect this error by using a non-optimal rate for both direct transmissions and cooperative transmissions.

PDR. The PDR is the ratio of frames that are successfully decoded at the receiver to the number sent by the source, and therefore provides the best indication of the actual delivery probability [87]. There are two key issues with using PDR as the primary metric. Firstly, the PDR is a historical value and may not reflect the current link quality in fading channels or mobile networks. Secondly, the PDR will be different for different frame sizes and transmission rates, and therefore the statistical sample of previous frames may not represent the current frame properties [97].

Technically, the PDR is measured at the network layer and potentially includes multiple MAC-layer retransmissions as a single datum. This Thesis uses the terms frame delivery ratio (FDR) and PDR interchangeably and includes MAC-layer ARQ frames as transmissions the rate calculation.

SINR. The value of the SINR provides the most accurate information about the channel's outage capacity, but is challenging, if not impossible, to measure in practice [97].

Received Power. The absolute power received by devices is approximately measured by commodity wireless cards. The received power measures the incoming signal, but also includes the interference and background noise power. Therefore, it is insufficient to comprehensively quantify a link quality [97]. Protocols that use received power as a metric typically use values in watts or milliwatts [21, 99].

RSSI. The RSSI is an abstraction of the signal power and provides a simple metric to rank potential relays [12, 76]. The RSSI is measured by the receiver during the physical layer PLCP header, which is always transmitted at the base rate, and therefore provides a consistent result irrespective of the current data transmission rate. However, this also means that the relationship between RSSI and PDR is strongly dependent on the transmission rate. Furthermore, the RSSI value is only reported for frames that are decoded correctly (and can be allocated to a specific source node) and therefore frames with decoding errors are omitted from the survey.

Aguayo *et al* performed empirical channel measurements in the MIT Roofnet multi-hop network [5] and found there is little correlation between the RSSI and PDR measurements [6]. Judd and Steenkiste investigate this result further and identify this is caused by reflected multi-path signals causing inter-symbol interference in long distance transmissions using 802.11b with a 1 μs symbol time [58]. Therefore, the received power can be above the nominal minimum power threshold even thought the SINR is insufficient to decode the frame. Conversely, Judd and Steenkiste identify a strong correlation between RSSI and PDR when the multi-path propagation delay is short (compared to the symbol duration) such as indoor scenarios or using 802.11a/g with longer symbol periods [59].

There is no consistent approach to reporting RSSI values between wireless card manufacturers; Atheros report a value in the range of 0 to 60, Cisco use 0 to 100, while Intel reports values directly in dBm [97]. For consistency, this Thesis assumes that RSSI values are given in dBm.

2.5.3 Ideal Node Placement

There are three fundamentally different philosophies to identify the ideal node placement: all node positions have equal priority, nodes near to the destination have priority, or nodes mid-way between the source and destination have priority.

Equal Priority. It can be argued that all relays can potentially increase the diversity gain by providing an alternate transmission path without adding complexity to the relay selection process. Therefore, some protocols use the principle that as long as a node has decoded the source data frame and has connectivity to the destination, then it has equal access to relay the frame [9, 39, 40, 93].

Near Destination. The 802.11 MAC only receives frames from the physical layer that are decoded correctly, and therefore cannot propagate transmission errors. Given this initial reference, nodes with a better link to the destination have the lowest probability of failing to transmit the frame and are the best relay candidates [18, 76, 106, 112].

Mid-way. Conversely, some protocols define the best relay as being able to reliably receive the source frame in addition to retransmitting it to the destination. Therefore, the best relay placement is mid-way between the source and destination nodes. There are several methods to identify the centrality of a relay candidate: the harmonic average [21, 72], the minimum value [23], or other custom algorithms [99].

2.5.4 Contending Relay Set

There are three key approaches to defining the set of relays: use a single pre-defined node, elect a relay from all of the available candidate nodes, or elect a relay from a cluster which is a subset of the available nodes.

Single Node. A relay may be nominated during the transmission process [74, 87], or by some other method [107], such that it is the only relay which can potentially retransmit failed frames.

All Nodes. Allowing any node to participate in retransmission (which has already decoded the data frame and has connectivity to the destination) has the highest probability that at least one node is available to relay [9, 39, 93]. This method is simple and does not introduce further processing or network signalling overhead.

Cluster. Using all nodes in the contending set also exacerbates limitations of relay selection algorithms. That is, it increases the retransmission collision rate when using a distributed relay selection algorithm, and it increases the complexity of the code generation when using distributed space-time codes. Therefore, limiting the contending node set to a subset of the available nodes can improve retransmission performance. Maintaining a suitable candidate set for all links, either from a central source [40] or distributed algorithm [76], increases the control signalling overhead in the network.

2.6 Cooperative Retransmission Collisions

Cooperative retransmission collisions occur when two or more contending relays retransmit simultaneously. In the slot-based 802.11 transmission scheme, this means beginning the transmission during the same time slot. This collision probability is independent of hidden node collisions [16].

Some protocol authors assume that the slot timing is sufficiently accurate to synchronise transmissions as spatial diversity in a distributed array [61, 96]. The justification is that the timing resolution of off-the-shelf devices is sufficient for the 1 μs symbol times of 802.11b. Therefore, multiple devices can transmit 'simultaneously' and the destination will observe multiple copies of the same signal with different fading, which improves signal quality.

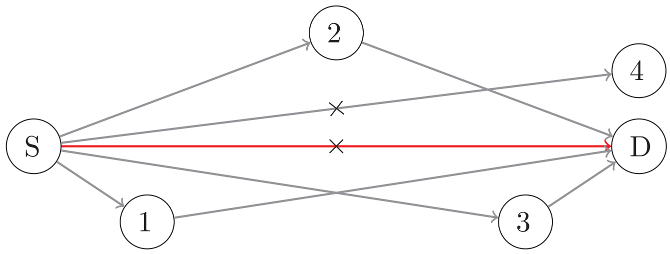

Figure 2.3: Approximate node layout for example scenario used to illustrate the protocol transmission sequence

Empirical testing by Kurth, Zubow, and Redlich shows the synchronisation is not sufficient for data transmissions [64]. ACK frames are the simplest to synchronise because they are transmitted immediately after decoding a data frame. Kurth *et al* used two identical devices configured with the same MAC address as the destination node. The two destinations were sufficiently synchronised to send 802.11g ACK frames with a 90% decoding rate at the source node [64]. However, the shorter symbol time of 802.11b limits the success rate to less than 30% for the higher 802.11b transmission rates.

Furthermore, introducing the distributed timing variations of an arbitrary number of back-off delay slots, including any frame buffering required, on homogeneous devices will generate a significant portion of retransmission collisions for data frames. Therefore, it is assumed that two or more relays 'simultaneously' forwarding a data frame will always result in a retransmission collision failure.

2.7 Opportunistic Routing Protocols to Improve Throughput

This section describes key MAC protocols which opportunistically choose routes to improve transmission throughput while maintaining the reliability of conservative routing protocols.

A simple example is followed for illustrating the protocol transmission sequence. The approximate node network is illustrated in Figure 2.3. In subsequent examples, it is generally assumed that the direct transmissions from S to D fails, and that relay node 4 also fails to decode the data frame.

In the subsequent transmission timing figures, all "blue frames" are unicast transmissions where the arrow indicates the source and destination, "red frames" are broadcast to all nodes, and "white" blocks indicate a channel access back-off time slot. All spaces between frames are assumed to be short inter-frame spaces (SIFS) unless noted otherwise. The distributed inter-frame spaces (marked explicitly as DIFS) effectively indicate a new frame cycle and in practice may result in being beaten to access the channel by another device. For the purpose of the illustrations it is assumed there are no hidden nodes. Finally, some protocol timing sequences are not explicitly defined, therefore some aspects of some protocols are inferred to best represent the protocol in good faith.

The key features of each protocol are summarised in Table 2.1.

2.7.1 GeRaF

The Geographic Random Forwarding routing protocol (GeRaF) by Zorzi and Rao was originally intended for wireless sensor networks but can be applied to traditional mesh networks [112]. The defining behaviour is that the source does not define a relay for the current hop; instead it sends its own location and that of the final destination. Relays know their own positions and use a distributed algorithm to divide up the total remaining transmission into regions.

After the source sends a RTS frame, relays in the region closest to the destination that decode the frame are the first to send a CTS response. If there is a collision between two or more relays, subsequent rounds are entered and the relays randomly decide to continue or not, thereby resolving the collision and electing a single relay. If no relay replies, the source requests relays in the second region to respond, and so on, until a relay is selected. The source then transmits directly to this relay and the process continues. An example frame transmission sequence for GeRaF is shown in Figure 2.4.

The probability that any one node near the destination receives the source frame is low because the path-loss is generally significant. Hence, for transmissions to be reliable, multiple relay nodes in the region close to the destination should be included in the cooperative set. However, this also results in a relatively high probability that multiple nodes decode the source frame and send ACK frames. These ACKs will collide at the source node and subsequent arbitration is required to select a single relay. This process introduces a significant coordination latency to retransmissions.

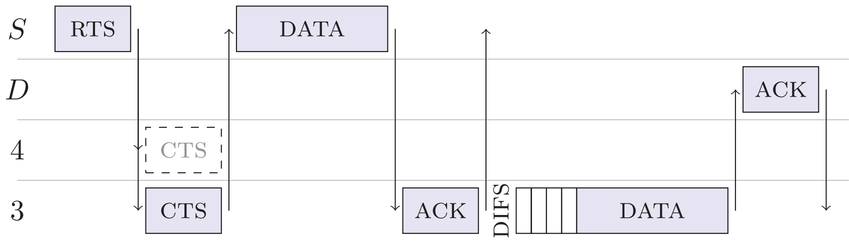

Figure 2.4: Cooperative retransmission sequence for GeRaF [112], nodes 3 and 4 are in the region closest to the destination, their CTS frames would collide but node 4 did not decode the frame, node 3 sends a CTS, then receives the data frame and forwards it to the destination

2.7.2 ExOR

The *Extremely Opportunistic Routing* protocol (ExOR) developed by Biswas and Morris uses a similar principle to GeRaF to forward frames as close to the destination as possible [17]. ExOR was designed for network layer routing, but the same principles are easily extended to MAC-layer retransmissions.

The ExOR relay negotiation is streamlined because the data frame includes an ordered list of candidate relays. Each relay is allocated a dedicated ACK slot to avoid collisions. Each relay that decodes the data frame sends an ACK in the corresponding slot, and other relays hear each other's ACKs. The relay closest to the destination (as defined in the relay list) then forwards the frame. An example frame transmission sequence for ExOR is shown in Figure 2.5.

The fundamental difference between ExOR and GeRaF is that ExOR nominates the relay list as part of the modified frame, where the destination may be more than one hop from the source to minimise the number of transmissions required to traverse an ad hoc network. Conversely, GeRaF maintains a forwarding list which is not part of the frame.

ExOR increases the throughput over conservative routing protocols which choose many reliable hops and is more reliable than aggressive minimum hop count metrics which choose fewer but longer hops. The forwarding scheme was subsequently revised to use the ETX link metric [35] to order the relay list [18]. However, there is still a significant

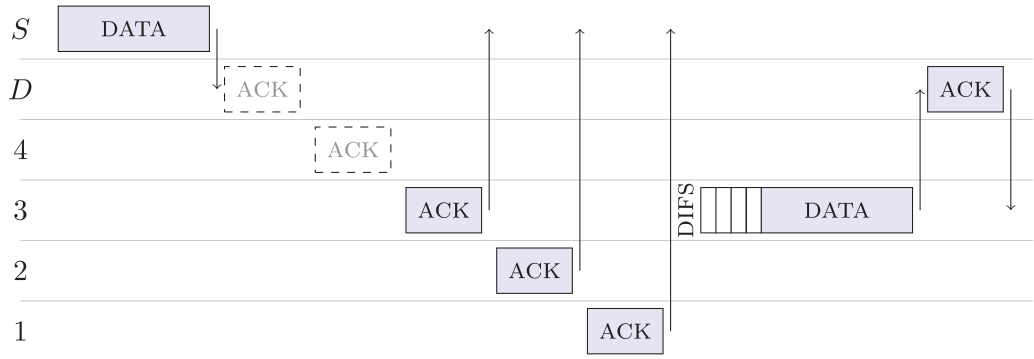

Figure 2.5: Cooperative retransmission sequence for ExOR [17], node 4 is ranked as closest to the destination but failed to decode the data frame, node 3 is the closest node to the destination that decoded the frame and is the relay

coordination overhead to collect sufficient link state information to create the ordered relay set.

2.7.3 rDCF

The *Relay-Enabled DCF* protocol (*r*DCF) proposed by Zhu and Cao is a foundation opportunistic routing protocol in rate-adaptive networks [109]. Nodes passively observe the transmission rates of their neighbours and compare their own rate to both source and destination. If the combined transmission time for the relay node is less than that of the direct transmission, this link is added to the relay node's 'willing list'. Nodes periodically broadcast this list to alert neighbours of their relaying potential.

Subsequently, source nodes check to see if the direct transmission or a potential relay transmission is faster. The source sends a relay RTS (RRTS1) frame to a nominated relay. This is processed at the relay, and if the relay link is still valid, a new RRTS2 frame is sent from the relay to the destination. If the destination accepts the relay route as faster, it replies to the original source with a relay CTS (RCTS), else it suggests using the direct path using a regular CTS frame. An example frame transmission sequence for *r*DCF is shown in Figure 2.6.

*r*DCF is shown to increase network throughput compared to the direct transmission with rate adaptation [110]. However, the neighbour nodes must be moderately dense to ensure a high rate relay is available to maximise the *r*DCF performance.

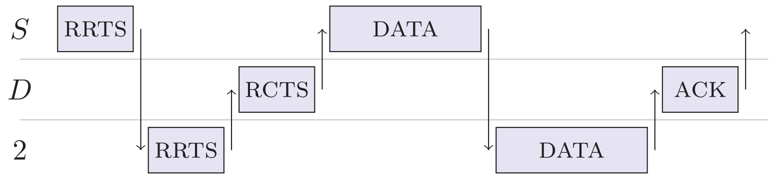

Figure 2.6: Cooperative retransmission sequence for *r*DCF [109], node 2 is selected as the relay by the source node and retransmits the data frame at a higher rate

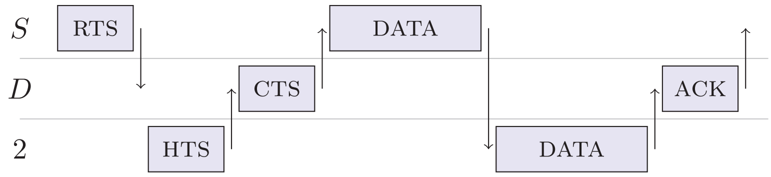

Figure 2.7: Cooperative retransmission sequence for CoopMAC I [74] is a very similar frame transmission sequence to *r*DCF (see Figure 2.6)

2.7.4 CoopMAC

Liu, Tao, and Panwar designed two variations of a *Cooperative MAC* protocol (CoopMAC) to improve throughput over a direct transmission [74]. The cooperation principle and transmission protocol of CoopMAC are similar to *r*DCF.

CoopMAC nodes passively monitor the transmission rates at which frames are sent and stores in a table at each device. When sending a frame, the source node compares the direct transmission rate against the equivalent data rate of the two-hop relay path. If the best identified path is faster than the direct transmission, the relay is nominated as part of the RTS frame. Using the variation CoopMAC I, if the relay is able to help, it will respond with a *helper ready-to-send* (HTS) frame. The source transmits the frame to the relay and the frame is delivered via the opportunistic path. If the relay is unavailable, the source transmits via the direct path at the slower rate. An example frame transmission sequence for CoopMAC I is shown in Figure 2.7.

The CoopMAC II variation is modified to be backwards-compatible with the 802.11 MAC by not using the HTS frame. This is an advantage over *r*DCF in mixed node scenarios [73]. The data frame is instead sent directly to the destination at the higher (cooperative) transmission rate and the relay is nominated as the fourth (optional) ad-

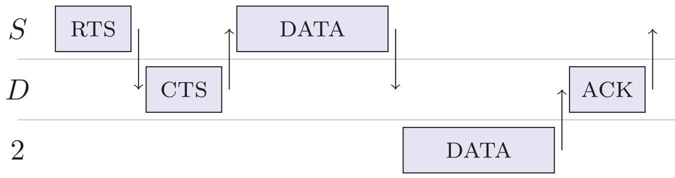

Figure 2.8: Cooperative retransmission sequence for CoopMAC II is faster because there is no explicit messaging to or from the relay node [74]

dress in the MAC header. The uncertainty in the retransmission process is outweighed by reducing the overhead (not sending the HTS frame). This slightly improves performance over CoopMAC I in most tested scenarios [73]. Although CoopMAC II is technically backwards-compatible with 802.11, all nodes involved must use the CoopMAC II protocol. If not, an 802.11 destination may decode the direct frame and immediately send an ACK frame, which would collide with the relayed data frame. An example frame transmission sequence for CoopMAC II is shown in Figure 2.8.

Korakis *et al* extended CoopMAC II to the ad hoc network use case [62]. The frame transmission sequence remains the same as in Figure 2.8. The RTS and CTS negotiation frames are modified to declare the intended transmission rate, and because they are sent at the base rate, they are assumed to be always successfully decoded by neighbours. This method distributes the rate information more effectively between nodes. The cooperative retransmission reduces spatial reuse of the channel. However, this is offset by the reduced total transmission time and the total network performance is improved.

2.7.5 CoopMAC-Zhao

Zhao, Wei, and Xi propose an opportunistic extension to the CoopMAC I protocol (hereafter denoted as CoopMAC-Zhao) [107]. The differentiating feature is the CoopMAC-Zhao source node does not maintain a table of suitable relay candidates. Instead, the relays opportunistically nominate themselves during the transmission process.

The source node transmits a RTS frame and the destination replies with a CTS frame. Both signalling frames also contain the transmission rate recommended by the respective node. If a relay overhears both frames and can support a higher combined rate, where

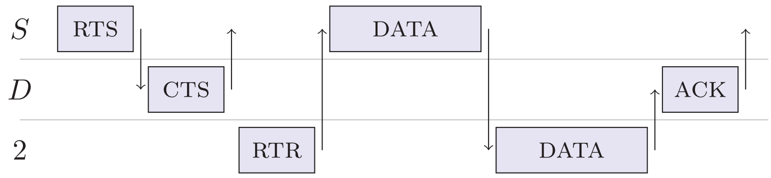

Figure 2.9: Cooperative retransmission sequence for CoopMAC-Zhao when the source elects to use the relay [107]

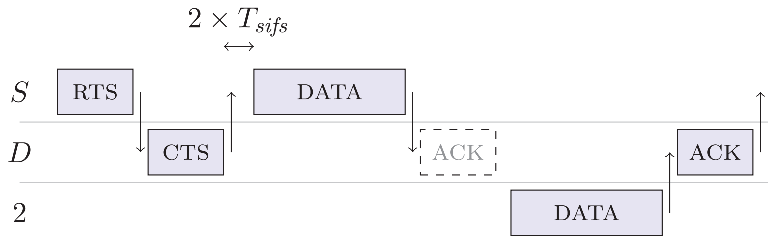

Figure 2.10: Cooperative retransmission sequence for CoopMAC-Zhao when the relay cannot reduce the combined transmission time, but the failed frame is opportunistically retransmitted [107]

the total relayed transmission time is shorter than the direct time, it sends a ready-to-relay (RTR) frame. If the source node accepts this relay, it will send the data frame to the relay at the higher rate. This frame transaction sequence is shown in Figure 2.9.

If the relay cannot decrease the total transmission time, it will not send the RTR frame. However, the relay is aware that it is positioned between the source and destination nodes and will observe the transmission in case retransmission is required. The source will wait an additional SIFS time to allow for the RTR frame before transmitting directly to the destination. If the direct transmission fails and the ACK frame times out, the relay immediately opportunistically retransmits the data frame to the destination because it has a higher transmission rate than the source. This sequence of transmissions is shown in Figure 2.10.

As it is defined, the CoopMAC-Zhao protocol can only accept a single relay candidate for a link. The authors suggest an extension to incorporate a slotted TDMA scheme (potentially similar to that used by ExOR) to isolate the RTR frames and opportunistically retransmit data frames from other contending relays.

2.8 *Opportunistic Retransmissions for Reliability*

The primary responsibility of the MAC is to coordinate frame transmissions to provide a reliable link between two devices within communication range of each other. This section discusses cooperative MAC protocols which improve the transmission reliability for the link.

The network scenario given in Figure 2.3 is continued for the following protocol descriptions.

The key features of each protocol are summarised in Table 2.1.

2.8.1 CMAC

One of the most primitive opportunistic retransmission protocols is the *Cooperative MAC* (CMAC) developed by Shankar, Chou, and Ghosh [93]. CMAC is fundamentally different to the protocols described previously, including the similarly named CoopMAC protocol, because it leverages cooperative communications to reduce the link outage rate instead of increasing throughput. This is achieved using a *cooperative ARQ* scheme where neighbour nodes retransmit failed frames on behalf of the source node.

The basic principle is if a frame is not decoded correctly at the destination, nearby nodes observe the absence of an ACK frame and will attempt to opportunistically forward the data frame to the destination. In case there are multiple such relays available, each attempts to access the channel using the standard 802.11 CSMA/CA back-off scheme. The source node also participates in the retransmission process using the traditional ARQ mechanism. Cooperation is completed when the destination transmits an ACK frame to the original source node. An example frame transmission sequence for CMAC is shown in Figure 2.11.

This protocol is somewhat limited because it assumes that all relays will be equally effective at relaying the frame. That is, a relay with marginal connectivity to the destination has an equal probability of winning access to the channel as a relay node with a low path loss to the destination. Furthermore, in higher node density networks there may be many relays contending for the channel which leads to instantaneous channel saturation and a high probability for collisions.

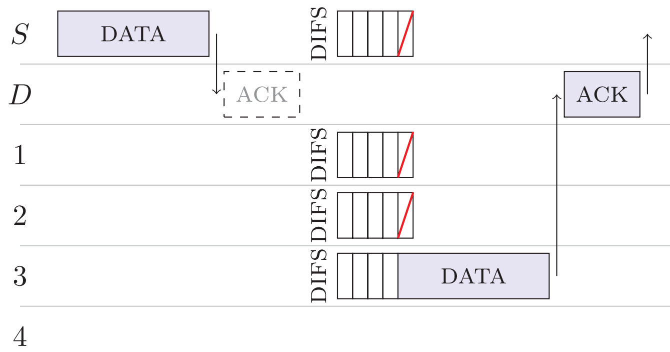

Figure 2.11: Cooperative retransmission sequence for CMAC [93]. All nodes that decode the source frame enter a CSMA/CA channel access contention to retransmit the frame

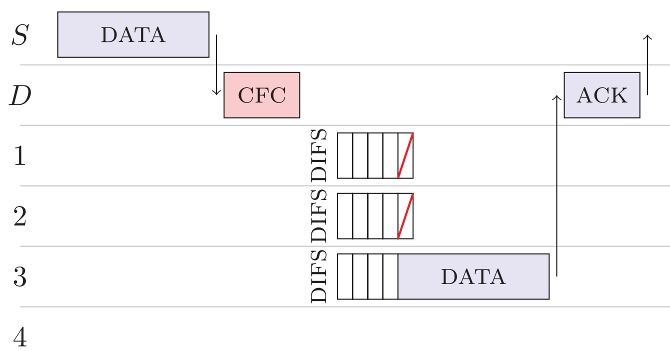

Figure 2.12: Cooperative retransmission sequence for PRCSMA [9], all nodes that decode the source frame enter a CSMA/CA channel access contention to retransmit the frame

2.8.2 PRCSMA

The *Persistent Relay Carrier Sensing Multiple Access* protocol (PRCSMA) by Alonso-Zárate *et al* is a similar cooperative ARQ scheme where the destination sends a call for cooperation (CFC) frame when it fails to decode a frame [9]. Subsequent developments limit the contending set size which reduces the collision rate and improves throughput [10]. An example frame transmission sequence for PRCSMA is shown in Figure 2.12.

The PRCSMA protocol assumes that the decoding error occurs after the MAC header, because the header is required to identify the frame information that the destination includes in the CFC frame. However, the MAC header is transmitted at the same rate as the frame payload and has the same probability of becoming corrupted as any other

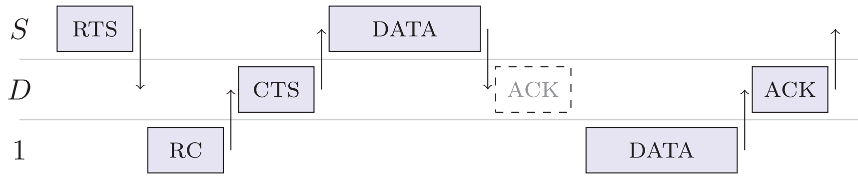

Figure 2.13: Cooperative retransmission sequence for OC-MAC [105]

symbol. Therefore, such protocols are more prone to errors than those which detect failures through the absence of an ACK frame.

2.8.3 OC-MAC

Yuan *et al* propose the *Opportunistic Cooperative MAC* protocol (OC-MAC) to reduce the link outage rate [105]. OC-MAC uses the same basic sequence as CoopMAC but avoids using two-hop neighbour information to reduce the coordination signalling overhead.

The OC-MAC source node nominates a relay in the RTS frame where the only selection criteria is the source to relay link quality. The relay sends a relay confirmation (RC) frame to the destination if it is willing to cooperate. The destination estimates the link quality from the received RC frame and calculates whether the relay can reduce the outage probability. In the case of a direct transmission failure, the relay immediately retransmits the frame to the destination. An example frame transmission sequence for OC-MAC is shown in Figure 2.13.

In principle, this selection scheme is effective in static scenarios when the optimal relay selection does not change frequently. If the scenario requires the relay to change frequently, OC-MAC may take several relay nominations to arrive at a suitable relay. Conversely, the selection scheme proposed by Korakis *et al* will converge on the optimal relay in fewer iterations because relays are selected as a function of both source and destination links through two-hop neighbour link knowledge. Therefore, in mobile scenarios, a small coordination overhead will improve the retransmission performance.

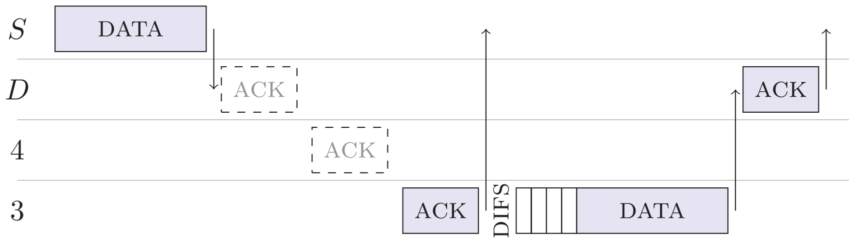

Figure 2.14: Cooperative retransmission sequence for HARBINGER [106] is similar to ExOR (see Figure 2.5) with the exception that once node 3 sends the ACK, nodes 1 and 2 remain silent to let 3 retransmit the data frame

2.8.4 HARBINGER

The *Hybrid-ARQ-Based Intra-Cluster Geographic Relaying* protocol (HARBINGER) was developed by Zhao and Valenti to reduce the link outage rate [106]. HARBINGER is largely an adaptation of GeRaF and ExOR as an opportunistic retransmission protocol.

HARBINGER assumes knowledge of node locations, which the source node uses to define an ordered set of relay candidates. If a direct transmission fails, nodes in the candidate set which decode the frame will send an ACK in its allocated slot. Once a candidate sends an ACK, the remaining candidates return to an idle state. The relay then enters a standard channel access and transmission process to retransmit the frame. HARBINGER also leverages Caire and Tuninetti's hybrid-ARQ model [29] which shows that combining frames containing errors reduces the outage rate. Therefore, HARBINGER uses frame combining at the destination to decode the data frame. An example frame transmission sequence for HARBINGER is shown in Figure 2.14.

HARBINGER is challenging to implement in a commodity device because of the localisation required to select and order a relay set. Furthermore, the relay sets for every (active) link must be distributed to all participating nodes. This introduces a significant overhead. Frame combining on 802.11 devices is theoretically possible, however, most practical devices immediately discard frames with errors. Therefore hardware modification is required to facilitate the combination of multiple frames containing errors.

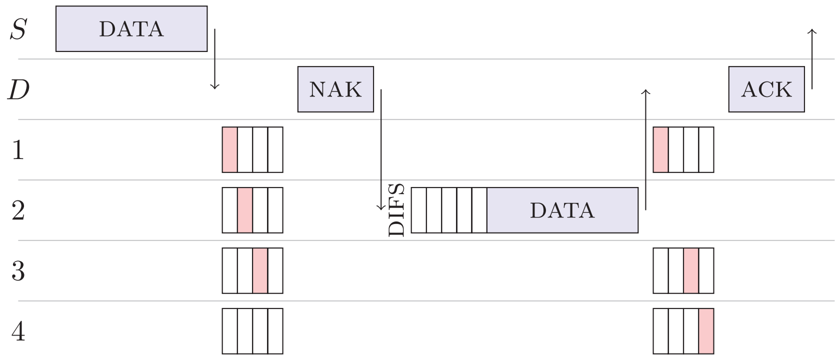

Figure 2.15: Cooperative retransmission sequence for SCARQ [12], node 2 is selected by the relay during the feedback stage, node 4 decodes the retransmission and joins the cooperative set in the second round

2.8.5 SCARQ

The *Selection Cooperation ARQ* protocol (SCARQ), proposed by Anghel and Kaveh, avoids the need to use GPS location by using received signal power to estimate link quality [12]. SCARQ is an extension of the HARBINGER protocol.

After each data transmission is decoded correctly, potential relays send a feedback symbol to alert the destination that it is a suitable relay. The destination measures the received power of each feedback symbol and uses a NAK transmission to nominate the relay with the best link quality to retransmit the frame. An example frame transmission sequence for SCARQ is shown in Figure 2.15.

The SCARQ transmission slot includes cooperative feedback for all frames (including frames correctly decoded by the destination) and therefore wastes a significant portion of the channel capacity. Feedback symbol transmission orthogonality is provided by allocating an ordered position for each node in the cluster. That is, a distributed cluster management scheme must also be introduced to maintain the cooperative set. Furthermore, while it is technically possible to transmit single bit feedback with 802.11 hardware, there remains the open problems of synchronising the feedback bits between contending relays and measuring the received power of every symbol at the destination. Therefore, the SCARQ protocol is not suitable to implement in commodity 802.11 hardware.

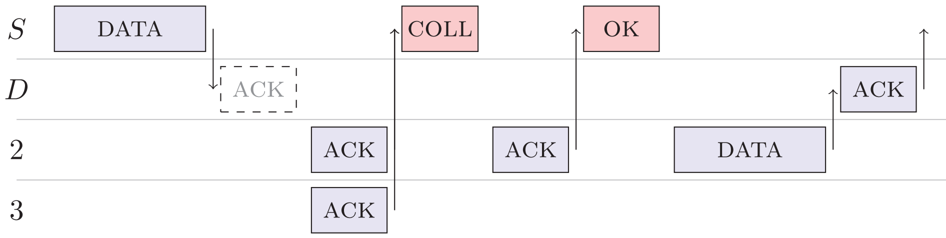

Figure 2.16: Cooperative retransmission sequence for Shah *et al*'s retransmission protocol [92], nodes 2 and 3 are quantised to the 'best' slot and collide during the first attempt, node 3 drops out and node 2 retransmits the data frame

2.8.6 Shah, Mehta, and Yim

Shah, Mehta, and Yim propose a similar relay selection algorithm where nodes contend using a feedback round after a failed transmission [92]. This protocol uses an abstraction of the link quality (simulations use the node separation distance and the path loss exponent to estimate the channel gain) and quantises the value to a result band. There are n result bands for a given scenario with n candidate relays such that, on average, there is one relay per band. Each band is allocated a slot in which to transmit an ACK frame to the source node where relays with the lowest path loss to the destination are ranked first. If two or more nodes collide, a subsequent round is entered, and there is a random chance that each node in that band will drop out of contention. The sequence is repeated until only one node wins contention. An example frame transmission sequence is shown in Figure 2.16.

Simulated results suggest that approximately 4 ACK slots are required to resolve contention with 6 neighbour nodes, or only 130 μs for 802.11n transmission rates. However, using the slower transmission rates of 802.11b, the same negotiation requires 1.7 ms and consumes a significant portion of the channel capacity. Therefore, this protocol is only suitable for fast transmission rates.

2.8.7 Bletsas et al

The retransmission diversity protocol proposed by Bletsas, Lippman, and Reed [21] differs from previous protocol because it uses instantaneous link quality observations

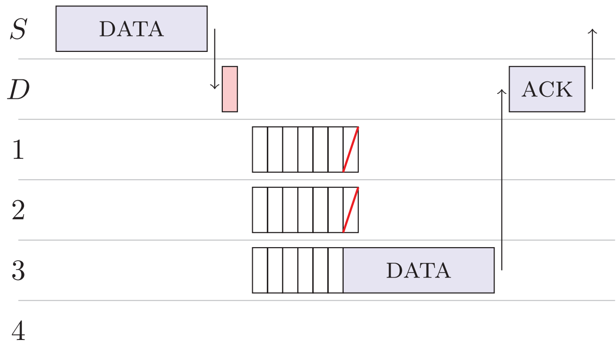

Figure 2.17: Cooperative retransmission sequence for Bletsas *et al*'s protocol with NACK feedback [20], adapted to the IEEE 802.11 frame structure. The collision rate is mitigated by spreading the contention over a large number of delay slots

to select a relay in a distributed system. The original scheme focuses on reducing the outage rate by relaying each frame [21], including those already successfully received by the destination. Subsequent enhancements by Bletsas, Khisti, and Win improved the channel efficacy by incorporating a NACK feedback bit to signal relays to begin the retransmission process [20].

The key innovation in Bletsas *et al*'s protocol is the relay selection via the "method of distributed timers". Relays use the received power (in watts) to both the source and destination to calculate a cooperation delay. The best relay has the lowest path-loss, and by extension a higher probability for successful retransmission, and generates the shortest delay duration. The shortest delay period expires first and this relay begins retransmission using AaF. Other relays hear this transmission and abort the contention process.

The delay period is nominally between 0 and 200 μs with a 1 μs resolution [21], as per the bit-period in the IEEE 802.11b standard [54]. However, this is significantly shorter than the turnaround duration (from receiving to transmitting) for practical devices and may result in collisions between devices with different delay values. The delay slot period can be increased to avoid such collisions but would also increase the retransmission latency.

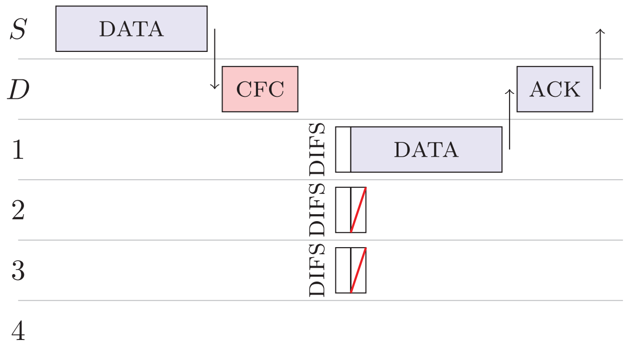

Figure 2.18: Cooperative retransmission sequence for Xiong *et al*'s protocol [101] is very similar to DQCOOP. However the cooperative relay selection typically uses fewer time slots

2.8.8 Xiong, Libman, and Mao

Xiong, Libman, and Mao propose a relay selection scheme where instead of relays selecting a back-off delay, relays have a probability τ to retransmit at the beginning of each time slot [101]. Contending relays each have the same value of τ irrespective of their link quality. To control the retransmission collision rate, the value of τ is inversely proportional to the number of participating relays. The analysis shows that the optimal value of τ will result in a high probability that retransmission is initiated after a very short delay period. An example frame transmission sequence is shown in Figure 2.18.

The key advantage to this method is the practical implementation, as subsequently discussed by Nikolyenko and Libman [82]. Specifically, once the MAC has passed the cooperative frame to the physical layer, the transmission cannot be cancelled if another relay initiates retransmission first.

The ideal value of τ is integral to the protocol performance but it is not clear how this can be efficiently maintained in practice. A potential shortcoming is that all candidates have equal probability of retransmission, however, not all have equal probability of retransmission success.

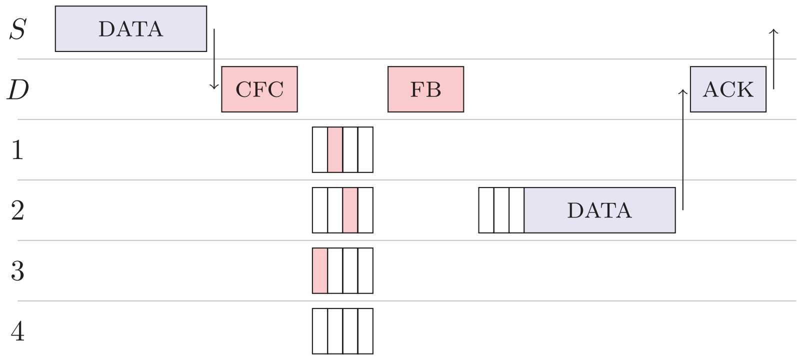

Figure 2.19: Cooperative retransmission sequence for DQCOOP [8]. All nodes send feedback bits in contention slots if they receive the data frame and the destination sends a feedback frame to select the relay(s). Relays then enter a second round of contention to resolve potential collisions before forwarding the data frame

2.8.9 DQCOOP

Alonso-Zárate *et al* also propose the *Distributed Queuing MAC Protocol for Cooperative Networks* (DQCOOP) [8]. A single relay is selected using the tree-splitting process patented by Campbell and Wu [30].

If the destination fails to decode a frame, it sends a broadcast call for cooperation (CFC) message to all potential relays. During the subsequent negotiation period, relays randomly select a time slot to send a feedback symbol to the destination. The destination processes each feedback symbol and, based on the received power and ability to decode the feedback symbol, determines how many relays transmitted in each slot and the relative link quality. The destination sends a feedback frame (FB) to nominate a specific feedback slot as the contention winner. Nodes remember in which slot they sent their feedback symbol and only the nominated relays continue participating. In case there are multiple nodes selected by the destination, any participating relays enter a second contention round using sequential random windows with a tree-splitting collision resolution algorithm. An example frame transmission sequence for DQCOOP is shown in Figure 2.19.

The DQCOOP relay selection process is significantly more complex than other algorithms. Furthermore, an integral component of the selection algorithm is patented and will complicate implementation and future manufacturing.

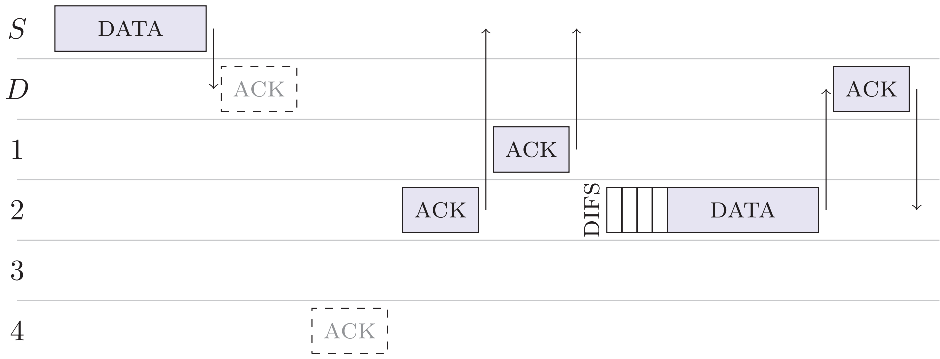

Figure 2.20: Cooperative retransmission sequence for ExOR-Wang [99] where the nominated destination and relays are {D,4,1}. Nodes 2 and 3 participate opportunistically between relays 4 and 1. Node 3 knows that node 2 is more centrally located, so node 3 does not participate to avoid a collision

2.8.10 ExOR-Wang

Wang, Li, and Chen propose an extension to the ExOR protocol [99], hereafter denoted as ExOR-Wang. This protocol introduces a mechanism where nodes not specified in the relay list can opportunistically contend and forward the frame. The 'local cooperative relays' estimate their positions in the transmission chain of nominated relays and opportunistically retransmit in a slot between the nominated relays 'closer' and 'further' than they are from the destination.

All nodes provide periodic link update broadcast messages to maintain two-hop link knowledge. If there are several nodes between nominated ExOR relays, only the 'best' relay positioned mid-way between the nominated relays will forward the message if it decodes the source frame. In the case that two or more relays have the same score (which is possible because the RSS values are quantised) then both relays will attempt to forward the frame during the one time slot between the nominated relays.

There are several opportunities to streamline the ExOR-Wang protocol. Firstly, there is no evidence to suggest that relays near the mid-point do provide the highest quality retransmissions. Secondly, the relay ranking algorithm is significantly more complex than other midpoint selection algorithms such as the harmonic average or the minimum link quality algorithms. Finally, the simulated results show the opportunistic retransmissions collide with each other more than 50% of the time using a realistic node density [99].

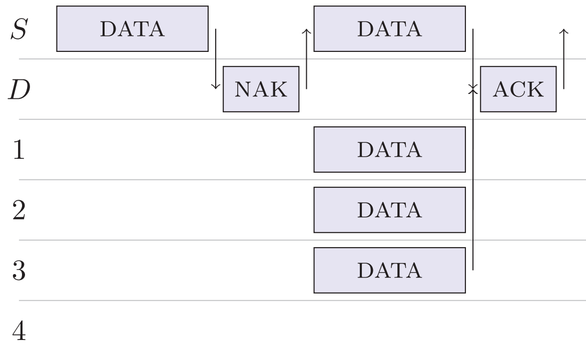

Figure 2.21: Cooperative retransmission sequence for NCSW [40], nodes that hear both the data frame and the NAK simultaneously retransmit the data frame using distributed space-time codes

2.8.11 NCSW

Dianati *et al* propose the *Node-Cooperative Stop and Wait* protocol (NCSW) where a failed transmission results in the cooperative retransmission by a cooperative cluster of nodes [40].

If the destination fails to decode a frame, it sends a NAK frame to request a cooperative retransmission. The entire cooperative set (including the source node) then simultaneously retransmits the failed frame using STC. The destination individually decodes each of the relayed frames, where retransmission is successful if any frame is decoded (i.e. frames are not combined). An example frame transmission sequence for NCSW is shown in Figure 2.21.

A distributed STC scheme for an arbitrary (and varying) number of nodes using individual clock sources is still an open research topic. Therefore the NCSW protocol is an interesting exercise to calculate the ideal outage capacity of a cooperative link, but is not suitable to implement with commodity hardware.

2.8.12 NCSW-Yi

The NCSW protocol was extended by Yi and Hong to select a single relay using the harmonic average of received power [70], hereafter denoted as NCSW-Yi. The result is a cooperative ARQ scheme which selects a relay using a process adapted from Bletsas, Lippman, and Reed [21]. NCSW-Yi uses the same transmission sequence as PRCSMA as shown in Figure 2.12, however, node 2 wins retransmission because it is centrally located between the source and destination.

The theoretical retransmission collision rate presented is less than 2% with a 1 μs slot time and a contention period of 200 slots. However, using the 802.11b MAC slot time extends this retransmission contention window to 4 ms, or approximately three full data frame transmissions and is a significant portion of the channel capacity. This also assumes very accurate signal power measurement, significantly more accurate than what is reported by commodity hardware. Alternatively, using the traditional slot window of 32 time slots would generate a collision rate in excess of 30%. Further, retransmission collisions have a high probability of repeating when the link quality remains fairly static.

2.8.13 SCA

Dai and Letaief propose the *Selective Cooperative diversity with ARQ* (SCA) algorithm [39] which uses STC to provide retransmission orthogonality similar to NCSW.

If the destination detects an error in the received data frame, it transmits a NAK frame to explicitly request cooperative retransmission. All neighbour nodes which correctly received the source frame and the NAK, including the source node, immediately retransmit the data frame using a distributed space time block coding scheme. Therefore, SCA transmissions follow the same protocol as NCSW, as illustrated in Figure 2.21.

A key difference to NCSW is that SCA combines the frames received at the destination before attempting to decode. The combining technique should reduce the outage rate compared to NCSW.

Dai *et al* subsequently show that using selective relaying (rather than using all available relays) can give similar performance to using all relays, but significantly improves the energy fairness of nodes [37]. Cooperative relays are offered an energy bonus to their own subsequent frames as a reward for participating. The energy bonus is effectively a guarantee that nodes will assist by retransmitting frames such that they provide additional energy to the frame and reduce the outage rate. This method is shown to increase the total network lifetime.

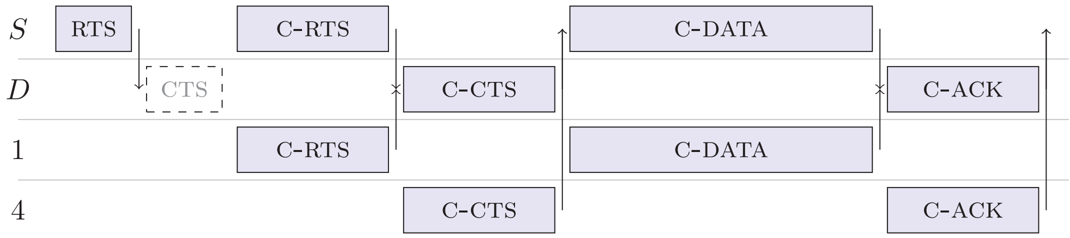

Figure 2.22: Cooperative retransmission sequence for CD-MAC [81] where node 1 is the cooperative partner for the source and node 4 cooperates with the destination

Similar to NCSW, SCA requires a distributed STC scheme with an arbitrary number of relays and is not applicable to commodity hardware.

2.8.14 CD-MAC

The CD-MAC protocol was proposed by Moh *et al* [81]. CD-MAC is a distributed version of Alamouti's MIMO transmission scheme [7].

All nodes select a relay partner, nominally the node closest to it irrespective of the distance or path loss to any potential source or destination. Cooperative transmissions are initiated after if the source does not receive a response CTS frame. Cooperative frames are sent over a series of time slots, where each time slot is split into two phases. The source sends a symbol to the relay during the first phase, which is received and re-encoded using an orthogonal matrix conversion by the relay. Then both the source and relay send the orthogonal frames in the second phase. This process is used for all frames in the transaction; RTS, CTS, data, and ACK. An example frame transmission sequence for CD-MAC is shown in Figure 2.22.

The interleaved transmission structure means that the entire cooperative frame sequence is sent at half of the direct transmission rate. CD-MAC avoids the complex distributed STC scheme used by NCSW and SCA by using one fixed relay. However, this also means that the relay selection is generally not optimal and will use more channel capacity and have a higher outage rate than the ideal relay selection.

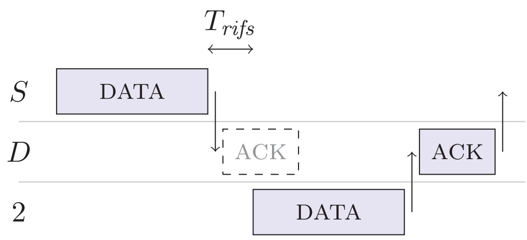

Figure 2.23: Cooperative retransmission sequence for UTD MAC [4], where retransmission begins before another device can access the channel

2.8.15 UTD MAC

The UTD MAC protocol was developed by Agarwal *et al* [4]. Cooperative retransmissions are scheduled to avoid interruptions from other data flows by implementing a shorter contention period, denoted as relay inter-frame space (RIFS). This duration is sufficient to allow an ACK to begin, but it begins transmitting before other devices can access the channel. An example frame transmission sequence for UTD MAC is shown in Figure 2.23.

The UTD MAC protocol does not extend to selecting the cooperative relay to be used. The key contribution of UTD MAC is the higher priority allocated to the relay by the shorter RIFS period (which is shorter than the DIFS period normally required to access the channel). However, current commodity hardware cannot immediately detect whether the channel is busy at the MAC layer. Therefore, it cannot detect whether the destination has started transmitting an ACK frame or not. The MAC only receives updates from the physical layer once frames are either received or transmitted in commodity hardware [82].

2.8.16 2rcMAC

Khalid *et al* propose the *Two Relay Cooperative MAC* protocol (2rcMAC) [61] to opportunistically address the limitations of CoopMAC and UTD MAC. While CoopMAC can improve the throughput, it is not reliable in mobile or highly dynamic fading scenarios and can reduce throughput when the high rate path fails.

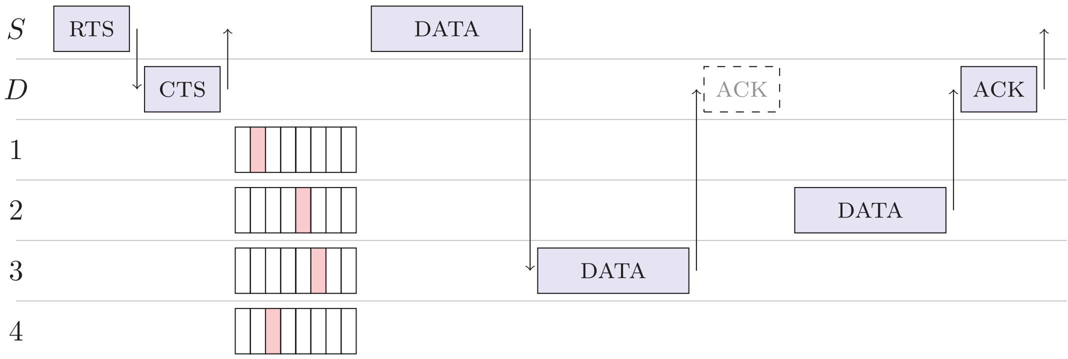

Figure 2.24: Cooperative retransmission sequence for 2rcMAC [61], node 3 offers the fastest total transmission, but is backed up by node 2 if it fails

2rcMAC selects two relays during the initialisation process, the same high-rate relay as CoopMAC, and an additional higher-reliability relay (probably at a lower transmission rate) that will intervene if the high rate cooperation fails. Contending relays measure the signal strength of both RTS and CTS frames and estimate the maximum rate they can sustain to each node. These rates are coded to a 60 bit broadcast relay response (RR) frame sent by each relay. The source monitors the response and selects relays based on the bits set in the response (not the relay address itself). The source nominates the slots in which the high rate and the high reliability relays responded. The relays remember their response and know whether to participate or not. An example frame transmission sequence for 2rcMAC is shown in Figure 2.24.

As the 2rcMAC protocol is defined, it is limited to selecting from four transmission rates in the RR frame. This is nominally the four rates available to 802.11b, but could be extended to 802.11a/g by either selecting four rates to use or increasing the size of the RR frame.

It is assumed that candidate relays will have a unique combination of transmission rates to the source and destination; the source cannot detect whether more than one relay sent a specific RR bit. However, the authors assume that, in the case of two equal relays, no collision will occur because the transmissions will combine at the destination. However, the empirical results of Kurth *et al* show this is not the case, and the colliding transmission has a high probability of failure [64].

2.8.17 Madan et al

Madan *et al* propose such a cooperative beamforming protocol to retransmit failed frames [78]. Beamforming is an attractive option to dynamically focus a transmission to a specific destination. However, it is generally limited to a single device using multiple antennas because of the increased complexity required to synchronise distributed nodes, such as that previously assumed by 2rcMAC.

A key contribution of this design is that it incorporates the cost of obtaining sufficient CSI to identify both which contending nodes offer the greatest benefit to the retransmission effort and the phase at the destination in order to synchronise the distributed transmissions. This is in contrast to other protocols which simply assume the signals will combine to improve the decoding probability [61,96]. Even with this added coordination signalling, the proposed protocol can reduce the retransmission energy consumption by up to 16% for a given outage rate.

After the M relays overhear a failed transmission to the destination, they all simultaneously send a known training sequence to the destination. From the combined received sequence, the destination identifies which relays have the best link and how many relays are required to ensure a successful retransmission. The destination notifies the cooperative relays in a CSI feedback frame. The selected cooperative set uses the information in the feedback frame to tune the power and phase of the cooperative retransmission. An example frame transmission sequence is shown in Figure 2.25.

This protocol meets the theoretical requirements for distributed cooperative beamforming. However, it is too complex for implementation in currently available commodity hardware.

2.8.18 Δ-MAC

Sen *et al* propose the Δ-MAC protocol [87] as a modified 802.11 MAC. Furthermore, the Δ-MAC protocol is already implemented in commodity hardware using a modified MAC layer. All Δ-MAC nodes maintain a sliding window sample of the received PDR from neighbours, which is assumed to be approximately reciprocal. The nodes periodically broadcast this to promote two-hop neighbour PDR information.

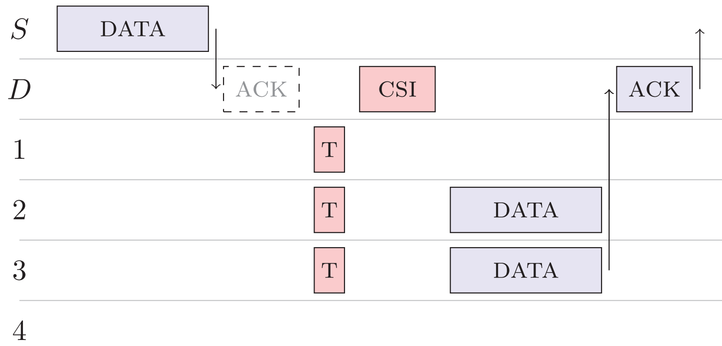

Figure 2.25: Cooperative beamforming retransmission sequence for Madan *et al*'s protocol [78], where nodes 1, 2, and 3 send a training sequence to the destination, which selects nodes 2 and 3 to retransmit the data frame

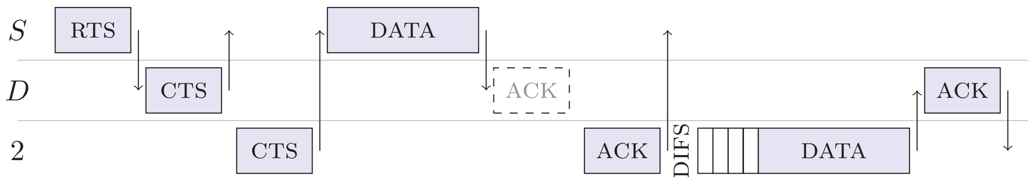

Figure 2.26: Cooperative retransmission sequence for Δ-MAC [87], node 2 has the best joint PDR to both source and destination and is the nominated relay

When a source node is ready to transmit to a destination, it checks the enhanced neighbour table to identify which neighbour has the highest joint PDR to both itself and the destination. This node is then nominated as the opportunistic relay as part of the RTS frame. If this is acceptable, the destination replies with a CTS frame, followed by a CTS from the relay. If the destination decodes the data frame with an error, it remains silent. If the relay decodes it correctly (and observes the absence of the destination's ACK), it sends an ACK to the source and assumes responsibility for subsequent retransmission. An example frame transmission sequence for Δ-MAC is shown in Figure 2.26.

The Δ-MAC protocol avoids retransmission collisions by nominating a single relay as part of the RTS and data frames. However, there is a cost in not only enforcing the use of RTS/CTS signalling, which significantly reduces the available channel capacity, but the transmission signalling is also extended to include an additional CTS and ACK frame even when the direct transmission succeeds.

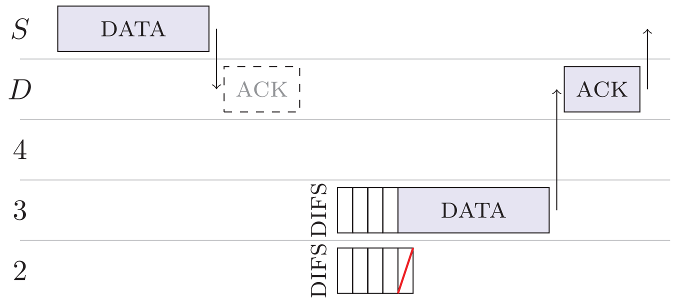

Figure 2.27: Cooperative retransmission sequence for PRO [77], node 4 is ranked as closest to the destination but does not participate because it did not decode the data frame, node 1 does not participate because the cooperation threshold is already met

2.8.19 PRO

The Protocol for Retransmitting Opportunistically (PRO) was proposed by Lu, Steenkiste, and Chen [76], and is implemented and empirically evaluated using commodity hardware. All nodes periodically broadcast a link update frame which contains the RSS and PDR values for its one-hop neighbour links. The two-hop link information is disseminated to all nodes. This allows a distributed relay selection algorithm to generate the same results without additional coordination feedback. For a given source to destination link, the relay selection algorithm ranks all relays by the RSS to the destination, with the RSS to the source resolving any ties. The selection algorithm determines the joint PDR of the relay link and adds more relays to the contending set until the cumulative joint PDR for all links reaches a threshold value, nominally $Th_r = 0.95$ [77]. Limiting the participating relay set to a subset of possible relays reduces the number of retransmission contentions, thereby reducing the number of retransmission collisions.

When idle, participating PRO relays overhear a failed transmission attempt by noticing the absence of an ACK frame. They begin the retransmission process using a random CSMA/CA back-off, where the contention window size is proportional to the relay's cooperative rank. The relay priority is based on the Enhanced Distributed Channel Access model of 802.11e [54] such that relays with a lower path loss to the destination use a smaller contention window and have a higher probability of retransmitting first. An example frame transmission sequence for PRO is shown in Figure 2.27.

Table 2.1: Summary of protocol features

Name	Purpose	Knowledge	Selection	Metric/Location
GeRaF [112]	Throughput	GPS	Cluster slot	Distance (N_d)
ExOR [17, 18]	Throughput	2-hop	Ordered slot	Distance (N_d)
rDCF [109]	Throughput	Local	Fixed in RTS	Rate (both)
CoopMAC [62, 73, 74]	Throughput	2-hop	Fixed in RTS	Rate (both)
CoopMAC-Zhao [107]	Throughput	Local	None	Rate (both)
CMAC [93]	Reliability	Local	Random delay	None
PRCSMA [9, 10]	Reliability	Local	Random delay	None
OC-MAC [105]	Reliability	Local	Fixed in RTS	RSS (N_s)
HARBINGER [106]	Reliability	Local	Ordered slot	Distance (N_d)
SCARQ [12]	Reliability	GPS	Ordered slot	RSS (N_d)
Shah *et al* [92]	Reliability	Local	LQ delay	Distance (N_d)
Bletsas *et al* [20, 21]	Reliability	Local	LQ delay	Power (both)
Xiong *et al* [101]	Reliability	Local	Random delay	None
DQCOOP [8]	Reliability	Local	Tree-split slot	None
ExOR-Wang [99]	Hybrid	2-hop	Distr. score	Power (both)
NCSW [40]	Reliability	Local	STC - all	None
NCSW-Yi [70]	Reliability	Local	LQ delay	Power (both)
SCA [37, 39]	Reliability	Local	STC - cluster	None
CD-MAC [81]	Reliability	Local	STC - fixed	Power (near)
UTD MAC [4]	Reliability	Local	None	None
2rcMAC [61]	Hybrid	2-hop	Feedback bit	Rate/PDR
Madan *et al* [78]	Reliability	2-hop	Feedback bit	Power (both)
Δ-MAC [87]	Reliability	2-hop	Fixed in RTS	PDR (both)
PRO [76, 77]	Reliability	2-hop	Random delay	RSS (N_d)

PRO is arguably the best practical, general purpose, cooperative retransmission MAC published for commodity 802.11 hardware. The two aspects that may potentially limit performance are the link quality update signalling and that relays must be idle before cooperating.

2.9 MAC in Routing

The MAC layer model significantly impacts both the network performance at the routing layer and above, and also the metrics used to calculate the route paths. This section discusses the different link layer models used in the analysis of cooperative MACs, and also the impact of cooperative MAC-layer retransmissions in a multi-hop mesh network.

2.9.1 Link Layer Models

There are a number of approaches that different protocols use when estimating the channel response and corresponding link behaviour. These range from a comprehensive BER response through to simple maximum transmission range comparisons. The ideal model is a balance between computation complexity and accuracy. The MAC layer model is particularly important in multi-hop routes because inaccuracies are compounded through multiple transmissions.

Physical layer diversity performance is typically plotted against the bit error rate (BER), where there is an arbitrarily placed relay with a known BER [65]. This model can provide exact performance information using a variety of theoretical devices. However, such models do not translate well into real-world scenarios because an accurate BER is challenging to capture in a physical device.

Network layer modelling is typically at the opposite end of the spectrum where routing analyses often assume that if a node is within a given transmission distance it will always correctly receive frames, while nodes outside of this range fail to decode frames [80,103].

Aguayo *et al* show there is no distinct transition between "in range" and "out of range" for links [6]. Instead there is a transition of partial connectivity. This is explored in greater detail by Judd and Steenkiste performing experimental tests to quantify the RSSI to PDR relationship [58] using a FPGA channel emulator [57]. Judd and Steenkiste's emulator results create an empirical model of the receiver decoding probability which is vastly different to the "digital threshold" model used by OMNeT++ [42] and ns2 [24].

It is important to distinguish between the receiver decoding probability model and the channel model. The receiver model determines the probability for successfully decoding a frame received at a given power. A channel model estimates the channel gain with a combination of path loss, fading caused by multi-path propagation, and object shadowing. A realistic receiver model is required to provide an accurate estimate of the link performance under any channel model.

Hassan, Krunz, and Matta propose a Markov model to characterise channel behaviour [51]. The state machine models periods of severe and non-severe fading, corresponding to periods of outages and connectivity, respectively. Yu and Miller extend this design by proposing a four state Markov model to improve the generality of the response [104]. The two additional states represent when nodes have sufficiently low path loss that they are never subject to severe fading, and when the path loss is high enough that connectivity is a rare event. The four state model accurately reproduces the frame delivery behaviour in fading channels in the ns2 simulator.

2.9.2 Cooperative MACs with Multi-hop Routes

MAC-layer cooperation is not intended as a substitute for a network layer routing protocol. Routing protocols are still required to find a path from one side of a multi-hop network to the other. However, supporting routing protocols in mobile networks with cooperative MACs can significantly improve the per-link reliability, hence improve the end-to-end performance.

Proactive protocols must compromise on the path discovery and maintenance control messages in order to limit the protocol overhead. The result of this is a significant delay in proactive mesh protocols establishing a new route when the topology changes. Empirical test-beds show the route convergence time is between 14 seconds and one minute depending on the routing protocol [1]. This is a significant outage duration in real-time scenarios, where a frame latency of more than one hundred milliseconds is sufficient to cause noticeable errors in streamed media [75]. MAC-layer cooperative retransmissions are established on a per-frame basis and can virtually eliminate the path outage until an alternate path is found.

Furthermore, a recent empirical energy consumption study by Saavedra *et al* shows that a significant portion of energy consumed is from processing routing information and passing frames between layers in the stack [45]. Empirical observations show a large number of path outages in multi-hop routes in static test-beds [98]. Therefore, using a small amount of cross-layer information and reducing the interaction of higher-layer processing will effectively reduce the energy consumption of cooperative relays.

Wang, Li, and Chen incorporate a cooperative MAC with the ExOR routing protocol [99]. The PDR increases by up to 10% in mobile scenarios where the ExOR protocol is using outdated and incorrect link information. Note that the MAC cooperative retransmission collision rate is approximately 50%, which suggests there is significant opportunity to further improve cooperative performance.

Conversely, Zheng incorporated the CoopMAC protocol with the ETX routing protocol [108] to improve the individual link throughput in a multi-hop mesh. The principle is that ETX selects the path with the fewest hops, however, this may result in selecting longer hops at a lower transmission rate in multi-rate scenarios. Incorporating CoopMAC opportunistic routes between the relay nodes selected by ETX improved the total network throughput by approximately 30% in the simulated scenario.

In summary, coupling a cooperative MAC with a multi-hop mesh routing protocol can offer a significant performance improvement, yet this field is relatively unexplored.

2.10 Evaluation Methods

The cooperative MAC protocols must be evaluated to ensure they improve network performance. The simplest method is to use a wireless network simulator, however, simulators also introduce a number of potential pitfalls that generate misleading results [63]. Instead, this section describes some of the physical test-beds developed and the limitations imposed by the analytic models created to evaluate cooperative protocols.

2.10.1 Real-World Test-Bed Experiments

Some of the more recent cooperative MAC protocols have been implemented in real-world test-beds.

Bletsas and Lippman used simple, custom microcontroller hardware to illustrate cooperative retransmissions, but did not adhere to 802.11 frame transactions [22]. The test-bed was limited to one link, that is, one source node, one destination, and three relay candidates. The results show cooperative retransmissions reduce the outage rate for the link, however, there is a significant amount of work remaining to implement a cooperative protocol to leverage the relay selection algorithm.

Bradford and Laneman used USRP software-defined radio to illustrate an implementation of a single-relay system with emulated 802.11 hardware [26]. Empirical results show that a simple, fixed relay Decode-and-Forward protocol exhibits a significantly faster SNR to BER fall-off than a direct transmission even without frame combining.

Lu, Steenkiste, and Chen implemented PRO using the MadWiFi driver and set up a test-bed [76]. Experiments were conducted to compare the PRO cooperative MAC against the SampleRate transmission rate adaptation algorithm [60] and an unspecified mesh networking protocol. This experiment was conducted in two different scenarios subject to different fading patterns and pedestrian (mobile scattering) activity.

Nikolyenko and Libman implemented Δ-MAC as an extension to the Linux Soft-MAC 802.11 as a kernel module [82]. This implementation can increase TCP throughput by a factor of three in high path loss links, with a similar reduction in frame losses. The *coop80211* module does not prescribe a single relay selection algorithm and provides a suitable platform for comparing different algorithms. However, the kernel module is currently limited (as are all similar implementations) because the MAC does not have access to information at the physical layer; there is no interrupt or flag register to notify the MAC that a frame is currently being received. This feature is critical for most distributed cooperative retransmission MACs which opportunistically elect a relay after the direct transmission fails.

Each experiment showed that cooperative retransmission improved the link outage rate. However, no experiment to date has implemented multiple cooperative retransmission protocols and compared them in a test-bed. Implementing a cooperative protocol in a hardware test-bed is challenging. Implementing several protocols on the same hardware platform and evaluating them in a meaningful comparison has not yet happened.

2.10.2 Comparing Retransmission Protocols in Analytic Models

A direct comparison of the performance of cooperative algorithms is challenging because of the limitations and specificity of existing analytic models. Therefore, many published retransmission algorithms only evaluate cooperative performance against non-cooperative ARQ retransmission schemes.

Some of the assumptions made in the analytic models used to simplify the analysis of cooperative retransmission protocols include:

- the relay always receives the source frame and it successfully forwards the data frame without error [93].
- a relay is located is always located at the optimal location midway between the source and destination nodes [4].
- there are no retransmission collisions [32].
- provided that retransmissions do not collide, then they always succeed [10].
- relays do not collide, but instead are sufficiently synchronised that any retransmissions during the same slot will combine to improve the frame SNR at the destination [61].
- there is a transitional data frame decoding probability, but all RTS, CTS and ACK control frames are correctly decoded [87].
- all links have an identical probability of transmission success [40, 55, 77, 101].

Therefore, it is almost impossible to generate a meaningful conclusion by comparing the analytic models used to evaluate cooperative MAC protocols.

There is a significant opportunity to create an analytic model which evaluates the retransmission performance of a variety of cooperative protocols and relay selection algorithms without implementing the complete protocol in a simulator. It would also be beneficial to allow a variety of path loss models and receiver decoding probability models into the retransmission model.

2.11 Conclusion

A comprehensive literature review was undertaken to identify the highest performing cooperative retransmission MAC protocols and relay selection algorithms. This search focused on cooperative protocols which may be applied to IEEE 802.11 devices without requiring significant modification to the physical layer.

This search has shown that the PRO and Δ-MAC protocols provide the best performance benchmarks for future work. They are the most comprehensively defined, and importantly, are implemented in commodity hardware in practical test-beds.

This literature review revealed four opportunities to improve the performance of cooperative MAC protocols:

- Avoid coordination signalling between contending neighbour nodes by using a relay selection algorithm which requires only partial link state information already available at the MAC layer;
- Optimise the relay selection algorithm to elect a single relay without increasing the computational complexity at the node;
- Evaluate the synergy performance gains created by incorporating a cooperative MAC into multi-hop mesh routing protocols; and,
- Develop an accurate cooperative retransmission outcome model which evaluates the cooperative protocol and relay selection algorithm performance without implementing the entire algorithm in a simulator.

Chapter 3

DAFMAC COOPERATIVE RETRANSMISSION PROTOCOL

3.1 Introduction

Cooperative retransmission protocols typically require an exchange of control messages to coordinate retransmissions by distributed nodes. This chapter evaluates the overhead introduced by the PRO and Δ-MAC retransmission protocols as a function of the node density and frequency of cooperative retransmissions. It is hypothesised that the cooperative coordination signalling overhead occupies a significant portion of the available channel capacity and hence is a limiting factor in determining the total network capacity.

This chapter proposes DAFMAC - a cooperative retransmission protocol that operates in a distributed and autonomous manner without coordination messaging. The fundamental protocol is explained and a simple relay ranking algorithm is described. Performance of DAFMAC is estimated by simulating the cooperative retransmission success rate of the relay selection algorithm. The results indicate that DAFMAC potentially offers cooperative retransmissions with a lower total overhead than other protocols. This will be established analytically in subsequent chapters.

Finally, pathological scenarios are discussed and potential solutions are proposed to improve DAFMAC performance.

3.2 Objective of Cooperative Retransmission Protocols

Retransmission protocols (including non-cooperative retransmissions such as 802.11 ARQ) reduce the link outage rate by providing temporal diversity. That is, after a transmission failure, the source node waits some period of time for the channel fading to improve and retransmits the frame. This process can take several attempts, which increases the energy consumption and lowers the priority of the data flow by using a larger contention window to allow the channel fading to pass. The ideal cooperative retransmission improves each of these facets.

The most important objective of a cooperative retransmission protocol is to reduce the per-transmission outage rate. This translates to increasing throughput, decreasing frame jitter, and decreasing the rate of dropped frames at the MAC layer.

Secondly, a cooperative retransmission protocol should not increase the energy use of the network. A popular concern with cooperative protocols (at both MAC and network layers) is why a node should expend energy to help another node without any reward. Therefore, a successful cooperative protocol should provide a motivation for cooperation, the most direct of which is to actually reduce the energy consumption.

The final key objective is to improve the fairness of links. That is, cooperation should not benefit some users at the expense of others. This objective is measured by comparing the performance equity across each data flow in a network.

Secondary objectives could include: maintaining backwards compatibility with the 802.11 MAC, minimising the implementation footprint and computational complexity, and minimising the relay coordination signalling and messaging overhead.

3.3 Overhead of Cooperative Retransmission Protocols

The primary motivator is the hypothesis that a significant fraction of the channel capacity is consumed by retransmission coordination control updates. The following sections discuss the function of the coordination broadcasts, their implementation, and estimate their impact on the channel utilisation.

3.3.1 Purpose of Coordination Update Transmissions

The PRO [76] and Δ-MAC [87] opportunistic retransmission protocols periodically broadcast neighbour link quality to disseminate two-hop neighbour information. The periodic broadcast consumes significantly less channel capacity than the per-retransmission feedback messaging, such as that employed by the SCARQ protocol [12]. Both PRO and Δ-MAC use the neighbour link quality in a unique way.

PRO uses the two-hop neighbour information to ensure that all neighbour nodes are aware of the link quality to both the source and destination nodes for each potential relay [77]. The purpose is to facilitate the ranking of neighbour nodes to identify those with the highest probability of successful retransmission. Because the information is broadcast to all neighbours, each node can use a distributed ranking scheme to produce the same result. The ordered node list is used to limit the number of participating nodes, which reduces retransmission collisions.

Δ-MAC uses the neighbour information at the source to identify which neighbour has the best relay prospects to the destination [87]. The source node then nominates a suitable relay as part of a customised RTS frame. This almost eliminates the possibility of retransmission collisions, at the expense of forcing the mandatory use of the RTS/CTS collision avoidance frames.

3.3.2 Broadcast Update Frame Implementation

The broadcast update processes for PRO and Δ-MAC are similar. In ad hoc network scenarios, each device broadcasts the link parameters for each neighbour.

PRO's broadcast messaging frame format has not been explicitly defined in the literature, therefore, the following conservative assumptions are made:

- a 48-bit MAC address is used as the node identification field as no assumptions are made about the network layer;
- the PDR is quantised with 8-bit precision; and
- the moving average RSS value is quantised with 8-bit precision.

Assume a large and uniformly distributed random network topology where each node has ρ_n neighbours within transmission range. Therefore, the payload of a PRO coordination message contains $M_{upd}^{P} = 64\rho_n$ bits of information.

The Δ-MAC relay selection algorithm only requires link PDR, thus a Δ-MAC coordination message payload contains $M_{upd}^{\Delta} = 56\rho_n$ bits.

Table 3.1: Timing parameters for 802.11

Parameter	Time using 802.11b at 11 Mb/s (μs)	Time using 802.11a/g at 54 Mb/s (μs)
T_{sifs}	10	16
T_{slot}	20	9
T_{difs}	50	34
T_{phy}	192	24
T_{rts}	206.5	28
T_{cts}	202.2	28
T_{data}	1235	246
T_{ack}	202.2	28
T_{rts}^{Δ}	210.9	28

3.3.3 Broadcast Update Channel Usage

Each broadcast transmission consists of a PHY header, a MAC header, and the data payload. Additionally, the channel is also reserved for one DIFS period after the transmission before another device can access it. The frame transmission duration is:

$$T_{tx} = T_{phy} + \frac{\left\lceil \frac{M_{mac}+M_{tx}}{M_{sym}} \right\rceil}{R_{sym}} \tag{3.1}$$

where T_{phy} is the duration of the PHY training sequence and frame header; M_{mac} is the size of the MAC header, frame check sequence (FCS) and trailer; M_{sym} is the number of bits per symbol for a given transmission rate; and R_{sym} is the symbol transmission rate. Example transmission periods are given in Table 3.1 are based on a 1400 byte data frame and the modified Δ-MAC RTS frame [87]. The 802.11b 11 Mb/s transmission rate uses $R_{sym}^{11\text{M}} = 1.375 \times 10^6$sym/s and $M_{sym}^{11\text{M}} = 8$bits; while 802.11a/g at 54 Mb/s uses $R_{sym}^{54\text{M}} = 250 \times 10^3$sym/s and $M_{sym}^{54\text{M}} = 216$bits. Note, the duration of the broadcast update is significantly increased when using the "base transmission rates" as suggested by the 802.11 Standard [54]. However, most modern devices are capable of transmitting the higher rates, thus it is assumed that devices are capable of receiving at all rates.

Assume each node has approximately the same transmission range. Therefore, a node should receive ρ_n updates per update period T_{upd} from its neighbours. In addition, nodes will receive interference from updates outside of the transmission range. The interference range is approximately 1.78 times the transmission range [102]. If there are $\rho_n + 1$ nodes inside the transmission range, including the source, there are approximately:

$$N_{int} \approx 3.2(\rho_n + 1) \tag{3.2}$$

nodes inside the interference range [102]. Therefore, the proportion of the channel consumed by broadcast updates from all devices in the interference range is:

$$T_{int} = \frac{T_{prd}}{N_{int} T_{tx}^{upd}} \tag{3.3}$$

where the update period is nominally $T_{prd} = 1$ second for both PRO [76] and Δ-MAC [87].

3.3.4 Estimating the Overhead of Cooperative Protocols

There are two components of cooperative retransmissions which consume the channel capacity: the coordination signalling, and retransmissions that are not decoded correctly at the destination.

The durations of a PRO direct transmission, and a full cooperative retransmission, are:

$$T_{msg}^{P} = T_{difs} + T_{data} + T_{sifs} + T_{ack} \tag{3.4}$$

$$T_{coop}^{P} = 2T_{difs} + 2T_{data} + 2T_{sifs} + 2T_{ack} \tag{3.5}$$

respectively, without RTS/CTS collision avoidance enabled. Conversely, the respective Δ-MAC direct and retransmission durations, including the modified RTS/CTS signalling, are:

$$T_{msg}^{\Delta} = T_{difs} + 5T_{sifs} + T_{rts}^{\Delta} + 2T_{cts} + T_{data} + 2T_{ack} \tag{3.6}$$

$$T_{coop}^{\Delta} = 2T_{difs} + 8T_{sifs} + 2T_{rts}^{\Delta} + 3T_{cts} + 2T_{data} + 3T_{ack}. \tag{3.7}$$

Let R_r be the rate of direct transmission failures where retransmission is required. Denote the rate of retransmission collision where subsequent retransmission attempts are required as R_c. PRO has an average collision rate of approximately $R_c \approx 4\%$ [77] and

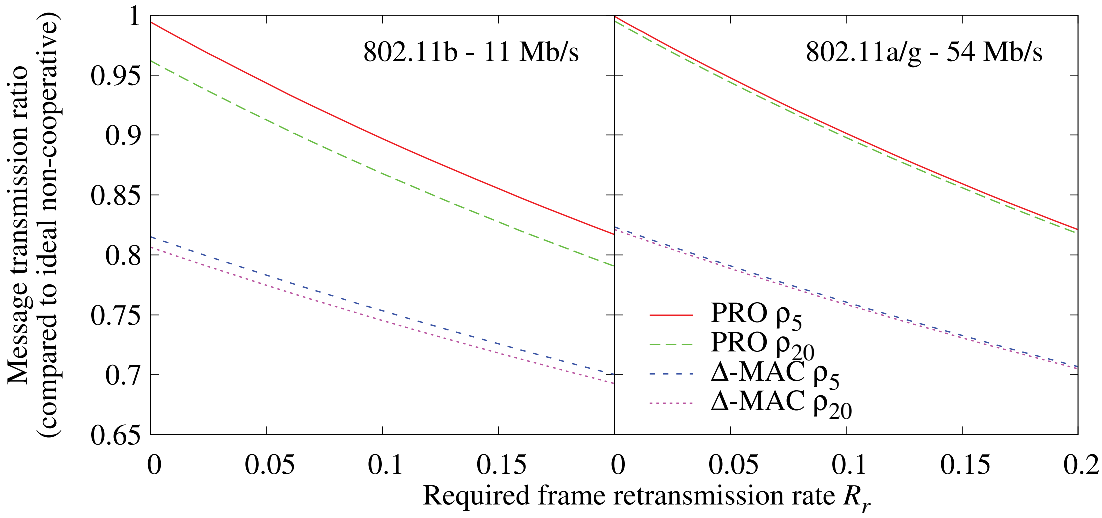

Figure 3.1: The impact of the Δ-MAC overhead is significantly greater than PRO because of the forced custom RTS/CTS transaction for all data transmissions

Δ-MAC is assumed to have zero collisions because the source node specifies a single relay to participate in retransmission.

The rate of user messages that can be transmitted per second is therefore:

$$N_{msg} = \frac{1 - T_{int}}{(1 - R_r)T_{msg} + \frac{R_r}{1-R_c}T_{coop}} \tag{3.8}$$

using the protocol-specific values for T_{int}, T_{msg}, T_{coop} and R_c. This message rate efficacy is the ratio of the rate in (3.8) compared to the ideal number of frames per second of a non-cooperative protocol. For the Δ-MAC ratio, the non-cooperative transmission rate includes RTS/CTS transmissions.

A plot of the normalised maximum message rate is shown in Figure 3.1. The first key observation is the impact of the Δ-MAC overhead is significantly greater than the PRO overhead because of the modified control frame sequence in addition to the the broadcast updates and regular RTS/CTS frames. Secondly, increasing the number of neighbours in the broadcast update has an insignificant impact using a 54 Mb/s transmission rate, but may impact the available channel using lower transmission rates because of the increased update message transmission duration.

3.3.5 Allowable Collision Rate for Equivalent Performance

Cooperative retransmission protocols can attempt to select a relay using a distributed algorithm without explicit coordination signalling, as demonstrated in [21,92]. There will be some rate of retransmission collisions where two or more relays attempt to retransmit in the same contention slot. This section calculates the equivalent collision rate for such protocols where the total channel wasted is equivalent to the PRO and Δ-MAC overhead.

Eliminating the coordination transmissions sets channel interference time to $T_{int} = 0$. From (3.8), the equivalent performance is when:

$$\frac{1}{(1-R_r)T_{msg}^{Eq} + \frac{R_r}{1-R_c^{Eq}}T_{coop}^{Eq}} = \frac{1-T_{int}}{(1-R_r)T_{msg} + \frac{R_r}{1-R_c}T_{coop}}. \tag{3.9}$$

Re-arranging this gives:

$$R_c^{Eq} = 1 - \frac{T_{coop}^{Eq}(1-T_{int})R_r}{(1-R_r)(T_{msg} - (1-T_{int})T_{msg}^{Eq}) + \frac{R_r}{1-R_c}T_{coop}} \tag{3.10}$$

as the maximum equivalent collision rate for equal performance. For a more balanced comparison, the T_{msg}^{Eq} and T_{coop}^{Eq} values should include the RTS/CTS signalling exchange when comparing overhead to Δ-MAC.

A reasonable range for the R_r value is $R_r \in [0, 0.1]$; less than 10% of frames would require retransmission in a realistic scenario. It is anticipated that values greater than this would justify a network layer routing solution for greater medium efficacy.

The equivalent collision rate equal retransmission performance approximates a hyperbolic function and is shown in Figure 3.2. That is, as the expected rate of retransmissions increases, the maximum rate of collisions must decrease to maintain a constant delay profile.

The lowest retransmission overhead is for PRO using 802.11a/g at 54 Mb/s which has an equivalent collision rate of between 5% and 8% depending on the neighbour density. The PRO overhead is higher when using 802.11b transmissions at a lower data rate. Due to the significant overhead of Δ-MAC, the equivalent collision rate is above 50% even when the zero-coordination protocol includes RTS/CTS control frames.

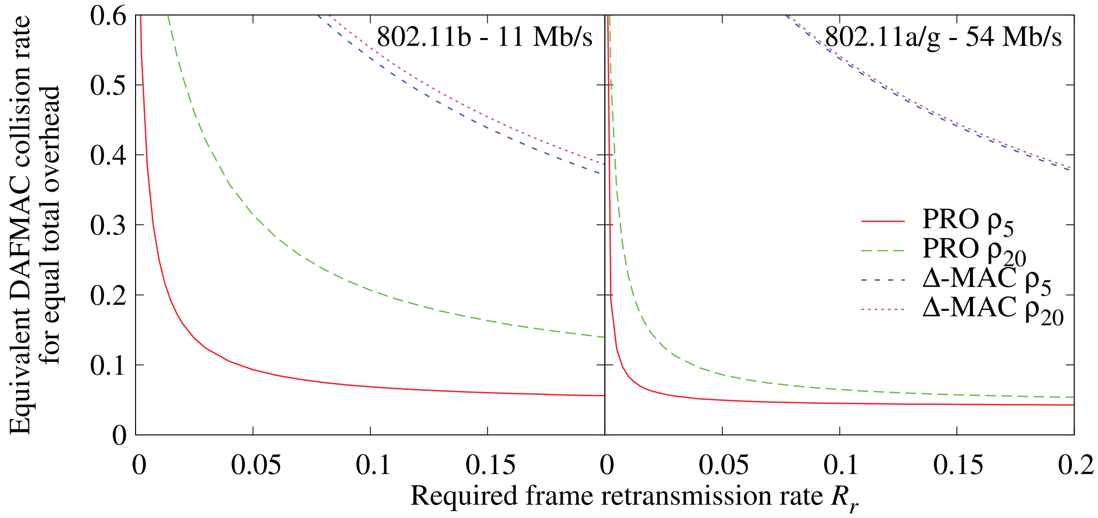

Figure 3.2: The minimum equivalent collision rate for PRO is between 5% and 8%, while Δ-MAC has a significantly higher overhead

The zero-coordination retransmission concept is viable if the collision rate approaches (or is less than) the equivalent loss rate. When retransmissions are required less frequently, the collision rate has a smaller impact on channel usage compared to the (constant) link quality update broadcasts. By extension, a zero-coordination protocol will not impact the network capacity in scenarios where retransmission is never required.

3.3.6 Discussion of Protocol Overhead

This is a simplified model of transmission performance that does not consider the possibility of direct transmission collisions between users (see Bianchi's analysis [15] for such a discussion).

However, this model clearly shows that both PRO and Δ-MAC require a significant coordination overhead to facilitate cooperative retransmissions. A retransmission protocol without explicit coordination overhead will be competitive as long as the total outage probability remains lower than the calculated overhead. The objective of the remainder of this chapter is to show the equivalent collision rate for a zero-coordination cooperative retransmission protocol may be low enough to outperform PRO and Δ-MAC.

3.4 DAFMAC Cooperative Retransmission Protocol

The Decode And Forward MAC (DAFMAC) protocol is proposed as a zero-messaging distributed approach to relay selection for opportunistic cooperative retransmission. This section introduces the basic DAFMAC design philosophy and cooperative retransmission protocol.

While DAFMAC maintains a focus on the performance objectives outlined in Section 3.2, the protocol design is fundamentally different to existing cooperative retransmission protocols. A key difference between DAFMAC and some other retransmission protocols is the altruistic behaviour of nodes; relays with a frame already buffered to send will also participate in retransmission. Philosophically, a node may sacrifice an opportunity to transmit its own frame in order to cooperatively retransmit, with the expectation that this 'favour' may eventually be returned when one of its frames requires retransmission. This has a significant benefit on retransmission fairness as the network load increases because it ensures all suitable relays actually participate even if they already have a frame buffered.

The second key design difference is that DAFMAC does not use coordination signalling between nodes contending to retransmit frames. Therefore, DAFMAC does not introduce any overhead when cooperative retransmissions are not required. Instead, the hypothesis is that local link quality knowledge is sufficient to elect a single cooperative relay using a distributed timer scheme similar to that proposed by Bletsas *et al* [21, 22].

The basic DAFMAC protocol operates as follows. A source node N_s transmits a data frame to destination N_d and a set of nodes $\mathcal{N}_n$ are neighbours (within transmission range) of both N_s and N_d. This transmission is overheard and decoded by a set of contending relays, $\mathcal{N}_c \subseteq \mathcal{N}_n$, and stored in a buffer on each. If destination N_d receives the message, it acknowledges with an ACK packet and the relays flush their buffers. Relays expect to hear an ACK after one SIFS period (T_{sifs}), as per the IEEE 802.11 MAC standard [54], otherwise they enter a cooperative retransmission contention period. The 'best' contending relay, $N_b \in \mathcal{N}_c$, will transmit first and forwards the data frame to N_d. After retransmission, N_b immediately flushes its buffer and returns to idle. Upon receiving the cooperative retransmission, other potential relays flush their buffers and return to the idle state. In summary, the set of $\mathcal{N}_c$ nodes will contend for retransmission, but only the best node N_b will actually cooperate.

Selection of the best relay is a significant area of research and there is no single best method which is optimal for all networks. Several techniques are discussed in Chapter 2. DAFMAC retransmissions are opportunistic because the source has already sent the frame (and the set of contending relays has already received it) before cooperation is initiated. Therefore, the source-relay link may be ignored in the relay selection algorithm because neighbours that failed to receive the frame simply return to an idle state. The best contending DAFMAC relay is defined as that with the best signal to noise ratio (SNR) on the channel from the relay to the destination, i.e.:

$$SNR_{b,d} \geq SNR_{i,d}, \ \forall N_i \in \mathcal{N}_c. \tag{3.11}$$

The relay estimates the channel gain using the received signal strength (RSS) of frames received from N_d and by assuming the forward and reverse channels are reciprocal and devices are identical. In reality, all devices are not homogeneous [58], however, this approach is sufficient for relay node selection. Relay devices may be in a physical location that provides a small path-loss to the destination but the RSS information is outdated and suggests a high path-loss. In such cases, the relay will contend with a longer contention delay until the RSS value is updated. The impact of this effect is expected to be insignificant in most scenarios.

The retransmission protocol uses distributed timers where a potential relay will transmit once its timer delay expires, as first introduced by Bletsas, Lippman, and Reed [21]. Node N_i generates a contention delay t_i that is inversely proportional to the perceived relay-destination link quality. Thus, the relay with the best link to the destination will wait for the shortest time, $t_b \leq t_i$, and hence retransmits first. The value of the delay t_i is calculated using the relay selection algorithm described in Section 3.5. Contending nodes are approximately synchronised because all timers begin their count-down process when the ACK frame times out.

Relay N_b forwards the original frame where the only modification is to set the retry flag in the MAC header. The relay node effectively masquerades as the original source and the process is transparent to the destination. Frames flagged as retries are omitted

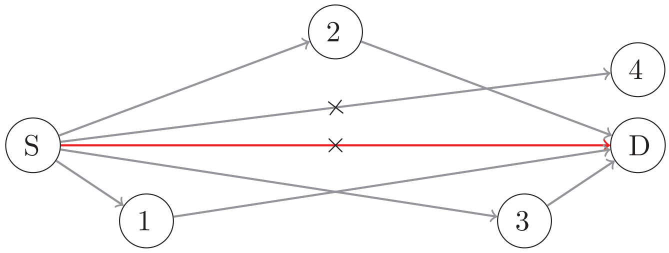

Figure 3.3: The same example scenario where N_s transmits a frame that is received by N_1, N_2, and N_3, but not by N_d or N_4

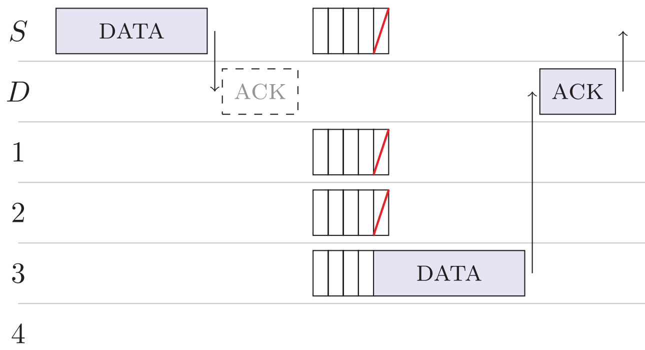

Figure 3.4: Timing diagram of a DAFMAC cooperative retransmission

from any RSS measurements by other nodes to avoid corrupting the link quality table with incorrect values and are never retransmitted by another relay. The destination N_d receives the data frame with N_s as the MAC frame header source address, which is then used as the ACK frame destination address.

The same example network configuration used in Chapter 2 is shown in Figure 3.3. The corresponding DAFMAC retransmission timing diagram is shown in Figure 3.4. In this case, N_1, N_2, and N_3 overhear the frame but N_4 does not. Relay N_3 has the best link to the destination, therefore generates the shortest contention delay and retransmits the data frame first.

DAFMAC nodes retain the traditional IEEE 802.11 ARQ system if no suitable cooperative relays are available. However, the source node N_s retransmission timeout period is calculated using the cooperative relay selection algorithm instead of the traditional exponential back-off window. Therefore, N_s effectively participates in the cooperation contention. This improves performance when N_s has a relatively low-loss path to N_d

and the transmission failure is an anomalous event (for example, due to transient noise). It also prevents the ARQ random back-off algorithm generating a short retransmission delay and interrupting a cooperative retransmission with a higher probability of success. In the previous example, N_1 and N_2 abort cooperation when N_3 transmits, but N_s freezes the back-off counter and is ready to resume if the cooperative retransmission fails.

Figure 3.5 shows the protocol operations performed by N_s and N_i during a transmission attempt. N_d behaves in exactly the same manner as a standard IEEE 802.11 destination node.

The DAFMAC protocol is compatible with legacy 802.11 networks, in the sense that plain 802.11 nodes will perform no worse than in a pure 802.11 network. In the case where the destination is plain 802.11 and the source uses DAFMAC the destination can benefit from cooperation. A plain 802.11 destination will acknowledge the incoming data frame and will not be aware of the cooperative retransmission. However, DAFMAC retransmissions will be of no benefit to a legacy source node because it will expect the ACK frame before the cooperative retransmission is complete and will therefore enter the ARQ retransmission process. In this case, the destination will acknowledge the cooperative frame, but the source will ignore the ACK and continue the non-cooperative retransmission. DAFMAC will only benefit legacy 802.11 source nodes if a delayed ACK is accepted by the MAC firmware implementation.

3.5 DAFMAC Cooperative Contention Resolution Strategy

This section discusses the DAFMAC contention delay algorithm parameters and describes how the values are selected. All parameters are defined as part of the DAFMAC configuration or are physical values that must be measured on each device. A proof-of-concept contention delay algorithm is then described.

3.5.1 Algorithm Parameters

The DAFMAC delay algorithm parameters are summarised in the following list.

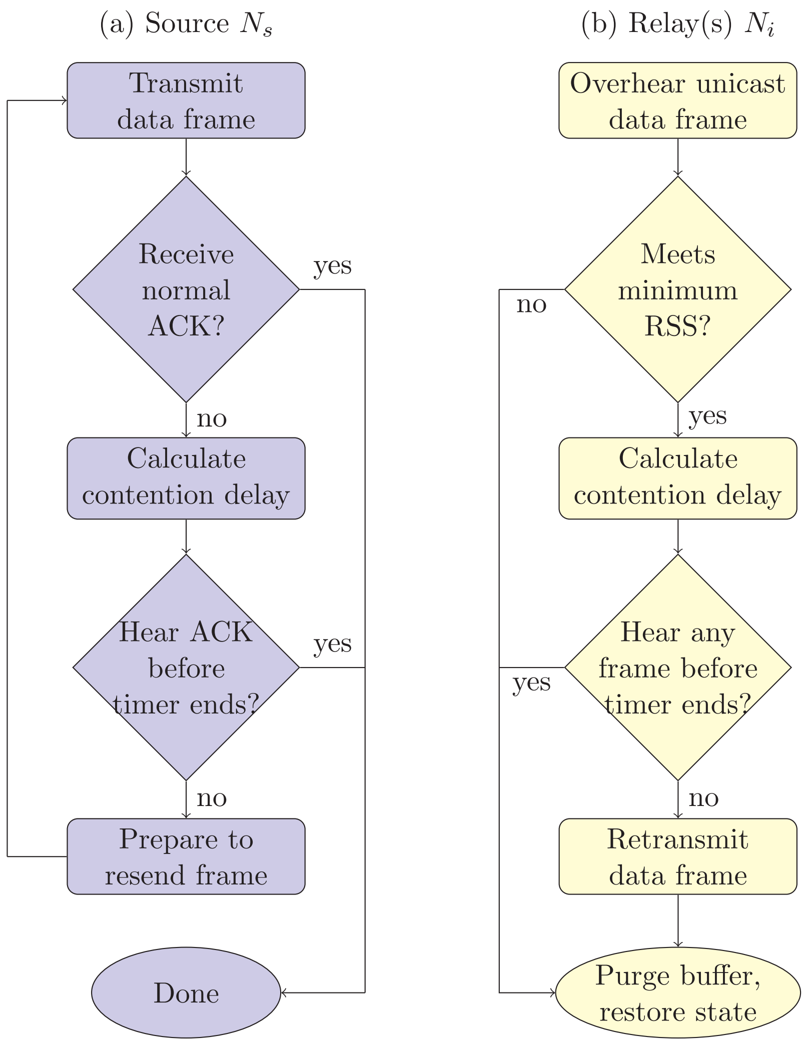

Figure 3.5: DAFMAC protocol flow chart for the source node N_s (a) and all relays N_i (b) during a cooperative attempt

- s_{max} – the maximum value for contention delay t_i, in units of T_{slot}. The nominal value is $s_{max} = 32(T_{slot})$, the same as a regular channel access contention window for 802.11.

- $d_{a,b}$ – the distance between nodes N_a and N_b.

- $d_{0.9}$ – the distance between nodes where the data frame transmission success rate is 0.9. This is used to normalise the distance $d_{a,b}$.

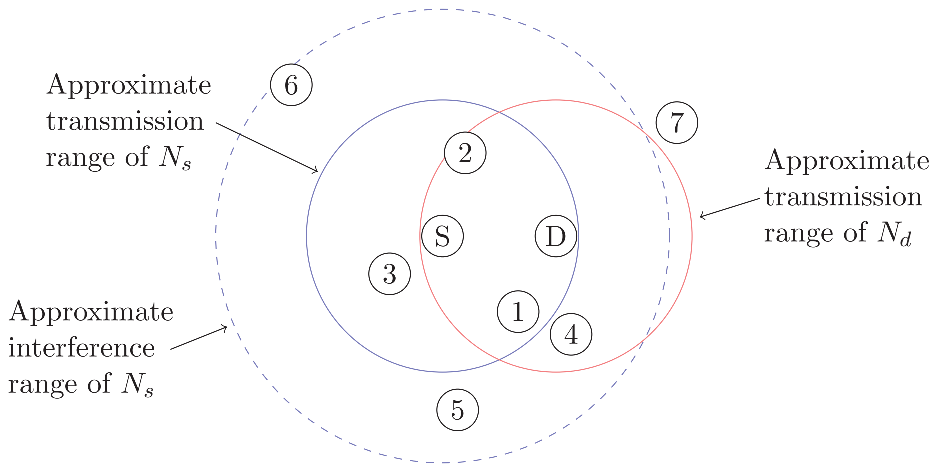

Figure 3.6: A random layout for $\rho_n \approx 4$; participating relays are a subset of the one-hop neighbours, and transmissions from nodes in the interference zone can consume the channel

- ρ_n – the neighbour density and the expected number of neighbours for a given node. It is measured on individual nodes by examining the MAC neighbour table and may reach 20 or more in dense or long-range networks. An example scenario where $\rho_n \approx 4$ is shown in Figure 3.6.

- $RSS_{a,b}$ – the received signal strength at N_b for a message transmitted by N_a. It is assumed the RSS value is reported in dBm. The RSS measurement is discussed further in Section 4.2.2.

- $SNR_{a,b}$ – defined as the difference in RSS and either receiver sensitivity or ambient noise on the channel from N_a to N_b. It is calculated using:

$$SNR_{a,b} = RSS_{a,b} - \max(RSS_{0.9},\, N_o) \tag{3.12}$$

where N_o is the noise (in dBm). For example, a RSS of -62 dBm with a sensitivity of -88 dBm and noise -96 dBm would result in $SNR_{a,b} = 26$ dB. The receiver sensitivity is the limiting factor in low noise environments. Note, the accuracy of device noise measurements may vary significantly between devices [58] and may not accurately measure the RSS and noise values [97].

- $SNR_{0.9}$ – defined in the IEEE 802.11 Standard as the received SNR at which the probability of successfully decoding a frame is 0.9 [54].

- SNR_{off} – an offset that determines the minimum link quality of cooperating devices. Relays must have $SNR_{i,d} \geq SNR_{0.9} + SNR_{off}$ to contend for the retransmission. Using SNR_{off} values proportional to ρ_n dynamically regulates the number of participating nodes.

- SNR_{rng} – the SNR range (in dB) expected from relays. If N_i has:

$$SNR_{i,d} > SNR_{0.9} + SNR_{off} + SNR_{rng}, \tag{3.13}$$

  then it has a higher SNR than expected and will automatically be allocated delay $t_i = 0$. Otherwise it will have a delay in the range $t_i \in [0, s_{max} - 1]$.

3.5.2 Contention Delay Algorithm

The contention delay algorithm is a two step process - firstly the cooperative rank (CR) of a node is calculated, then the range of CR values is distributed over the contention period to create a timer value that favours higher quality links. The CR value is an abstraction of the expected usefulness of the relay where lower values indicate a higher probability of retransmission success.

The cooperative rank CR_i of node N_i is:

$$CR_i = \max\left(SNR_{rng} - \max\left(SNR_{i,d} - SNR_{off}, 0\right), 1\right) \tag{3.14}$$

This method results in $CR_i = 1$ when $SNR_{i,d} \geq SNR_{rng} + SNR_{off} - 1$ and $CR_i = SNR_{rng}$ when $SNR_{i,d} \leq SNR_{off}$.

The retransmission delay algorithm spreads the range of rank values CR over the period s_{max} in a quantised piece-wise linear function as shown in Algorithm 3.1. This algorithm is computationally efficient and does not require any floating point calculations. Tables 3.2 and 3.3 show example results from the delay generation calculation. The top row indicates the rank CR_i of the relay and the bottom row gives the corresponding delay t_i. The rank CR_i may be spread over two or more time slots if $s_{max} > SNR_{rng}$, and the delay t_i is randomly selected from these values. Conversely, several cooperative ranks may result in the same contention delay if $SNR_{rng} > s_{max}$.

This relay selection algorithm follows the DAFMAC design philosophy but is a proof-of-concept only. The full relay selection algorithm is derived and evaluated in Chapter 4.

3.6 Simulated DAFMAC Retransmission Performance

This section describes the simulation configuration and compares DAFMAC's performance to the default 802.11 ARQ scheme. DAFMAC's retransmission collision rate is also calculated to evaluate its overhead against PRO and Δ-MAC.

3.6.1 Network Topology and Algorithm Parameter Configuration

DAFMAC is simulated using a Monte Carlo approach and the MATLAB Communication Toolbox [79]. The stochastic results are the average of 25×10^3 randomly distributed network topologies. All devices are assumed to have an omnidirectional radiation pattern and have a single half-duplex interface with identical physical layer characteristics.

The relay selection algorithm parameters used in the simulations are $s_{max} = 32$, $SNR_{rng} = 64$ and $d_{s,d} = d_{0.9}$ unless specified otherwise. These parameter values provide good cooperative performance with a mean timer delay of approximately $15T_{slot}$.

3.6.2 Dynamic SNR Offset Experiment

The SNR_{off} value has a complex effect on the retransmission performance. A negative SNR_{off} value increases the collision rate at high node density, while a positive value reduces the number of potential relays for low neighbour densities and may result in suitable relays not meeting the retransmission criteria. A dynamic SNR_{off} based on the neighbour density ρ_n provides a high retransmission success rate in a range of scenarios.

Cooperative success is consistently high when $SNR_{off} \propto \rho_n$ as shown in Figure 3.7. Empirical evaluation shows a value of $SNR_{off} = \rho_n - 8$ provides a near-ideal performance for all node densities, and is therefore used in subsequent experiments. Note that this

Algorithm 3.1: Delay calculation for t_i

if $SNR_{i,d} \geq SNR_{off}$ **then**
  $CR_i \leftarrow \max(SNR_{rng} - \max(SNR_{i,d} - SNR_{off}, 1), 0)$
  if $s_{max} > SNR_{rng}$ **then**
    $T_G \leftarrow \left\lfloor \frac{s_{max}}{SNR_{rng}} \right\rfloor + 1$
    if $CR_i < \mod (s_{max}, SNR_{rng})$ **then**
      $t_i \leftarrow CR_i \times T_G + \lfloor X_i \times (T_G + 1) \rfloor$
    else
      $t_i \leftarrow s_{max} - (SNR_{rng} - CR_i) \times (T_G - 1) + \lfloor X_i \times T_G \rfloor$
  else
    $T_G \leftarrow \left\lfloor \frac{SNR_{rng}}{s_{max}} \right\rfloor + 1$
    if $CR_i < SNR_{rng} - \mod (SNR_{rng}, s_{max}) \times T_G$ **then**
      $t_i \leftarrow \left\lfloor \frac{CR_i}{T_G} - 1 \right\rfloor$
    else
      $t_i \leftarrow s_{max} - \left\lfloor SNR_{rng} - \frac{CR_i}{T_G} \right\rfloor$

where:
  max - selects the maximum value listed
  mod - modulo operation (remainder of integer division)
  X_i - an i.i.d. random value in [0, 1)

Table 3.2: Example delay calculation for $SNR_{rng} = 7$ and $s_{max} = 10$

CR_i	1	2	3	4	5	6	7
t_i	0–1	2–3	4–5	6	7	8	9

Table 3.3: Example delay calculation if $SNR_{rng} = 16$ and $s_{max} = 10$

CR_i	1	2	3	4	5–6	7–8	9–10	11–12	13–14	15–16
t_i	0	1	2	3	4	5	6	7	8	9

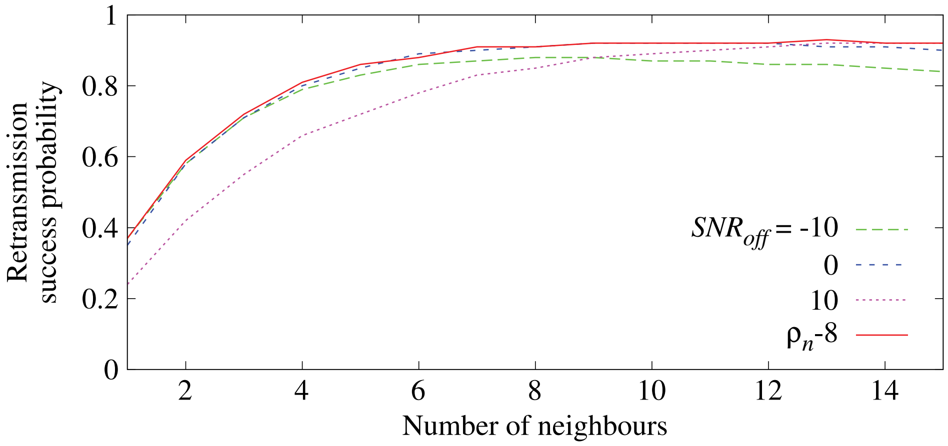

Figure 3.7: Cooperative success is consistently high when $SNR_{off} \propto \rho_n$

does not invalidate scenarios where there are less than eight neighbour nodes, rather, it decreases the minimum SNR requirement for devices to enter retransmission contention.

3.6.3 Simulated Protocol Performance and Discussion

Cooperative retransmissions reduce the outage rate when $SNR_{s,d}$ is poor, such as when distance $d_{s,d}$ increases due to node mobility. DAFMAC makes a progressively higher contribution to transmission success as node density increases as shown in Figure 3.8. DAFMAC improves the reliability by more than 70% over ARQ even with low node neighbour densities when the node separation increases beyond $d_{s,d} > 1.05d_{0.9}$. The overall retransmission success rate remains high as $d_{s,d}$ increases despite the rapid decline in the reliability of a direct transmission.

The aforementioned parameter values resulted in a mean cooperation latency of approximately $15T_{slot}$ and is similar to retransmission delay of ARQ. Hence, for the same per-transmission delay, DAFMAC offers superior retransmission performance to ARQ.

DAFMAC provides communication to devices temporarily out of transmission range in a similar fashion to a network layer ad hoc routing protocol. DAFMAC operates at the link layer of the network stack and uses passive link observations to elect a relay. Conversely, a routing protocol generally plans the route prior to the initial data transmission. The best empirically measured proactive route convergence time after a link fails is approximately 14 seconds [1]. DAFMAC has an average retransmission

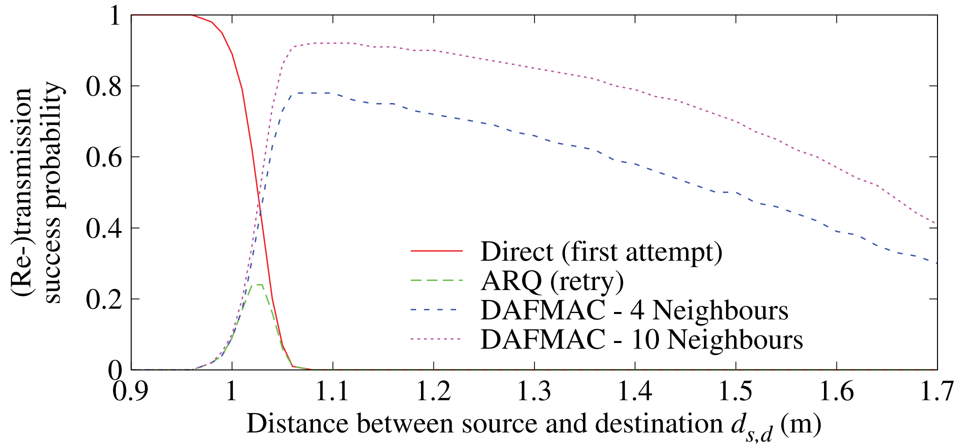

Figure 3.8: DAFMAC cooperation has significantly greater probability of a successful retransmission than traditional 802.11 ARQ

contention latency of 150 microseconds, therefore has a latency four orders of magnitude faster than network layer link healing. It is important to note the multi-hop route convergence time is that required to repair a single link and not to establish a full route. Therefore DAFMAC improves the stability of ad hoc routing protocols by reducing transient link failures. This is of particular benefit to streaming media where temporary link failures result in severe disruption to the user experience (eg. gaps in audio, frozen or blocky video etc.).

The probability of DAFMAC successfully exploiting cooperation increases with the node density ρ_n. However, there are several causes of cooperative failure that limit performance where a 'failure' is an unsuccessful cooperation attempt. The failure modes are: no relays are available; selected relay N_b has a poor link quality; a retransmission collision occurs between two or more relays; and a hidden relay interrupts the transmission. The stochastically derived probability for each failure mode with a randomly distributed topology is shown in Figure 3.9. Note, these results are an average of random node placements and the specific characteristics of each scenario and topology will differ.

The probability of no relay being available decreases as the node density increases. Decreasing the value of the SNR_{off} threshold relaxes the minimum link quality requirement of N_b and increases the probability that at least one neighbour will meet the link quality requirements to retransmit a frame using the DAFMAC protocol. However, this

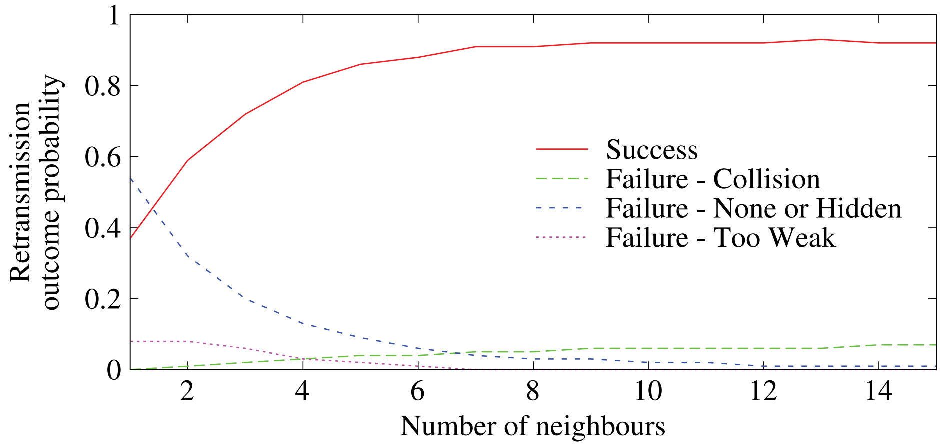

Figure 3.9: The probability of successful cooperation increases with node density despite the increase in retransmission collision rate

correspondingly increases the probability that $SNR_{b,d}$ will be too weak for successful cooperation.

A retransmission collision failure occurs when two or more relays begin retransmission during the same time slot. The collision probability increases with node density as shown in Figure 3.9. Relaxing the SNR_{off} requirement increases the number of potential relays and hence increases the opportunity for collision. A low value for SNR_{rng} increases the probability that devices have $SNR_{i,d} > SNRs, d + SNR_{off} + SNR_{rng}$ and generating a timer delay of 0. The collision rate is reduced using ρ_n-dependent value for SNR_{off} (such as $\rho_n - 8$ in this example) because the minimum link quality requirement increases with the node density ρ_n and limits the number of contending relays. Finally, increasing s_{max} reduces the collision rate at the cost of increasing the cooperation latency.

A hidden node failure occurs if a second relay N_i begins transmitting after N_b has already started. This may only occur when the channel $SNR_{b,i}$ is poor, hence the relays are hidden from one another. The probability that N_b is close to N_d increases with node density ρ_n. In turn, this reduces the hidden device failure rate because N_d is visible to N_i by definition. The probability of hidden nodes is only significant if SNR_{off} is negative (i.e. very weak links are permitted between relay and destination) and is negligible under practical operating conditions.

3.7 Retransmission Overhead Comparison

This section evaluates the DAFMAC retransmission collision rate and shows that DAFMAC collisions waste less channel time than PRO and Δ-MAC use for coordination overhead.

The initial results suggests that DAFMAC can effectively retransmit failed frames with a competitively low cooperative overhead. That is, a cooperative retransmission protocol without an explicit coordination overhead is feasible.

The results show that DAFMAC has a collision rate of 0.05 to 0.08 when $\rho_n \in [5, 15]$. This collision rate is typically lower than the overhead introduced by PRO or Δ-MAC as shown in Figure 3.2. This is a key result and demonstrates that even a primitive DAFMAC relay selection algorithm can effectively retransmit failed data frames with a lower cooperative overhead than Δ-MAC or PRO (when using 802.11b) in a random network configuration. The case where PRO is used in an 802.11a/g network at 54 Mb/s has a marginally lower overhead than the preliminary DAFMAC results. However, the difference is relatively small in this case and would be undetectable to a user in a real-world scenario.

Therefore, DAFMAC is a viable cooperative retransmission protocol.

3.8 Practical Test-bed Proof of Concept

An important design feature of DAFMAC is that it is a low-complexity retransmission protocol that is suitable for existing hardware, using only modifications to software. This section describes a simplified version of DAFMAC developed for off the shelf 802.11 hardware. Experimental methods and results are also presented.

3.8.1 DAFMAC Implementation Details

The test-bed nodes are low powered embedded PCs running Voyage Linux [2]. The DAFMAC protocol is implemented in the Broadcom BCM4306 [27] firmware using a modified version of the OpenFWWF source code [44]. The limited hardware capability of the BCM4306 means that only the timing critical components of DAFMAC are implemented as modifications to the firmware. The remaining DAFMAC components, such as the retransmission contention time algorithm are implemented in the b43 Linux driver [71]. The two components communicate via shared memory registers.

Frames to be retransmitted cannot be stored in the limited device memory and are therefore stored in the driver buffer. This necessitates a compromise in the implementation where devices only participate in retransmission if there is no frame already buffered and ready to transmit.

The operating system kernel does not provide the same timing resolution offered by the BCM4306's embedded CPU, and may be subject to additional latency caused by other kernel modules contending for CPU time. This design requires a period of approximately $4T_{slot}$ to buffer the incoming frame, check the timer algorithm for the appropriate delay and prepare for retransmission. Therefore, the contention delays for all retransmission attempts are increased by this time.

For simplicity, the minimum link quality threshold offset is set to a static value of $SNR_{off} = 0$. This is sufficient for the limited number of contending relays in the test-bed scenario.

3.8.2 Test-bed Configuration

The experiment used a single data flow from N_s to N_d with one, two, or three participating relays. $d_{s,d}$ is varied in 5 m increments. Participating relays are located at the midpoint between N_s and N_d and are spaced 5 m apart, as shown in Figure 3.10. All nodes are configured with BCM4306 devices, using the 802.11b physical layer and transmitting at 11 Mb/s. The transmission power is set to the default value of 15 dBm and each device used a 5.5 dBi omnidirectional antenna. Nodes are placed approximately 0.3 m above a flat, grassy field with no objects interfering with transmission propagation. The actual throughput load is approximately 680 kb/s.

This is a pathological case for DAFMAC. DAFMAC uses the RSS to rank contending relays and this case uses static nodes of approximately equal path loss, therefore using more than one relay should result in a significant retransmission collision rate. However, this scenario also provides a worst-case behaviour for DAFMAC when testing retransmission performance.

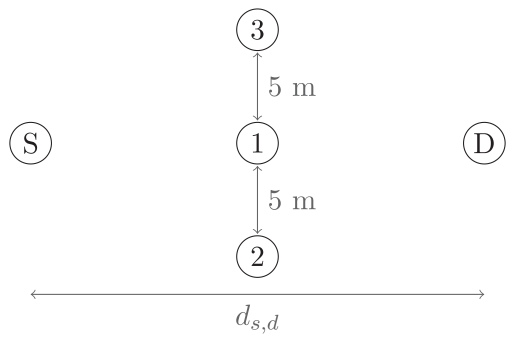

Figure 3.10: Experimental layout of physical test-bed

3.8.3 Test-bed Simulation Performance Baseline

The DAFMAC retransmission protocol is also implemented in the QualNet 4.5 network simulator [85]. An experiment is configured similarly to the above test-bed, where several QualNet parameters are estimated from preliminary experimental observations to give a similar direct transmission performance. The channel is modelled using a two-ray path-loss, Rician fading channel with K-factor of 10 and fading velocity of 1 m/s. The simulated result is the average performance of 10^4 random seed values.

The simulation exhibits a general trend of improving the transmission success rate in high path-loss channels as shown in Figure 3.11. DAFMAC performance is limited by two distinct factors; retransmission collisions and path-loss failures. Retransmission collisions effectively dominate the outage rate over shorter transmission distances and a single relay performs best in such scenarios. Conversely, transmission failures are more significant over longer distances and three relays provide the greatest diversity gain despite the potential for collisions.

The simulated retransmission collision rate for this pathological scenario is shown in Figure 3.12. This result highlights the need to reduce collisions in pathological cases.

3.8.4 Experimental Test-bed Results

The test-bed experiment shows that DAFMAC cooperative retransmissions significantly improve the transmission success probability in high path loss channels. This is shown in Figure 3.13 where the direct transmission success probability rapidly approaches zero

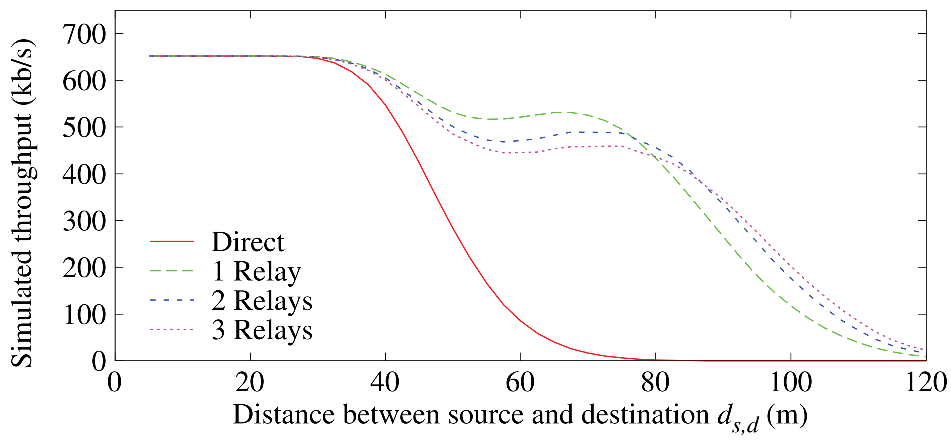

Figure 3.11: QualNet simulations show DAFMAC significantly increases throughput for higher path loss channels

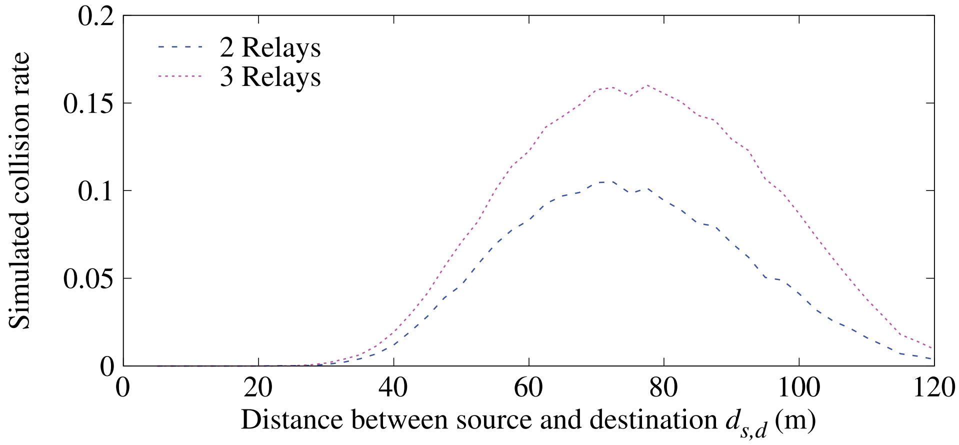

Figure 3.12: Collisions are the primary cause for retransmission failures when using more than one relay in this pathological scenario

when $d_{s,d} > 55$ m. Conversely, using opportunistic DAFMAC relays can provide a useful link up to $d_{s,d} = 75$ m.

The test-bed results cannot match the simulated retransmission performance in high path-loss channels. This could be a function of inconsistencies between the simulated channel and the physical environment. The collision rate will increase if the physical channel exhibits smaller variations. An increased cooperative collision rate explains the similar direct transmission performance observed, but the retransmission efficacy is lower than expected. Actively monitoring collisions at the driver layer is challenging and is not incorporated into this implementation.

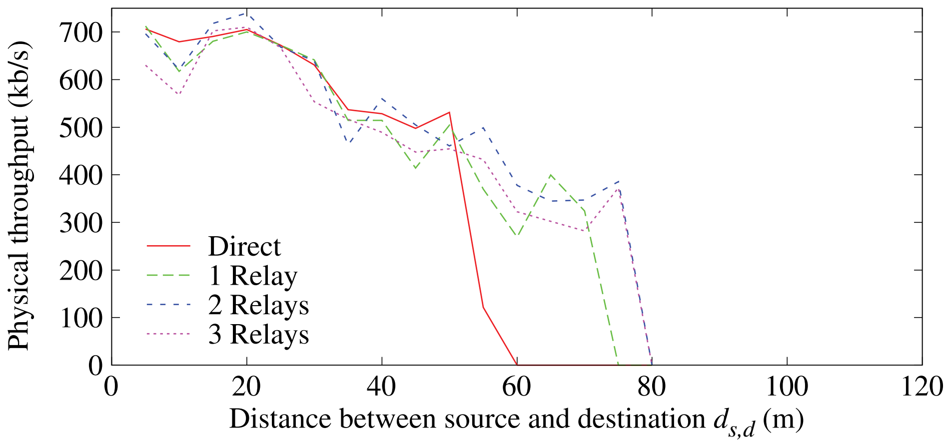

Figure 3.13: The DAFMAC implementation significantly improves transmission reliability in weak channels

DAFMAC is not specifically intended to improve the transmission range of devices in static channels. Instead, this scenario provides a more controlled analogue to path loss induced by shadowing or fading in order to establish basic retransmission functionality.

3.8.5 Discussion

This development and experiment shows that DAFMAC can be implemented in existing real-world devices without hardware modification and significantly improves the transmission performance in high path-loss channels. The retransmission performance is even more significant because of the compromises required to implement DAFMAC for the BCM4306 device.

3.9 Conclusion

This chapter evaluates the total cooperative coordination overhead of PRO and Δ-MAC as a function of both the broadcast coordination frames and the cooperative retransmission collision rate. The cooperative coordination overhead is expressed as an equivalent retransmission collision rate. The equivalent collision rate is then used as a comparative metric to assess the feasibility of other potential retransmission protocols and relay selection algorithms.

The DAFMAC retransmission protocol is described as a fundamental design that does not require explicit coordination signalling. A simple relay selection algorithm is proposed that uses only passively-observed link quality information already available at the MAC layer. Preliminary Monte Carlo simulations show that DAFMAC improves retransmission performance by up to 70% over non-cooperative ARQ retransmissions with randomly distributed relay locations. The initial DAFMAC retransmission collision rate is less than 8%, which suggests that DAFMAC's design is feasible when compared to PRO's equivalent overhead loss of 5–20% and Δ-MAC's of approximately 50%.

This chapter has shown that DAFMAC is a viable protocol. There is still a significant opportunity to increase the retransmission performance by reducing the cooperative collision rate by improving the relay selection algorithm. Chapter 4 analytically explores the relay selection algorithm to identify and quantify the algorithm behaviour.

Chapter 4

DAFMAC RELAY SELECTION ALGORITHM

4.1 Introduction

This chapter extends the DAFMAC protocol by optimising the relay selection algorithm to minimise retransmission collision probability and maximise cooperation efficacy. The key contributions and results of this chapter are:

- To propose a general link-quality based contention delay algorithm with a random delay component and analytically derive appropriate algorithm parameter values;
- To propose a simple, zero-overhead preferred relay scheme to minimise the cooperative retransmission collision rate. Comparative simulations show the addition of a preferred relay scheme reduces retransmission collisions by approximately 50%;
- Comprehensive simulation performance evaluation of throughput and frame jitter in a diverse range of scenarios and configurations. Both network-wide performance and the relative fairness between individual flows using Jain's Fairness Index are evaluated; it is demonstrated that fairness need not be sacrificed to improve total network performance and that DAFMAC outperforms both traditional 802.11 and PRO in terms of both throughput and fairness under realistic network conditions;
- Investigation of the network energy consumption using cooperative retransmission protocols. Simulations show that cooperative retransmissions reduce the overall network energy costs because it takes less energy to retransmit a frame than it does to listen to it repeatedly fail; and,
- Analysis of the relative computational complexity for the DAFMAC and PRO implementations. Complexity becomes a limiting factor in the scalability of pro-

tocols in very large networks and can impact on retransmission performance in resource-constrained devices.

4.2 Retransmission Delay Algorithms

Contending relays estimate their suitability for retransmission using a scoring function. This section examines several scoring functions and evaluates their effectiveness for the DAFMAC algorithm.

4.2.1 Basic Delay Algorithm

The objective of the delay algorithm is to autonomously select a single relay for retransmission. Many nodes may be potentially capable of successfully relaying the frame; it is not strictly necessary that the *best* relay forwards the frame, so long as multiple relays do not attempt to do so simultaneously.

Link quality is quantified as a function of the received signal strength (RSS). Details of the RSS measurement and assumptions are described in Section 4.2.2.

The relay scoring function F_i defines the relationship between the measured RSS values and the expected relaying capability of the node. The value of F_i varies between the minimum (F_{min}) and maximum (F_{max}) scoring function values, based on the scoring function values for the minimum and maximum observed RSS values respectively. Nodes autonomously estimate F_{min} and F_{max} purely based on local knowledge and observations; there is no need to distribute this information amongst nodes.

The contention delay algorithm is independent of the exact RSS scoring function used to generate F_i. The delay is calculated by

$$t_i = \left\lfloor \left(\frac{F_i - F_{max}}{F_{min} - F_{max}} \right) s_{max} \right\rfloor T_{slot} \tag{4.1}$$

where s_{max} is the maximum contention delay in MAC slot times and T_{slot} is the MAC slot time in microseconds [54]. As F_i approaches F_{max},

$$\lim_{F_i \to F_{max}} t_i = 0 \tag{4.2}$$

such that the relays with the highest link quality generate the shortest contention delays.

4.2.2 Received Signal Strength Measurement and Storage

The RSS for a given link is measured for every successfully received frame that can be attributed to a specific source node [97]. It is measured during the PLCP header, which is always transmitted at the minimum rate. This provides a consistent measurement of link quality even in devices using rate adaptation. The DAFMAC RSS table consists of the RSS measurement for each neighbour (mapped to their MAC address) and the time of the last RSS measurement.

Because the RSS is updated for each frame received, it has less temporal inertia than metrics such as packet delivery ratio where historical performance may influence the value without indicating the current link state [97]. The RSS measurements can be filtered to provide a more consistent value for channels with fast fading, if required. For example, PRO uses an exponentially weighted moving average filter [77]. Optimal filtering requirements are scenario-specific, therefore no single method is prescribed in the DAFMAC contention algorithm.

The RSS of a transmission from N_s as received at N_i is denoted $RSS_{s,i}$; similarly, the RSS of a transmission from N_i at N_d is denoted $RSS_{i,d}$. The RSS values at each end of a link are assumed to be approximately equal because the path loss is reciprocal and nodes are assumed to have identical physical-layer characteristics.

In practice, individual 802.11 wireless devices exhibit different physical-layer properties, even nominally identical devices from the same manufacturer [59]. A heterogeneous network consisting of a variety of different devices, each with potentially different transmission power and receiver sensitivity, results in some degree of channel non-reciprocity which will affect the performance of DAFMAC. The performance of DAFMAC in a heterogeneous network is an interesting open research problem and is an avenue for future work.

4.2.3 Relay Scoring Function Review

The relay scoring function is intended to give preference to optimally placed nodes. Two alternatives have been proposed for defining for the ideal choice of relay. A node located at the midpoint between N_s and N_d is optimally positioned to transmit to both nodes with equal efficacy [20, 23, 72, 99]. Conversely, if the data frame has already reached a potential relay, then the best relay is that which has the smallest path loss to the destination [46, 77]. The output of different scoring functions is not always directly comparable and is intended only to rank nodes using a common function.

The *Harmonic Average* scoring function (HASF) gives the highest score to nodes midway between N_s and N_d [20, 72]. It is defined as:

$$F_i^{ha} = 10\log_{10}\left(\frac{2P_{s,i}P_{d,i}}{P_{s,i}+P_{d,i}}\right) \tag{4.3}$$

where $P_{s,i}$ and $P_{d,i}$ are the received signal powers (in watts) of a frame received at N_i transmitted by N_s and N_d, respectively.

The *Quartic Root* scoring function (QRSF) [99] was designed for use with the ExOR routing protocol [18]. However, the scoring function may be adapted to operate within DAFMAC. QRSF also gives the highest score to relays mid-way between N_s and N_d. The function is defined as:

$$F_i^{qr} = 10\log_{10}\left(\left(\sqrt[4]{P_{i,d}^{-1}} + \sqrt[4]{P_{i,s}^{-1}}\right)\left(\ln\sqrt[4]{\frac{\max(P_{i,d}^{-1}, P_{i,s}^{-1})}{\min(P_{i,d}^{-1}, P_{i,s}^{-1})}} + \ln\left(\sqrt[4]{P_{i,d}^{-1}} + \sqrt[4]{P_{i,s}^{-1}}\right)\right)\right). \tag{4.4}$$

The *Minimum Link Quality* scoring function (MLSF) algorithm is also maximised mid-way between N_s and N_d and is preferred over HASF for its low computational complexity [23]. MLSF is defined as:

$$F_i^{ml} = \min(P_{s,i}, P_{d,i}). \tag{4.5}$$

Comparing centre-weighted functions is challenging because suitable scaling bounds are difficult to estimate. A relay positioned midway between N_s and N_d is in the ideal location for relaying and should generate a contention delay close to zero. However, the node can only tell that it has equal link quality to the source and destination; therefore, it could potentially be anywhere on the perpendicular bisector of the link. Most transmission failures should occur when the RSS approaches the receiver sensitivity threshold. Suppose the minimum input value F_{min} is the receiver sensitivity threshold plus a 1 dB margin. The log-normal path loss over distance d, expressed in dB, is given by:

$$PL = 10n \log_{10} \frac{d}{d_0} + PL_0 \tag{4.6}$$

where PL_0 is the known path loss at distance d_0 and n is the path-loss exponent for a given environment. A relay at the midpoint has an $RSS_{s,i}$ which is $3n$ dB greater than at the destination. Assuming a typical indoor path loss exponent of $n = 2.6$ [11], the $RSS_{s,i}$ at the midpoint is approximately 8 dB above the sensitivity threshold; this defines the maximum input value (F_{max}). Transmission failures may still occur despite a RSS greater than F_{min} - for example, due to localised interference or the presence of hidden nodes. The latter may result in a contention attempt where several nodes equal or exceed the expected F_{max} value and therefore generate a contention delay of 0 - a *retransmission collision*. Increasing F_{max} may mitigate this effect but compresses the range of useful delays into a smaller region. This is also sub-optimal.

The *Outer Weighted* scoring function (OWSF) is an extension of that used in PRO [77], and the proof-of-concept relay selection algorithm presented in Chapter 3, and gives preference to relays nearer to either N_d or N_s. It is the weighted sum of the RSS (in dBm) at N_i from both N_s and N_d and is calculated using the function

$$F_i^{ow} = a_{r,d} RSS_{i,d} + (1 - a_{r,d})\, RSS_{i,s} \tag{4.7}$$

where $a_{r,d}$ is the weighting of the $RSS_{i,d}$ value, $a_{r,d} \in [0, 1]$ which determines whether preference is given to potential relays nearer to N_d or N_s.

4.2.4 Delay Shapes and Collision Regions

Distributed retransmission algorithms typically use a timer generation function to calculate the contention delay, where better placed relays are subject to shorter retransmission delays than other relays. The *delay shape* is a contour representation of the contention delay as a function of relay location. The region which results in the minimum contention delay implicitly defines the 'ideal' placement of a relay node.

The delay contours of the aforementioned relay scoring functions are shown in Figure 4.1. This example uses the physical device characteristics of a Senao 802.11b device [88] transmitting at 11 Mb/s. The source and destination are placed such that a direct transmission has a probability of successful delivery of 0.9, which corresponds to approximately $d_{s,d} = 80$ m in this configuration. The white outer regions represent areas with insufficient connectivity to either N_d or N_s and will not contend for cooperative retransmission.

Each contour line represents a contention delay value that is an incremental integer multiple of one time-slot. All nodes within the same contour band generate the same delay and will collide if they have computed the equal lowest delay of all relays. Assuming uniform node distribution, delay functions which result in larger areas for the lowest delay values are more likely to generate contention collisions. The obvious visual result is that HASF and QRSF both generate the smallest contention delays over a relatively large area. By contrast, OWSF and MLSF generate the minimum delays in a relatively small area, hence minimising the probability that multiple nodes are positioned to generate the same delay and collide.

The aforementioned collisions are limited to cooperative retransmission collisions caused by two contending relays retransmitting simultaneously. This excludes collisions from nodes external to the retransmission process initiating their own transmission. Such external collisions affect all retransmission delay algorithms equally and are ignored for the purpose of this comparison.

The only parameter that can influence the region of collision is the OWSF $a_{r,d}$ coefficient. The optimal value for $a_{r,d}$ is derived in Section 4.3.

4.2.5 Scoring Function Collision Comparison

A simulation is conducted to establish which scoring function produces the lowest collision rate. Source and destination nodes are placed 80 m apart, and use the previously configured IEEE 802.11b physical layer parameters. $|\mathcal{N}_n|$ nodes are randomly placed

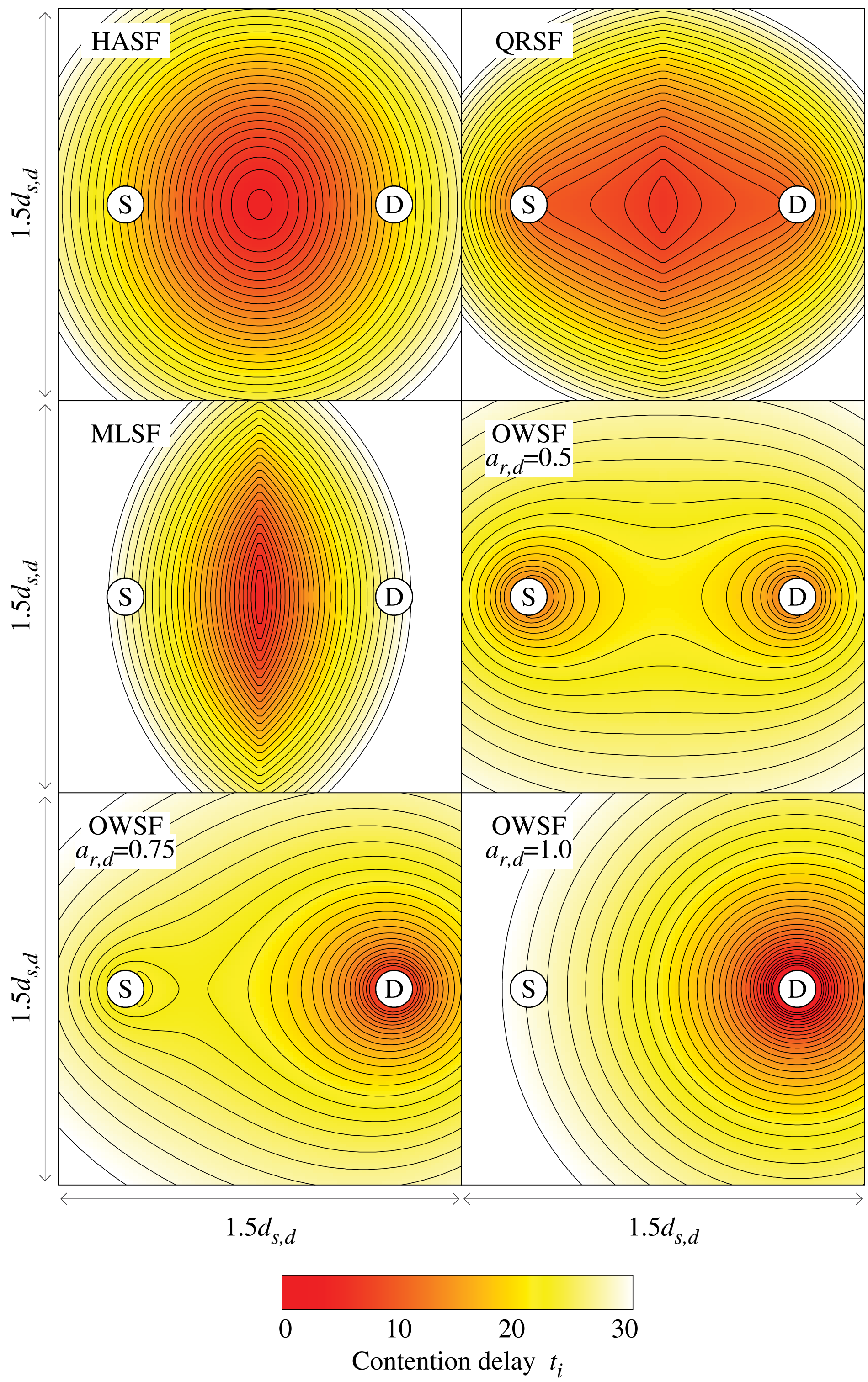

Figure 4.1: Contour plots of contention delays using HASF, QRSF, MLSF, and OWSF with $a_{r,d}$ of 0.5, 0.75 and 1.0, respectively, where $t_i \in [0, 31]$

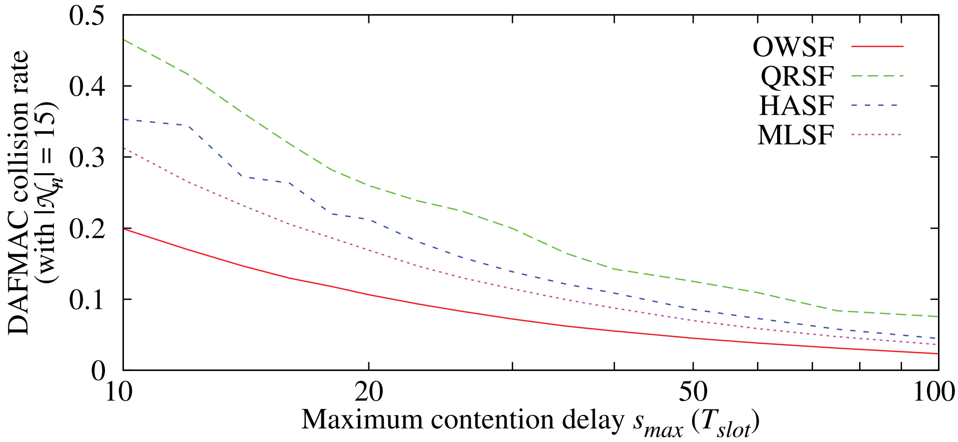

Figure 4.2: OWSF (where $a_{r,d} = 1$) results in a lower collision rate than HASF, QRSF or MLSF

in a 120 m × 120 m simulation area and the contention delays of all (valid) relays are calculated and compared. This is repeated for 10^5 random node configurations for $|\mathcal{N}_n| \in [5, 25]$ nodes and $s_{max} \in [10, 100]$ time slots.

Figure 4.2 shows that OWSF, where $a_{r,d} = 1$, results in significantly fewer collisions than HASF, QRSF or MLSF. While all scoring functions are capable of ranking relays using RSS observations, OWSF is the scoring function most likely to result in the selection of a single 'best' relay. Hence, all further DAFMAC modelling and simulation uses OWSF.

This analysis only considers the collision probability and ignores the potential for relays to not decode the source frame. In reality, placing the relay near to the destination means the relay may not receive all source frames correctly. However, OWSF will use relays with lower path-loss to the source if required in such cases and maintains the lowest rate of retransmission collisions.

4.3 Optimal Algorithm Parameter Derivation

The behaviour of the DAFMAC algorithm is controlled by three key parameters. This section discusses the effect of these parameters on DAFMAC performance and derives optimal numerical values (or ranges of values) for each under the assumption of a simple log-normal path loss channel with no significant fading. This approach is validated in

Section 4.5, where retransmission performance is simulated in a more realistic quasi-static Rician fading environment.

4.3.1 Deriving the Optimal Link Quality Weighting, $a_{r,d}$

The parameter $a_{r,d}$ defines the weighting between $RSS_{i,s}$ and $RSS_{i,d}$ to give a single link quality metric. This section derives the value of $a_{r,d}$ that generates the fewest contention collisions.

A collision occurs if:

$$t_b = t_i \quad \exists N_i \in \mathcal{N}_c, i \neq b. \tag{4.8}$$

By definition, $F_b > F_i,\ i \neq b$; however, the delay algorithm may generate two quantised delay values that are equal. From (4.1) and (4.8), optimal relay N_b and an arbitrary relay N_i retransmit in the same slot if:

$$\begin{aligned}
\left\lfloor \left(\frac{F_i - F_{max}}{F_{min} - F_{max}} \right) s_{max} \right\rfloor &= \left\lfloor \left(\frac{F_b - F_{max}}{F_{min} - F_{max}} \right) s_{max} \right\rfloor \\
\left(\frac{F_i - F_{max}}{F_{min} - F_{max}} \right) s_{max} &< \left\lfloor \left(\frac{F_b - F_{max}}{F_{min} - F_{max}} \right) s_{max} \right\rfloor + 1 \\
F_i &< \frac{\left\lfloor \left(\frac{F_b - F_{max}}{F_{min} - F_{max}} \right) s_{max} + 1 \right\rfloor (F_{min} - F_{max})}{s_{max}} + F_{max}
\end{aligned} \tag{4.9}$$

$a_{r,d}$ value should be set such that F_i changes as quickly as possible with respect to relay position so as to minimise the probability of a collision. Combining (4.6) and (4.7) gives F_i^{ow} as a function of node separation. It is assumed that all nodes have identical physical-layer characteristics. Now:

$$RSS_{i,s} = RSS_0 - PL_{i,s} \tag{4.10}$$

$$RSS_{i,d} = RSS_0 - PL_{i,d} \tag{4.11}$$

where RSS_0 is the RSS at d_0. Substituting into (4.7) results in:

$$\begin{aligned}
F_i^{ow} &= a_{r,d} \left(RSS_0 - 10n \log \frac{d_{i,d}}{d_0} \right) + (1 - a_{r,d}) \left(RSS_0 - 10n \log \frac{d_{i,s}}{d_0} \right) \\
&= RSS_0 + 10n \left(\log d_0 - (1 - a_{r,d}) \log d_{i,s} - a_{r,d} \log d_{i,d} \right)
\end{aligned} \tag{4.12}$$

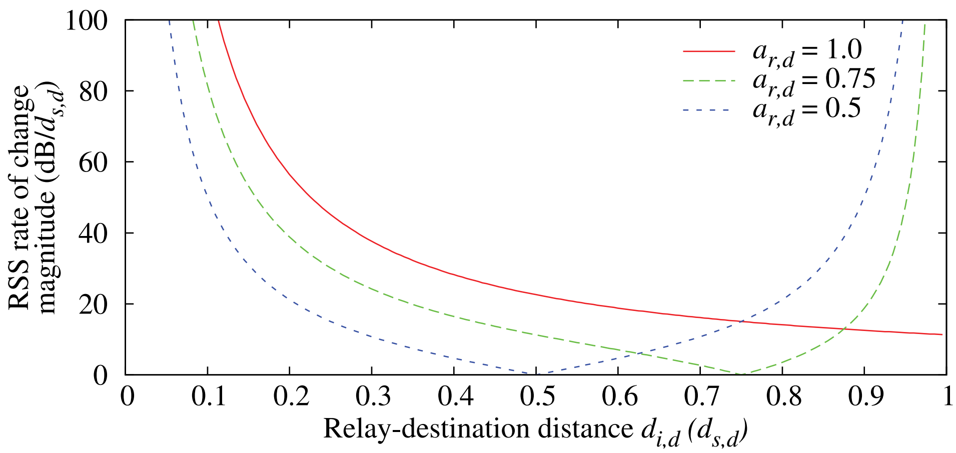

Figure 4.3: The rate of change of F_i^{ow} with respect to $d_{i,d}$ is consistently at its maximum when $a_{r,d} = 1.0$ for $d_{i,d} \in [0.1d_{s,d}, 0.5d_{s,d}]$

The best relays have a small path loss to both N_s and N_d. Assume N_i is close to the direct transmission path, i.e.:

$$d_{i,s} \approx d_{s,d} - d_{i,d} \tag{4.13}$$

Combining (4.12) and (4.13) to a natural logarithm form gives:

$$F_i^{ow} = RSS_0 + \frac{10n}{\ln 10} \left(\ln d_0 - (1 - a_{r,d}) \ln(d_{s,d} - d_{i,d}) - a_{r,d} \ln d_{i,d}\right) \tag{4.14}$$

Differentiating with respect to $d_{i,d}$ results in:

$$\frac{\partial F_i^{ow}}{\partial d_{i,d}} = \frac{10n}{\ln 10} \left(\frac{1 - a_{r,d}}{d_{s,d} - d_{i,d}} - \frac{a_{r,d}}{d_{i,d}} \right) \tag{4.15}$$

A higher value of $\frac{\partial F_i^{ow}}{\partial d_{i,d}}$ helps to choose a single relay by reducing the geographic region potentially subject to collisions. Assume the N_s to N_d separation is $d_{s,d} = d_{0.9}$ for this analysis. Figure 4.3 shows $\frac{\partial F_i^{ow}}{\partial d_{i,d}}$ as function of $d_{i,d}$ for $a_{r,d} = 1.0,\ 0.75,\ 0.5$. Assume the region of interest is between $d_{i,d} \in [0.1d_{s,d}, 0.5d_{s,d}]$, since it is unlikely that more than one relay will be within $0.1d_{s,d}$ of the destination and highly probable that at least one relay will be within $0.5d_{s,d}$. Figure 4.3 shows $\frac{\partial F_i^{ow}}{\partial d_{i,d}}$ is the highest when $a_{r,d} = 1$ in this scenario. Hence $a_{r,d} = 1$ will result in the rate of collisions being minimised.

The values of $\frac{\partial F_i^{ow}}{\partial d_{i,d}}$ would be identical (but complimentary) for $a_{r,d} = 0$. The value $a_{r,d} = 1$ is preferred because the longest transmission was already successful if the node is participating in cooperation. Hence the only important factor remaining is the path loss to N_d. The path loss to N_s may be ignored.

4.3.2 Collision Mitigation with Random Delay Component, a_X

Many scenarios are essentially static and link quality does not vary significantly over time. This may result in situations where multiple potential relay nodes have similar link qualities to the destination and hence cause frequent cooperative collisions for a given source-destination pair. This problem can be mitigated by adding a random component to the link quality calculation in (4.1):

$$t_i = \left\lfloor \left((1 - a_X) \left(\frac{F_i - F_{max}}{F_{min} - F_{max}} \right) + a_X X_i \right) s_{max} \right\rfloor T_{slot} \tag{4.16}$$

where a_X is the weighting of uniformly distributed random variable X_i, where $a_X \in [0, 1]$ and $X_i \sim \text{Un}[0, 1)$.

At its minimum ($a_X = 0$), collisions have a greater impact because they will repeat until the path loss changes, the source transmission succeeds or the retransmission limit is reached. At the other extreme ($a_X = 1$), any contending node can generate any delay, with no regard to the node placement - providing greater opportunity for collisions even when no two nodes are at a similar distance from the destination.

The highest relay-scoring function value F_b must be similar to that of at least one other node in order for a collision to occur; nodes cannot collide if the scoring function values are sufficiently distinct. From (4.16), the potential range of collisions has the lower bound:

$$(1 - a_X) \left(\frac{F_b - F_{max}}{F_{min} - F_{max}} \right) + a_X X_b \leq (1 - a_X) \left(\frac{F_i - F_{max}}{F_{min} - F_{max}} \right) + a_X X_i \tag{4.17}$$

and upper bound:

$$(1 - a_X) \left(\frac{F_b - F_{max}}{F_{min} - F_{max}} \right) + a_X X_b + 1 > (1 - a_X) \left(\frac{F_i - F_{max}}{F_{min} - F_{max}} \right) + a_X X_i \tag{4.18}$$

The lower bound is tight, while the upper bound represents the worst-case scenario. Manipulating (4.17) and (4.18) results in:

$$X_b - X_i > \frac{(1-a_X)(F_i - F_b)}{a_X(F_{min} - F_{max})} - \frac{1}{a_X s_{max}} \tag{4.19}$$

and:

$$X_b - X_i \leq \frac{(1-a_X)(F_i - F_b)}{a_X(F_{min} - F_{max})} \tag{4.20}$$

for the range of random values that can potentially generate a retransmission collision. Because random variable X is a continuous uniform random variable, $X_i \sim \mathrm{Un}[0,1)$, the difference

$$X_\Delta = X_b - X_i \tag{4.21}$$

has a probability density function (PDF) of:

$$f_{X_\Delta}(x) = \begin{cases} x+1 & \text{if } -1 \leq x < 0 \\ 1-x & \text{if } 0 \leq x \leq 1 \\ 0 & \text{elsewhere.} \end{cases} \tag{4.22}$$

By definition, $F_b \geq F_i$; hence a collision requires that $X_b \geq X_i$ and the only region of concern in (4.22) is $0 \leq x \leq 1$. The collision probability is bounded by the area under the PDF in (4.22) within the limits given in (4.19), (4.20). Denote $\Pr_{coll}(N_i)$ as the collision probability between N_b and N_i, which is given by:

$$\begin{aligned} \Pr_{coll}(N_i) &= \Pr(t_i = t_b \mid F_i \approx F_b) \\ &\leq \int_{\frac{(1-a_X)(F_i-F_b)}{a_X(F_{min}-F_{max})} - \frac{1}{a_X s_{max}}}^{\frac{(1-a_X)(R(i)-F_b)}{a_X(F_{min}-F_{max})}} (1-x)\,\mathrm{d}x \\ \therefore \Pr_{coll}(N_i) &\leq \frac{1}{s_{max}a_X}\left(1 + \frac{1}{2s_{max}a_X} - \frac{(F_i - F_b)(1-a_X)}{a_X(F_{min} - F_{max})}\right) \end{aligned} \tag{4.23}$$

This is the collision probability if the sum X_Δ is bounded by (4.19) and (4.20). A comprehensive definition, then, is given by:

$$\Pr_{coll}(N_i) \leq \begin{cases} \frac{1}{s_{max}a_X} & \left(1 + \frac{1}{2s_{max}a_X} - \frac{(F_i-F_b)(1-a_X)}{a_X(F_{min}-F_{max})}\right), \\ & \text{if} \quad X_b - X_i > \frac{(1-a_X)(F_i-F_b)}{a_X(F_{min}-F_{max})} - \frac{1}{a_X s_{max}} \\ & \text{and} \quad X_b - X_i \leq \frac{(1-a_X)(F_i-F_b)}{a_X(F_{min}-F_{max})} \\ 0, & \text{otherwise.} \end{cases} \tag{4.24}$$

Equation (4.24) describes the probability of a collision when node N_i is inside the region of collision with N_b. The region of collision is small for low values of a_X and spreads out as a_X increases. The collision region is shown in Figure 4.4 for $a_{r,d} = 1$ with different values of a_X.

Let $\Pr_{coll}(\mathcal{N}_c)$ represent the combined collision probability for all contending relays, $N_i \in \mathcal{N}_c, N_i \neq N_b$. Therefore, the collision probability has an upper bound of:

$$\Pr_{coll}(\mathcal{N}_c) \leq 1 - \prod_{\substack{N_i \in \mathcal{N}_c, \\ N_i \neq N_b}} \left(1 - \Pr_{coll}(N_i)\right). \tag{4.25}$$

This model determines a suitable range of values for a_X. Nodes are placed at random locations within the contention area. 10^5 random node distributions are generated and stored, with the same set of node distributions used in all subsequent tests. The total probability of collision $\Pr_{coll}(\mathcal{N}_c)$ is then calculated for each node distribution and the mean value across the entire set shown in Figure 4.5. From this set of curves, it is apparent that $a_X = 0.1$ is a good value across a range of typical s_{max} retransmission contention window sizes. This plot shows the collision probability when 15 nodes are placed in the contention area; similar results are obtained with higher or lower potential relay density. This result is consistent with Figure 4.4; $a_X = 0.1$ results in a small area of potential collision but with a significantly smaller collision probability than $a_X = 0$. The model assumes that all relays always receive the frame from N_s. In reality, some relays may not decode the source frame, and hence will not contend for retransmission, resulting in a lower collision rate; this does not affect the conclusion drawn here.

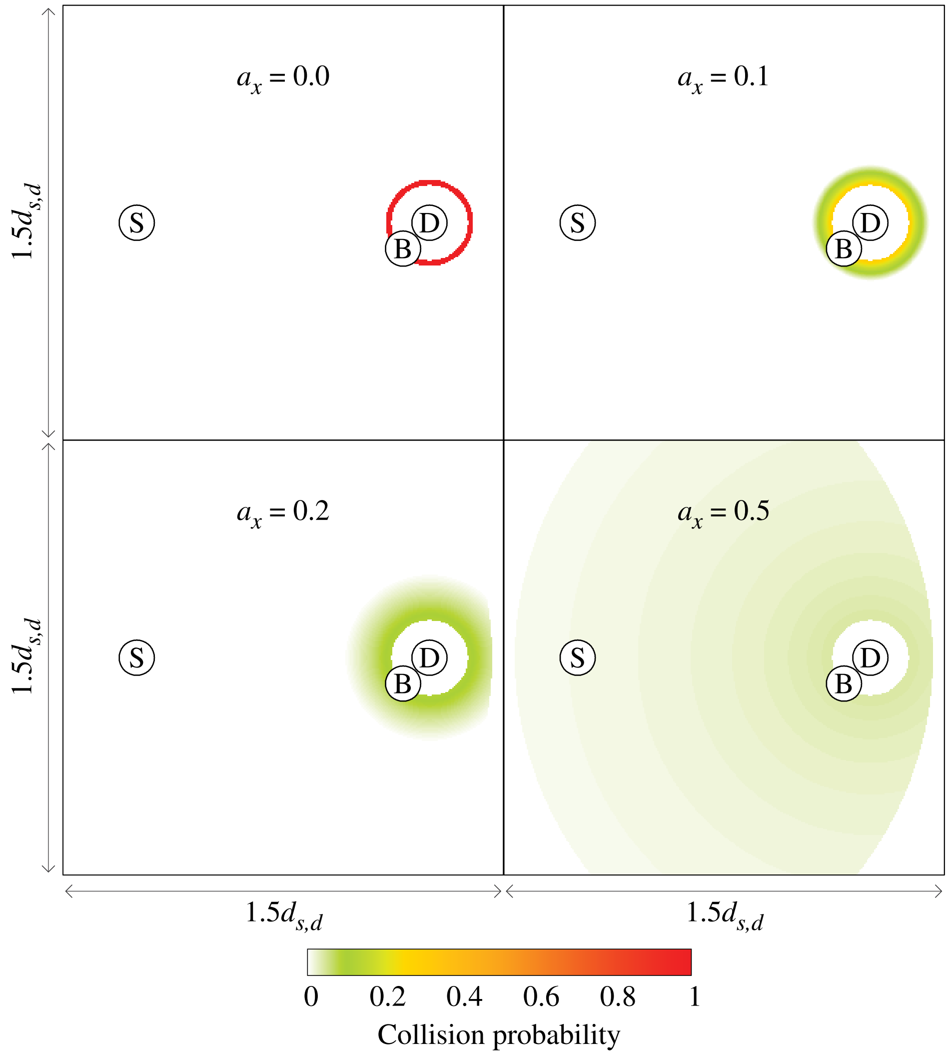

Figure 4.4: Collision probability decreases as a_X increases, however the potential *region* of collision increases in size.

Inconsistent behaviour is evident for small values of a_X, which is a result of the undefined behaviour in (4.25) when $a_X = 0$. This limitation of the analytic model has minimal influence on the region of interest near $a_X = 0.1$.

4.3.3 Optimising the Delay Range (s_{max}) for Maximum Throughput

The collision rate approaches zero as s_{max} increases because the RSS plus a random component will eventually be able to separate any contending nodes. This is shown in Figure 4.6. However, too large a value of s_{max} also reduces throughput, since nodes

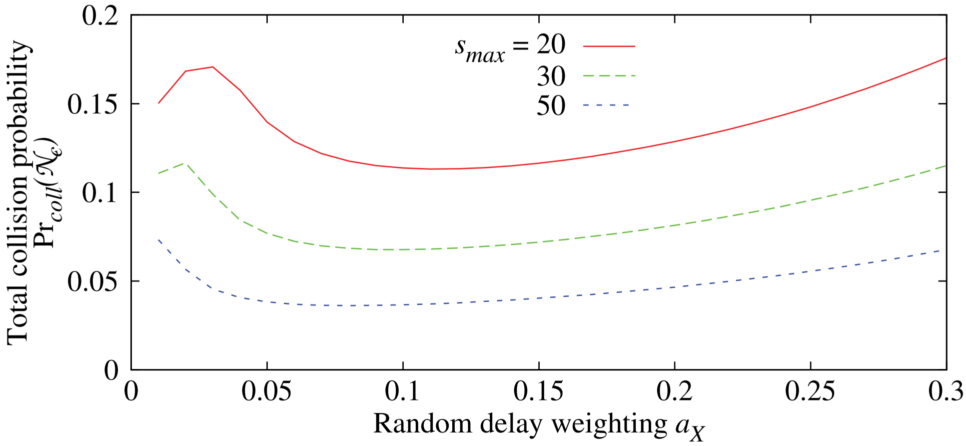

Figure 4.5: The collision probability $\Pr_{coll}(\mathcal{N}_c)$ is consistently low when $a_X \approx 0.1$ for $s_{max} \in [20, 50]$ and $|\mathcal{N}_n| = 15$.

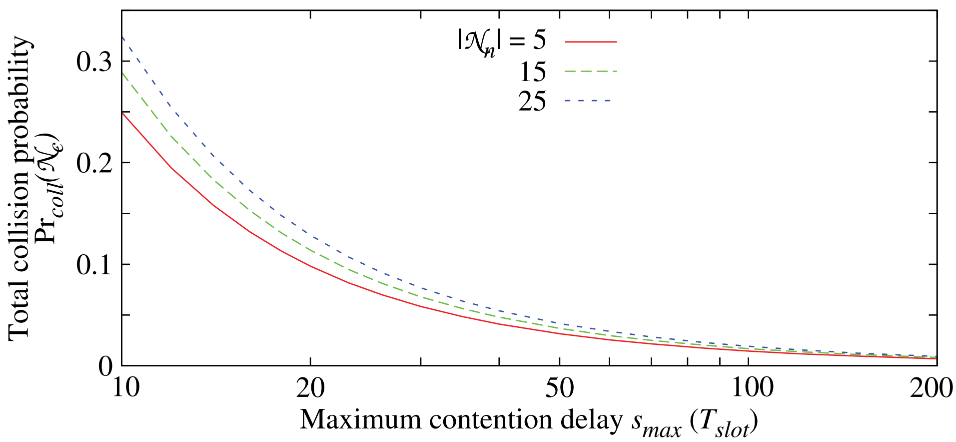

Figure 4.6: The retransmission collision probability $\Pr_{coll}(\mathcal{N}_c)$ exponentially decreases as s_{max} increases

waiting to cooperate are unable transmit their own frames. Therefore, a compromise value of s_{max} is required.

The total duration of a single data frame transmission may be expressed as a combination of deterministic and random components. The duration of a data frame transmission is:

$$T_{msg} = T_{difs} + T_{bo} + T_{data} + T_{sifs} + T_{ack} \tag{4.26}$$

where T_{sifs} and T_{difs} are the short and distributed inter-frame spaces as defined in the IEEE 802.11 standard [54]; T_{bo} is the CSMA/CA back-off delay in time slots; T_{data}

and T_{ack} are the data and ACK frame transmission times respectively. The cooperative retransmission time is:

$$T_{coop} = T_{con} + T_{data} + 2T_{sifs} + T_{ack} \tag{4.27}$$

where T_{con} is the cooperative contention delay. The total transmission time is given by:

$$\begin{aligned} t_{total} = T_{msg} & \\ & + (1 - \Pr_{tx}(N_s))T_{coop} \\ & + (1 - \Pr_{tx}(N_s))\Pr_{coll}(\mathcal{N}_c)T_{msg} \\ & + \dots \\ & + (1 - \Pr_{tx}(N_s))^L \Pr_{coll}(\mathcal{N}_c)^{L-1} T_{coop} \end{aligned} \tag{4.28}$$

where $\Pr_{tx}(N_s)$ is the probability of successfully sending the message from N_s to N_d and L is the transmission attempt limit (typically 4 or 7 depending on the frame size) [54]. Note that the value of $\Pr_{tx}(N_s)$ need not be derived as the actual retransmission performance does not depend on the direct link. This geometric series may be factorised, yielding the expression:

$$t_{total} = (T_{msg} + (1 - \Pr_{tx}(N_s))T_{coop}) \left(\frac{1 - ((1 - \Pr_{tx}(N_s))\Pr_{coll}(\mathcal{N}_c))^L}{1 - (1 - \Pr_{tx}(N_s))\Pr_{coll}(\mathcal{N}_c)} \right) \tag{4.29}$$

The same model, in which IEEE 802.11b devices operating at 11 Mb/s are spaced 80 m apart in a 120 m × 120 m area, is used to empirically estimate the minimum t_{total}. Figure 4.7 shows how the minimum t_{total} varies as a function of the number of neighbouring nodes, since the ideal retransmission contention window increases with the number of contending devices. From the figure, it is observed that selecting a value of $s_{max} \approx 50$ provides consistently good performance for a diverse range of network conditions. Using a small value for s_{max} increases the rate of collisions because the algorithm is not able to isolate a single relay from the contending set. Conversely, using a large value for s_{max} produces a small collision rate but increases the time per retransmission attempt and decreases throughput performance. The assumptions in (4.29) are $a_X = 0.1$, $T_{bo} = 15$, $L = 4$ and $\Pr_{tx}(N_s) = 0$ (in order to focus on the impact of cooperative collisions).

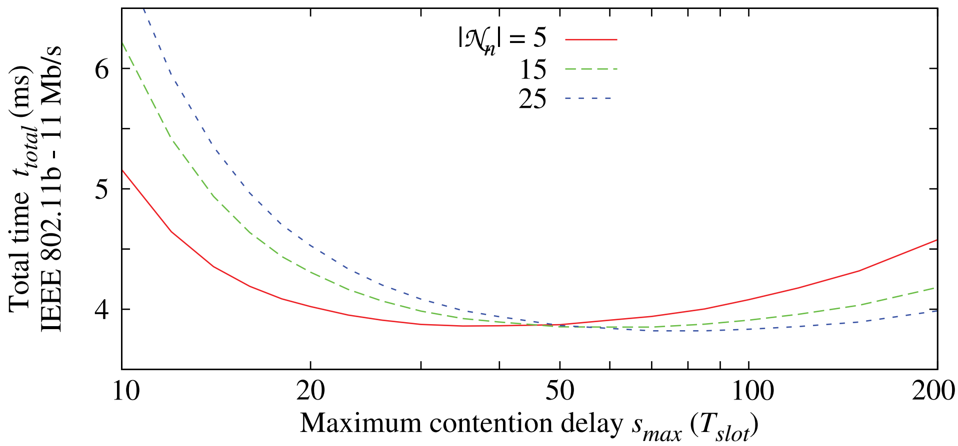

Figure 4.7: The minimum t_{total} occurs for $s_{max} \approx 50$ for IEEE 802.11b networks

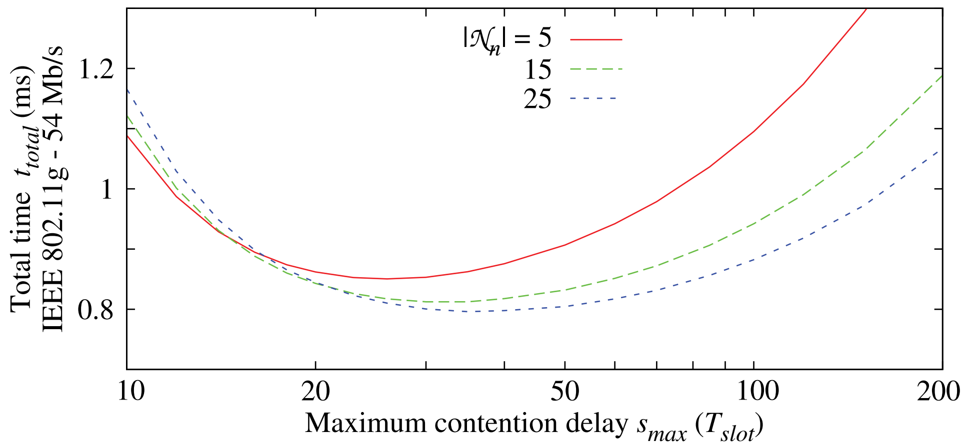

Figure 4.8: The minimum t_{total} occurs for $s_{max} \approx 30$ for IEEE 802.11g networks

The simulation is repeated to determine the minimum t_{total} for IEEE 802.11g devices, with the results plotted in Figure 4.8. Choosing too large a value of s_{max} for 802.11g increases the transmission time by more than the corresponding time lost to collisions because of the wasted capacity when using a faster transmission rate. Therefore, a contention range value of $s_{max} \approx 30$ should be used in 802.11g networks. Equivalent results may also be obtained for more recent 802.11 variants using a similar procedure.

4.4 Preferring Successful Relays

Two constraints on capacity in cooperative networks are cooperative collisions and contention delay. Both effectively waste a fraction of channel capacity for no benefit. It is hypothesised that if a relay successfully retransmits a frame, it is likely to be a useful relay again in the near future. If this hypothesis is correct, biasing relay selection towards previously successful relays will improve channel utilisation. This section describes the use of preferred relays in DAFMAC and validates the hypothesis by evaluating the reduction in contention collisions that is achieved when this feature is enabled.

4.4.1 Algorithm Implementation

A relay is 'preferred' by reducing its contention delay to zero (for a particular source-destination pair) while other relays contend using the modified contention delay range of $t_i \in [1, s_{max} - 1]$ time-slots. A *successful* relay designates itself as being a preferred relay; no announcement is made to other nodes. A relay immediately relinquishes its preferred status if it realises that it has missed a frame for the given data flow (by monitoring the sequence numbers of received frames), if it hears a retransmission for the source-destination pair for which it is preferred, or if it determines that a frame that it had relayed failed to arrive at the destination (through the absence of an acknowledgement after retransmission). After relinquishing its preferred status, the relay contends for subsequent retransmissions via the default contention mechanism.

The contention delay algorithm is:

$$t_i = \begin{cases} 0, & i \text{ is preferred} \\ \left\lfloor \left((1 - a_X) \left(\frac{F_i - F_{max}}{F_{min} - F_{max}} \right) + a_X X_i \right) (s_{max} - 1) + 1 \right\rfloor T_{slot}, & \text{otherwise.} \end{cases} \tag{4.30}$$

Preferred relays retransmit in time-slot 0, which will result in a collision should two or more relays have preferred status. However, for this to occur, the first preferred relay would have to miss each of the source, retransmission and acknowledgement frames for a retransmission with the same sequence number that it has already received. With the possible exception of high mobility networks subject to deep fading, this is highly improbable. In the unlikely event that it does occur, network performance is not significantly impacted because only one frame retransmission attempt is affected by the collision; colliding preferred relays immediately relinquish their status and participate in a normal contention process for the following retransmission.

Although any relay can potentially serve any source-destination pair, the preferred relay status is only used for a specific source-destination link. Further, it is directional; the relay is not automatically preferred in the reverse path.

4.4.2 Effect on Retransmission Collisions

A simulation is conducted using QualNet 4.5 [85] to validate the hypothesis that preferring relays that were previously successful will reduce the rate of retransmission collisions. Source and destination nodes are placed 80 m apart in a 120 m × 120 m simulation area, with a number of additional neighbour nodes randomly distributed throughout the same area. The physical characteristics of the 802.11b nodes are based on a Senao device [88], giving an approximate transmission range of 80 m at a transmission rate of 11 Mb/s in this scenario (simulated hardware is described in more detail in Section 4.5.1). The number of neighbours is varied between one and twenty; in each case, 1000 random topologies are generated containing the specified number of neighbours. The source node transmits 1000 frames with 1400-byte payloads as CBR traffic in each simulation. The same sets of node distributions are used for all MAC configurations to allow for a direct comparison. The three MAC configurations used are:

1. A basic DAFMAC algorithm using (4.1) where $a_X = 0$ (i.e. no random component);

2. The DAFMAC algorithm with a random delay component $a_X = 0.1$ using (4.16); and

3. The full algorithm with $a_X = 0.1$ and preferred relays using (4.30).

As expected from the previous analysis, adding a random component to the contention delay algorithm significantly reduces the retransmission collision rate. Implementing the preferred relay scheme further reduces the collision rate by approximately half. The behaviour for each set of protocol options is shown in Figure 4.9.

The reduction in the rate of retransmission collisions using preferred relays is substantial, while the computational overhead introduced by the preferred relay scheme is insignificant. Relays track their preference status for each source-destination pair using a flag

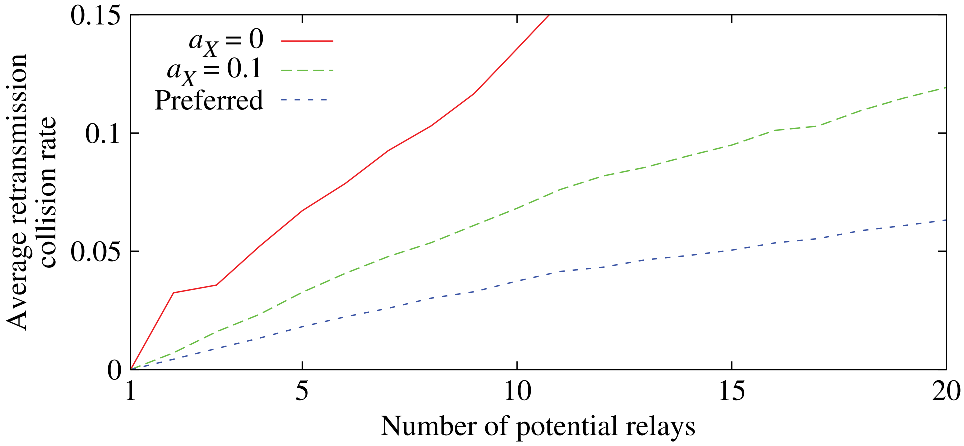

Figure 4.9: Enabling preferred relays significantly reduces the rate of retransmission collisions

in the DAFMAC link quality table, with a trivial memory cost of one bit per source-destination pair.

4.5 Retransmission Performance

The following simulations use a variety of network performance metrics to quantify the benefits of the DAFMAC and PRO [77] cooperative retransmission schemes over the default non-cooperative 802.11 ARQ scheme.

4.5.1 Basic Simulation Configuration

Uniformly random distributions of 25 nodes are used as the initial node layout in all simulations. Ten equal data flows of CBR traffic between fixed pairs of nodes are configured as shown in Figure 4.10. The payload size is 1400 bytes.

The physical layer is configured as either IEEE 802.11b with an 11 Mb/s rate and a transmission power of 15 dBm, or IEEE 802.11g with a 54 Mb/s rate and a transmission power of 13 dBm. Collision avoidance is limited to the basic mode of operation using carrier sensing with no RTS/CTS signalling. The base contention window size is set to 32 T_{slot} for all protocols; ARQ exponentially increases this window on repeated transmission attempts [54] and PRO increases the window size for lower-ranked relays where required [77].

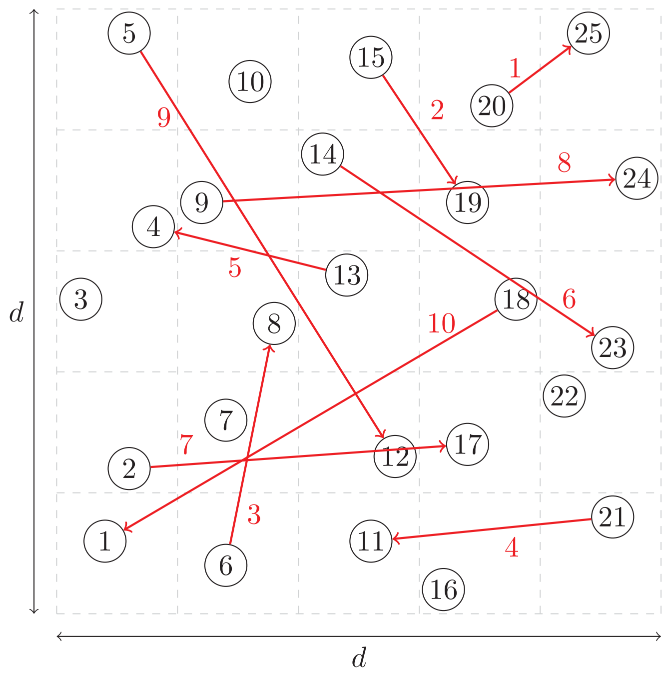

Figure 4.10: Example uniform random node distribution showing the source and destination nodes of the 10 data flows

Rician fading with a K-factor of 5 and a fading velocity of 5 is used to simulate static nodes with mobile scatterers. The path loss exponent is set to a typical indoor value of 2.6 [11]. Each node uses a single vertical omnidirectional antenna with a gain of 3 dBi.

Simulations are conducted using QualNet 4.5 [85]. All simulation configurations are created using 100 different random seed values to generate unique uniform random node locations and fading patterns. The same random scenario is then used across all MAC protocols, which are therefore subject to exactly the same node positions and channel conditions. Each simulation ran for 600 seconds of simulation time. The median result is presented, and error bars (where shown) represent the central 90% of results.

4.5.2 Saturated 802.11b Network Throughput

For most applications, the most important network characteristic is throughput. In these simulations, the total network load is 6 Mb/s, which is close to the saturation point for an 802.11b network. This simulation is repeated for a range of node densities (by varying

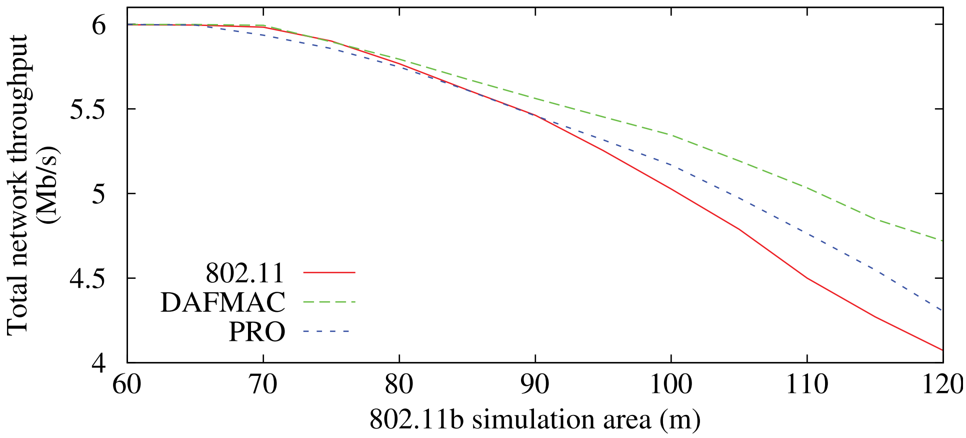

Figure 4.11: DAFMAC provides the highest total network throughput as the path-loss increases in a larger simulation area

the simulation area for the same number of nodes), and the combined throughput of all data flows is shown in Figure 4.11.

This simulation provides three key results. The first is that the DAFMAC protocol results in a higher total throughput than PRO for all network densities tested. The cause of this difference is explored throughout this and the following sections.

The second result is that cooperative retransmissions increase total throughput in higher path-loss networks. This result is different to the classical relay channel model, because the cooperative relay is selected on a per-frame basis, and direct transmission is used when the path-loss decreases.

Finally, both DAFMAC and non-cooperative ARQ outperform PRO when the node density is high. In this case, cooperative retransmissions are rarely required, therefore the PRO coordination overhead consumes channel capacity but does not contribute to useful throughput. Conversely, DAFMAC does not introduce an explicit overhead and converges to the 802.11 behaviour when retransmissions are not required.

There are two factors working against PRO in saturated networks. Firstly, the channel capacity used to maintain two-hop link information becomes significant. Secondly, and more importantly, PRO relays will only contend for retransmission if they are idle and do not have a frame already buffered. One of the key design features of PRO is that in order to reduce the retransmission collision rate, the *participating relay set* is a subset of the total neighbour set. However, this leads to conditions where some or all of the participating nodes are busy (either transmitting their own frame or waiting to retransmit another frame) and hence no PRO node retransmits the frame. This behaviour provides strong justification for one of the key concepts in the design of DAFMAC, that frames being relayed by a given node are given a higher priority than frames originating at the node itself.

It is anticipated that modifying the PRO protocol to allow nodes to participate in cooperation if they already have a frame buffered will slightly improve retransmission performance. However, this will also increase the retransmission collision rate when the contending set contains two or more relays.

4.5.3 Individual Flow Fairness in a Saturated 802.11b Network

While maximising the total network throughput is an important objective, individual users are typically more concerned with the throughput experienced by data flows to and from their own node. Therefore, equitable distribution of network resources, or *fairness*, between users becomes an important performance criterion for any given networking protocol. The 802.11 ARQ mechanism is inherently unfair, because failed transmissions increase channel access back-off times. While this improves overall network performance by reducing channel resources wasted on transmissions with a low probability of success, it means that some users benefit at the expense of others, depending on individual source-destination path losses.

The throughput for ten individual data flows for 802.11 ARQ, DAFMAC, and PRO in a 100 m $\times$ 100 m area containing 25 nodes is shown in Figure 4.12. Links 9 and 10 have the highest path loss, and therefore experience significantly poorer throughput compared to the other flows if plain 802.11 ARQ is used. By contrast, DAFMAC is more effective at ensuring throughput fairness than either PRO or ARQ. A quantitative comparison can be obtained using Jain's Fairness Index [56], a normalised, dimensionless measure of the relative equality of the resource allocation. A totally fair allocation will result in a fairness index of 1 and the index tends to $\frac{1}{n}$ as all resources are allocated exclusively to one of the n users. As a visual example, the fairness of the throughput distribution shown in Figure 4.12 is 0.92 for ARQ, 0.97 for DAFMAC, and 0.91 for PRO.

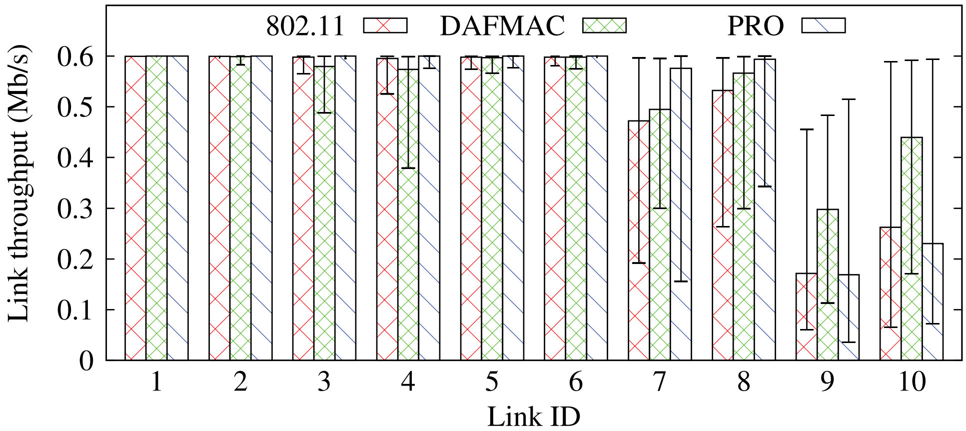

Figure 4.12: DAFMAC provides the highest throughput for the high path-loss links in a 100 m × 100 m simulation area

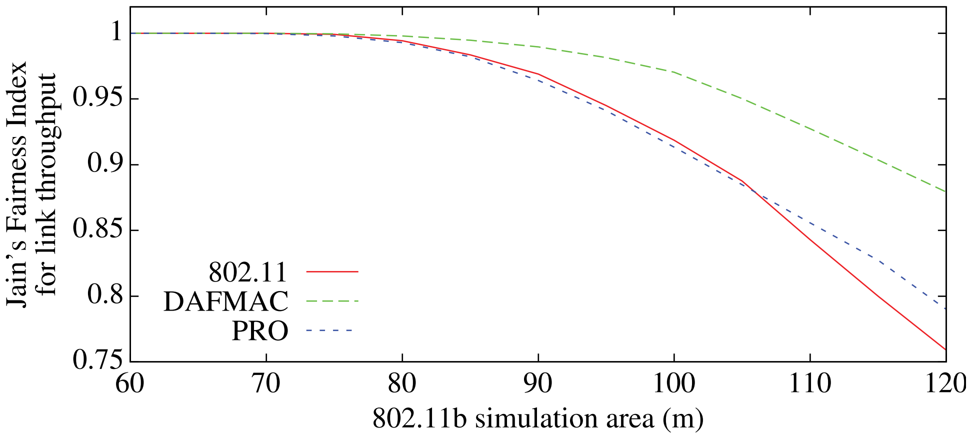

Figure 4.13: DAFMAC provides the most consistent throughput for all flows, as measured using Jain's Fairness Index metric

Figure 4.13 shows the fairness index for flow throughput distribution as a function of simulated network area. Fairness for all protocols decreases as the simulated area increases, and hence node density decreases, because the throughput in the high loss links decreases. However, DAFMAC fairness is significantly higher than either PRO or plain 802.11 ARQ, indicating that DAFMAC retransmissions also improve the equality between data flows in addition to improving the total network throughput.

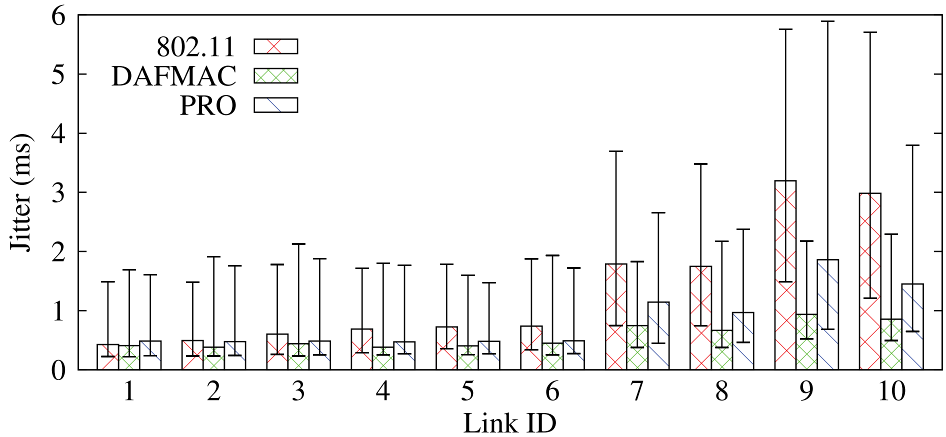

Figure 4.14: DAFMAC has the most consistent jitter with a 2 Mb/s network load

4.5.4 802.11b Frame Jitter

Jitter is a measure of transmission latency variation and is an important parameter for real-time applications such as streamed multimedia or real-time sensing or control applications. This scenario uses a 2 Mb/s total load (well below saturation in order to focus on protocol impact on jitter rather than the impact of saturation) spread over the 10 data flows in an 80 m × 80 m area, where most nodes will normally be within transmission range.

Figure 4.14 shows the jitter behaviour for individual flows in this scenario. DAFMAC maintains the lowest jitter for all flows, but the most significant result is the relative difference in the jitter for each protocol for the high path loss links. The relatively low jitter for high path-loss links shows that DAFMAC provides the fairest temporal behaviour across all flows. DAFMAC jitter is lower because of the relatively higher priority assigned to retransmissions by having all potential relays contend for access, compared to the subsets of participating and idle PRO relays. Similarly, if the direct 802.11 transmission fails, a slow-fading channel will remain sufficiently high path-loss that retransmissions soon after have a high risk of transmission failure, resulting in high jitter due to the invocation of the ARQ mechanism.

Jain's Fairness Index for the median per-flow jitter is 0.888, 0.751 and 0.648 for DAFMAC, PRO and 802.11 ARQ, respectively.

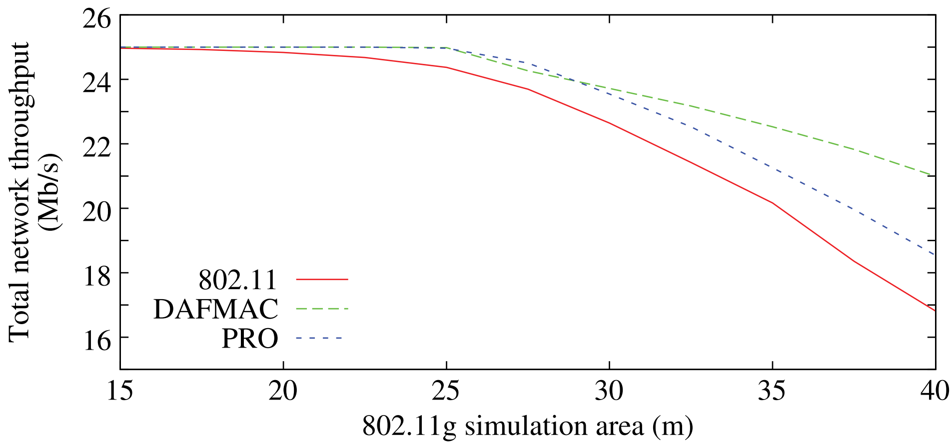

Figure 4.15: DAFMAC provides the highest total network throughput for a saturated 802.11g network

4.5.5 Saturated 802.11g Network Throughput Performance

The relative performance difference between DAFMAC and PRO is less pronounced in an 802.11g network, as shown in Figure 4.15. As discussed in Section 3.3, the PRO coordination broadcast updates are transmitted at a higher rate in 802.11g and therefore consume a smaller fraction of the channel capacity. Saturated network throughput performance is simulated using the same 10 data flows (as shown in Figure 4.10) with a total load of 25 Mb/s. The simulation uses uniformly distributed random node distributions in a square region with side lengths between 15 m and 40 m.

Total network throughput decreases as the simulation area and hence path loss increases. DAFMAC improves the throughput over the 802.11 baseline, and also provides better throughput than PRO at higher path losses even though the PRO coordination consumes a smaller fraction of the total channel capacity. Again, this is primarily due to the best PRO relays not always being eligible for retransmission because they are busy.

The throughput fairness, as measured using Jain's Fairness Index, is shown in Figure 4.16 for the saturated 802.11g network. The DAFMAC retransmission protocol still provides the most equitable throughput distribution between the data flows. PRO also significantly improves the fairness compared to the 802.11 ARQ baseline, but is limited by the lower priority that it allocates to retransmissions.

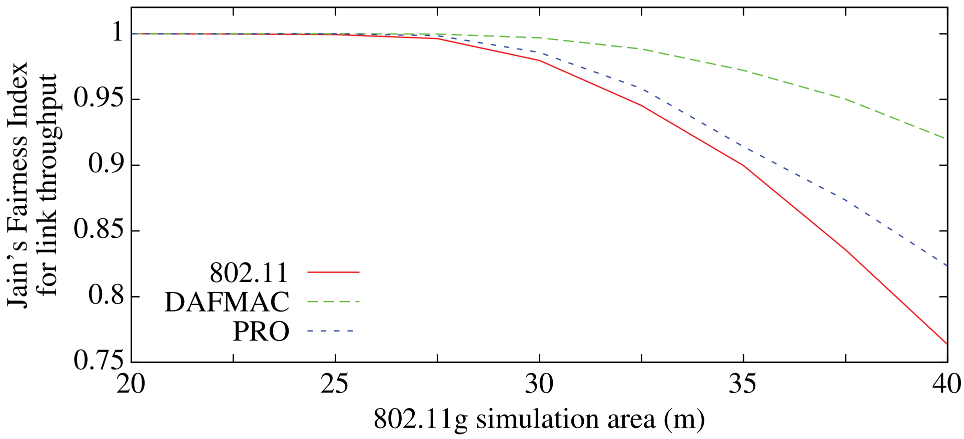

Figure 4.16: DAFMAC provides the most consistent throughput for all flows using the Jain's Fairness Index metric for a saturated 802.11g network

4.5.6 Mobile Network Performance

Network layer routing protocols are often compared in mobile scenarios to evaluate the protocol's ability to respond to topology changes. The expected result is that as node mobility increases, routes become less stable and hence throughput decreases. However, MAC-layer retransmission protocols are fundamentally different to network layer routing protocols because the transmission path is limited to one hop. Therefore, it is expected that MAC-layer retransmission protocols will converge on a suitable path to the destination in a significantly shorter time than a multi-hop routing algorithm [1].

A simple scenario is constructed using 25 802.11b nodes with 10 data flows and a total network load of 3 Mb/s. Nodes are initially uniformly randomly distributed in a 120 m $\times$ 120 m region. All nodes move according to a random waypoint mobility model; devices randomly select a random X and Y coordinate and travel with a velocity randomly selected in the range $v \in [10, 20]$ m/s. Once they arrive at the destination, devices pause their movement for between 0 s and 100 s (fixed for each scenario), then randomly select a new destination and repeat the process. The two-dimensional random waypoint model in [14] suggests the steady state average distance between any two nodes in this scenario will be approximately 62 m, which is less than the average transmission range of approximately 80 m predicted by QualNet. The total simulation time is 600 s. The channel is Rician fading with a K-factor of 3 and a fading velocity of 30 m/s.

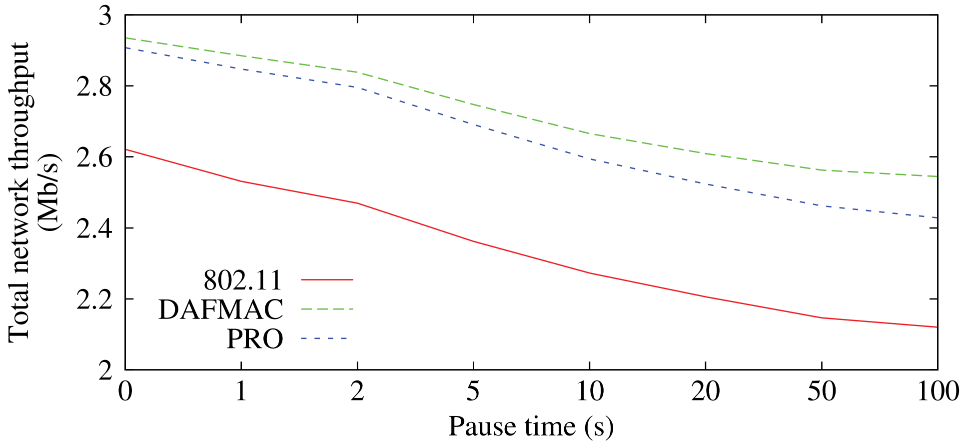

Figure 4.17: DAFMAC provides the highest total network throughput for all node pause times in a mobile (random waypoint) scenario

The results of this simulation are presented in Figure 4.17. The first observation is that throughput decreases as the pause time increases (i.e. nodes become more "static") for all protocols, which is the opposite of the behaviour normally expected in network layer routing protocols. There are three reasons for this behaviour. Firstly, highly mobile nodes have a greater probability of more frequently returning to be within transmission range, and hence are more likely to be able to transmit any buffered frames. Conversely, large pause times may result in a higher path loss for greater periods of time and may increase the period during which frame retransmission is required.

The second reason is that nodes with greater mobility approach the steady-state spatial distribution for random waypoint motion in a shorter period of time. As shown in [14], the steady state spatial distribution of the random waypoint mobility model is concentrated in the centre of the simulation area. Therefore, nodes which are more mobile are able to converge to a distribution with reduced path loss more quickly, increasing throughput.

Finally, while the node velocity in this scenario is relatively fast for the routing protocol, where the route update period is in the order of seconds, the node velocity is slow relative to the MAC-layer where operations are performed with millisecond periods. Even if devices are travelling at 20 m/s, they will travel less than 80 mm in a typical MAC-layer transmission and cooperative retransmission cycle using IEEE 802.11b at 11 Mb/s, and approximately 14 mm using 802.11g at a 54 Mb/s data rate. That is, the devices are effectively static at the MAC-layer and the point-to-point transmission performance is not significantly reduced where devices are within transmission range.

DAFMAC provides the highest total network throughput for all pause times, with the difference between DAFMAC and PRO increasing with larger pause times, when retransmission is required for extended periods.

The random mobility pattern ensures all data flows are subject to, on average, equal path losses. The Jain's Fairness Index value for the individual flow throughput in this scenario is greater than 0.999 for all protocols for all pause times.

A full study of node mobility, including vehicular mobility scenarios, justifies further exploration that is beyond the scope of this chapter and is potentially the focus of future work.

4.6 Energy Consumption to Throughput Efficacy

Relay protocols share the resources of individual nodes to improve the total network performance, which inevitably consumes energy at the relay. The real question, in the context of this work, is can a cooperative retransmission protocol reduce the total network energy consumption for a given throughput load?

The comprehensive energy consumption model presented by Saavedra *et al* [45] incorporates both communication and processing energy. The processing energy cannot be measured in QualNet simulations; therefore the relative computational complexity is explored separately in Section 4.7.

The simulation in Section 4.5.2 also captured the proportion of time each node spent actively transmitting (t_{tx}), actively receiving (t_{rx}) and idle (t_{idle}). Based on the empirical study presented by Feeney and Nilsson [43], it is assumed that the 802.11b transceiver is supplied by a $V = 4.74$ VDC source, draws a current of $I_{tx} = 284$ mA when transmitting, draws $I_{rx} = 190$ mA when receiving and draws $I_{idle} = 156$ mA when idle. The average power consumption for node N_i is then estimated using

$$P_i = V_i(t_{tx}I_{tx} + t_{rx}I_{rx} + t_{idle}I_{idle}). \tag{4.31}$$

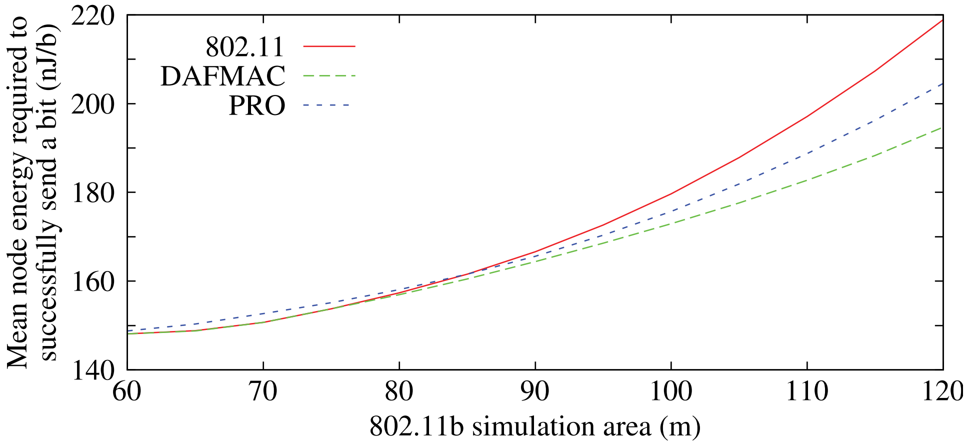

Figure 4.18: The DAFMAC protocol requires the least energy to successfully transmit a bit in an 802.11b network

The energy-throughput efficacy is defined as the average power consumed per node (watts) divided by the total network throughput (bits per second). This ratio represents the average energy used by each node in the *successful* transmission of a bit (measured at the application layer) in the network.

The energy-throughput efficacy for the simulated 802.11b network is shown in Figure 4.18. The key observation is that the DAFMAC protocol requires the least amount of energy per successfully transmitted bit out of all tested protocols, under all tested scenarios.

When the network area is sufficiently small, all link channels support reliable direct transmissions, and retransmissions are required very infrequently. The energy consumed by PRO's coordination overhead is evident in networks deployed in a square region 60 m to 70 m across in this scenario, as the retransmission protocol does not significantly contribute to the throughput but still consumes resources. In this case, the DAFMAC protocol converges to the 802.11 behaviour and does not reduce the energy efficiency, but nor is there any increased energy consumption or capacity lost to overhead.

As the network density decreases and the path loss becomes higher, more energy is needed to successfully transmit bits. The energy analyses by both Zhao *et al* [107] and Shah *et al* [92] suggest that transmission is the dominant energy use and the receiving energy can be ignored. Conversely, the simulation results presented in Figure 4.18

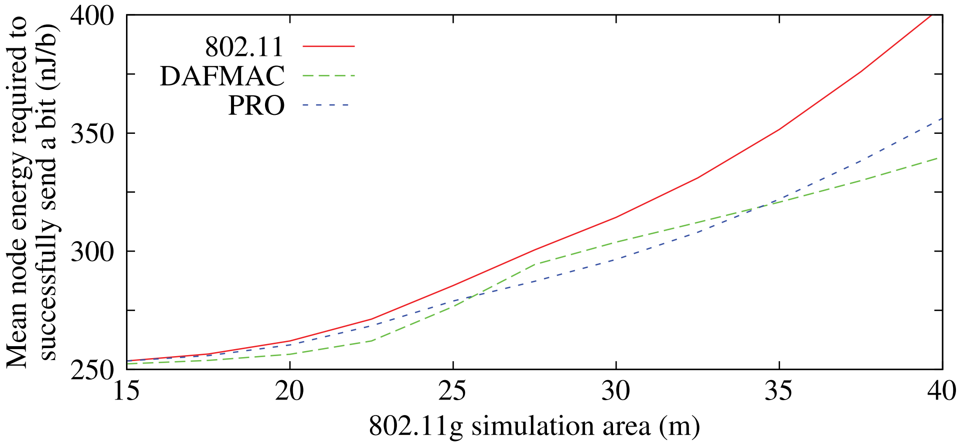

Figure 4.19: Cooperative retransmissions also reduce the total energy per bit in an 802.11g network

clearly show that while the receive power is lower than the transmission power, many nodes receive each transmission, and therefore receive power dominates the total network energy use. This is critical in higher path loss scenarios where many nodes receive frames that are not successfully decoded at the destination. The key result of this experiment is that nodes less energy to cooperatively retransmit a frame than to listen to messages fail repeatedly. Both DAFMAC and PRO cooperative retransmissions have a clear energy advantage in this case. DAFMAC consumes up to 12% less energy per successful bit than 802.11 ARQ retransmissions.

This result supports the DAFMAC philosophy that selfless retransmission improves the result for all nodes, even for a relay gaining no direct benefit itself in terms of data delivery. Complex schemes that offer credit-based rewards use additional processing and channel resources to maintain reward integrity, and retransmission performance suffers if nodes cheat to unfairly gain credits [100]. However, the simulation results obtained here suggest that, at least for opportunistic retransmissions, cooperation reduces both energy and bandwidth consumption and hence is its own reward.

The energy required to successfully transmit data with 802.11g is calculated using the same method. The empirical observations by Atheros Communications, Inc., [13] show the Atheros AR5001X+ consumes $P_{tx} = 8.36$ W during transmission, $P_{rx} = 8.54$ W during reception, and $P_{idle} = 1.56$ W when idle. Figure 4.19 shows the energy per successfully transmitted bit for the saturated network in Section 4.5.5. Cooperative retransmissions always reduce the energy consumption. DAFMAC is less energy efficient than PRO when retransmissions are infrequently required at moderate path losses, but become more efficient than PRO at higher path losses.

This analysis does not consider the complex behaviour of a chemical battery discharge [41]. Furthermore, energy consumption in cooperative networks is often analysed from an economics perspective using game-theoretic techniques to optimise network lifetime [91]. An in-depth analysis is an interesting topic for future research but is outside the scope of this Thesis.

4.7 Delay Algorithm Complexity

Contention delay is calculated periodically and represents a constant processing overhead. For a semi-static network, the delay may only need to be recalculated once every few seconds, while a more dynamic network may benefit from repeating the calculation several times per second. The significance of the computational complexity may be considered trivial compared to the processing capabilities of modern CPUs. However, it is worth evaluating as the computational overhead of the protocols may become important for large, dense networks.

The four computational complexity metrics are: memory accesses, integer calculations, floating point calculations and branch operations. The average number of operations per contention delay calculation is determined in a QualNet simulation by counting each time an operation is performed and dividing by the total number of retransmission contentions entered.

The order of complexity is a function of the loop nesting. The DAFMAC calculation is contained entirely within a single loop and all operations are proportional to the number of neighbours. PRO requires a nested loop to calculate the cumulative PDR for multiple transmissions. The orders of complexity for all metrics are shown in Table 4.1. By most metrics, DAFMAC's delay calculation is less complex than PRO by at least an order of magnitude. Figure 4.20 shows the ratio of the number of operations in PRO compared to DAFMAC.

Table 4.1: Complexity analysis for DAFMAC and PRO

Metric	Complexity	
	DAFMAC	PRO
Memory Required	$O(n)$	$O(n^2)$
Memory Accesses	$O(n)$	$O(n^2)$
Integer Ops	$O(n)$	$O(n^2)$
Float Ops	$O(1)$	$O(n)$
Branch Ops	$O(n)$	$O(n^2)$

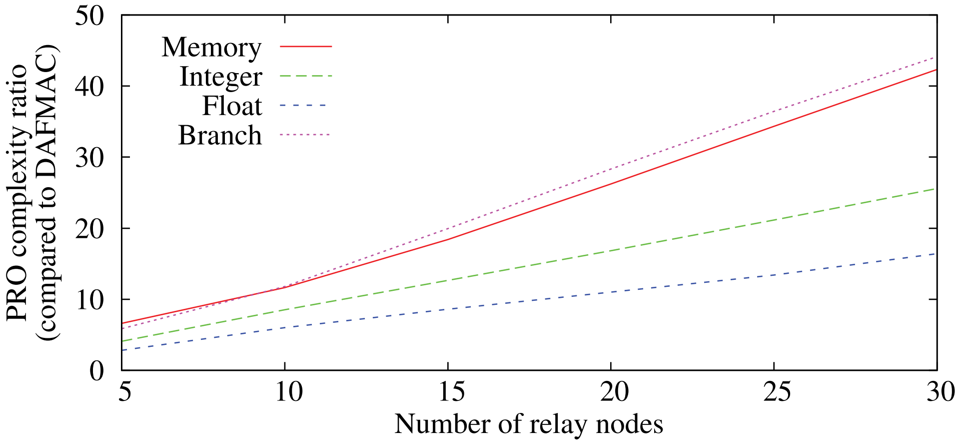

Figure 4.20: DAFMAC uses a fraction of the resources required by PRO to calculate the contention delay

4.8 Influence of Hidden Nodes, and RTS/CTS frames, on DAFMAC Performance

Hidden node interference occurs when nodes cannot directly sense each other's transmissions, however, their transmissions interfere with each other at the respective destination(s). This section evaluates the impact of hidden node collisions using cooperative retransmission protocols.

Hidden node interference occurs when the incoming signals are below the receiver sensitivity and therefore cannot be detected via the carrier sense mechanism. It is assumed that the signal power thresholds for successfully decoding a frame and for sensing a frame are independent.

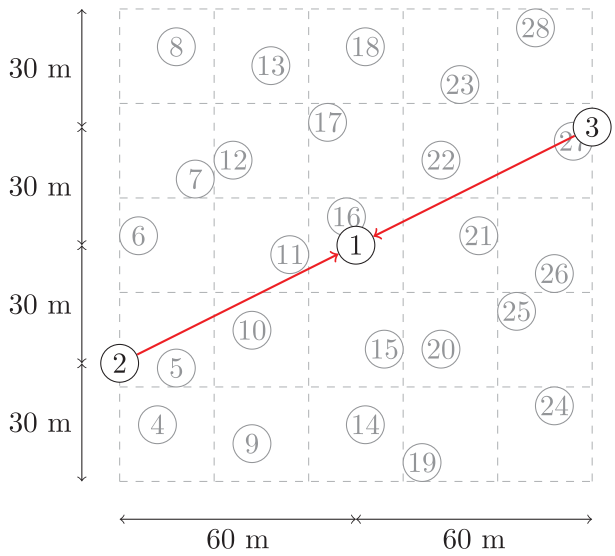

Figure 4.21: Example node placement for hidden nodes transmitting to a common destination, with uniformly distributed neighbours

A scenario is constructed where two source nodes transmitted to a common destination node, with an additional 25 uniformly randomly distributed neighbours nodes, as shown in Figure 4.21. Using the same physical device properties as previous simulations, the RSS for both links is approximately -82.5 dBm and is sufficient for reliable decoding of data frames. The simulation uses 100 random seeds to uniformly randomly place the 25 neighbour nodes and generate the channel characteristics. Each source node continuously sent CBR traffic (with a payload size of 1400 bytes) at a transmission rate of 11 Mb/s. The carrier sense threshold is varied from -83 dBm to -93 dBm to guarantee hidden node interference.

The first simulation establishes that hidden node interference is achieved with this configuration. No channel fading is used in order to eliminate channel-induced performance variability. Figure 4.22 shows very poor direct transmission performance for less sensitive receivers when the source nodes are unable to sense each other. The throughput improves significantly when the receiver sensitivity increases, which allows nodes to pause their own transmission and avoid interfering. This result shows transmission performance is severely limited by hidden node interference when the carrier sensing is poor.

Cooperative retransmissions from both DAFMAC and PRO significantly improve the throughput over non-cooperative ARQ when the source nodes are hidden from each

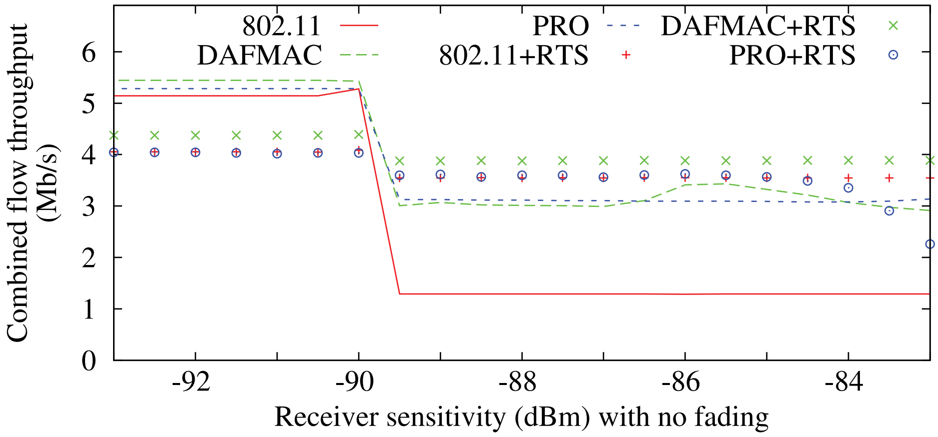

Figure 4.22: A sharp transition is evident at the receiver sensitivity of -90 dBm, where source nodes can sense each other's transmissions

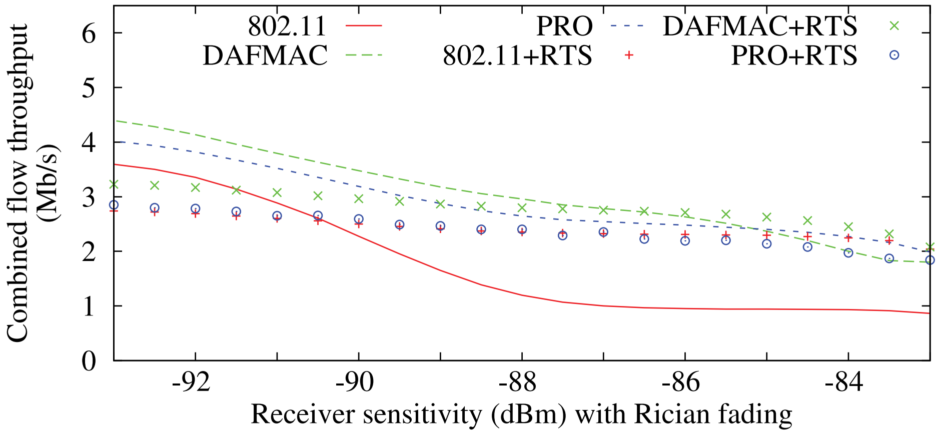

Figure 4.23: Cooperative retransmissions reduce the impact of hidden nodes in fading channels

other. Cooperative relays are closer to the destination, hence relays are better able to sense both source signals and retransmit frames without interfering with the other source or relays.

The throughput performance with RTS/CTS handshaking is significantly better than without when the source nodes are hidden from each other. While performance improves when nodes are visible to each other, total performance with RTS/CTS enabled is worse due to the signalling overhead.

The scenario is repeated using a Rician fading channel with a K-factor of 5 and a fading velocity of 5 m/s to represent a more realistic channel. Figure 4.23 shows that the throughput resulting from using cooperative retransmissions is always higher than with non-cooperative ARQ retransmissions. Therefore, hidden node interference has less impact when using cooperative retransmission protocols compared to ARQ. The performance for less sensitive receivers is lower because fading can increase the path-loss such that the data frame signal cannot be sensed at the destination.

Throughput for DAFMAC is generally higher than for PRO because the PRO participating relay set is limited to a small set of nodes near the destination, and these are the nodes most affected by hidden node interference. The result is similar to the previously observed case where no PRO relay is available to retransmit, although this time it is because relays cannot decode the frame. Conversely, DAFMAC uses all neighbour nodes which means that some nodes will always decode the source transmission, improving the probability of retransmission success.

4.9 Conclusion

This chapter develops and evaluates the DAFMAC relay selection algorithm, which is shown to significantly improve network performance over the 802.11 MAC protocol with ARQ retransmissions.

A motivation for this work is to extend the proof-of-concept DAFMAC cooperative protocol in Chapter 3 by reducing the cooperative retransmission collision rate. This is achieved via four incremental contributions:

- Identifying that the outer weighted relay scoring function is the most effective at isolating a single relay;
- Incorporation of a small random component, which adds a small number of additional random collisions but reduces repeated failures from relays with equal scoring function values;
- Deriving effective scoring function parameters; and
- Introducing a preferred relay scheme to re-use successful relays.

These result in a DAFMAC relay selection algorithm that achieves a low retransmission collision rate. Further, it is also significantly less computationally complex than the PRO relay ranking algorithm.

A comprehensive series of simulations quantifies DAFMAC's retransmission effectiveness. The key simulation results show that DAFMAC improves the total network saturated throughput and the relative fairness of individual link throughput, reduces the network-wide energy consumption per successfully received bit, reduces frame jitter and improves throughput performance in mobile scenarios, compared to both traditional non-cooperative ARQ retransmission and the PRO cooperative retransmission protocol.

The work in this chapter also identifies several interesting areas for future research, including evaluation of retransmission performance with heterogeneous devices, a more detailed examination of retransmission performance in scenarios using more complex mobility models and a detailed economic comparison of node energy consumption in cooperative retransmission networks.

Chapter 5

GENERAL COOPERATIVE RETRANSMISSION MODEL

5.1 Introduction

This chapter proposes a general model to analytically estimate the probability of successful retransmission in cooperative relaying schemes, including a detailed failure mode analysis. Retransmission performance is modelled by calculating the probability of each outcome, namely either: retransmission success, or failure caused by data frame corruption, ACK frame corruption, retransmission collision or no relay availability. Distributed retransmission algorithms typically use a slot-based delay scheme to arbitrate between contending nodes.

The key contributions and results of this chapter are:

- Derivation of the probability of the outcome for a retransmission attempt as a function of the cooperative contention delay time-out probability (Section 5.2);
- Derivation of the cooperation time-out probabilities for ARQ, CMAC, DAFMAC, Δ-MAC, and PRO (Section 5.3);
- Creation of a Markov model and derivation of a closed-form solution which describes the retransmission behaviour of DAFMAC when using preferred relays (Section 5.4);
- Validation of the analytic model by demonstrating its ability to accurately reproduce the results of a QualNet simulation (Section 5.5); and
- Evaluation of the retransmission performance of each retransmission protocol using the analytic model (Section 5.7).

5.2 Cooperative Retransmission Model

This section derives an analytic model for performance analysis of retransmission algorithms that is applicable to any slot-based contention algorithm. Cooperative retransmission algorithms typically employ some extension to the 802.11 CSMA/CA channel access mechanism for autonomous relay selection, such as the method of distributed timers introduced by Bletsas, Lippman, and Reed [21]. Nodes use channel state information available at the MAC layer (such as RSS and PDR) to estimate the probability of successful retransmission of a frame to its intended destination; nodes predicting that they can transmit with a high probability of success will attempt to transmit first.

The model calculates the probability of each outcome for a cooperative retransmission contention period: failures when no relays contend, data retransmission failure from the selected relay, ACK transmission failure, retransmission collision between two or more relays, or success when a single relay forwards the frame to the destination and the source hears the ACK.

5.2.1 Assumptions and Nomenclature

This model does not account for any retransmission algorithm computation complexity or control overhead. It also assumes nodes external to the cooperative process do not interrupt, which is valid for a lightly loaded network.

$\mathcal{N}_n$ is the set of neighbour nodes with non-zero PDR to both source and destination. The participating set $\mathcal{N}_p$ defines the neighbouring nodes that have elected to act as relays. Finally, the contending set $\mathcal{N}_c$ is the set of participating relays which receive the source frame. Hence, $\mathcal{N}_c \subseteq \mathcal{N}_p \subseteq \mathcal{N}_n$.

Potential relay node N_i may select a specific delay t_i [77], or it may randomly decide whether or not to contend for a given slot at the beginning of that slot [32]. The proposed model accommodates both strategies.

A relay with a pre-selected timer has three possible states; the timer expires before, during, or after a given time slot. Let the probabilities of being in each state be:

$$p_{ib}(t) \triangleq \Pr\{t_i < t\} \tag{5.1}$$

$$p_{it}(t) \triangleq \Pr\{t_i = t\} \tag{5.2}$$

$$p_{ia}(t) \triangleq \Pr\{t_i > t\} \tag{5.3}$$

respectively, for relay $N_i \in \mathcal{N}_c$ in time slot t. Therefore,

$$p_{ib}(t) + p_{it}(t) + p_{ia}(t) = 1. \tag{5.4}$$

$P_D(a, b)$ denotes the probability of a successful data frame transmission from node a to b. It is assumed that frame transmission errors are i.i.d., although more complex transmission models may be used to simulate bursty losses. Let $P_A(b, a)$ be the ACK transmission success probability from b to a. Analysis in [87] suggests using $P_A(b, a) \approx 1$, which may be substituted into the model.

Cooperative relaying schemes frequently use RSS or historical PDR values to evaluate the potential relay channel quality. It is assumed that these values are known to the node, and remain valid during the observation period. Channels and device hardware are also assumed to be approximately reciprocal; $RSS_{a,b} \approx RSS_{b,a}$ and $P_D(b, a) \approx P_D(a, b)$.

The outcome probability of the contending node set during an attempted cooperative transmission is the sum of outcome probabilities during each time slot $t \in [0, T_{max} - 1]$, where T_{max} is specific to each retransmission algorithm. Similarly, the outcome probability for a contending node set is the sum of individual node outcome probabilities.

5.2.2 Probability of Successful Relaying

This section derives an expression for a successful frame retransmission by defining how a node can 'win' the distributed contention phase in one time-slot and then extending to the general result of the entire network for the whole period.

A relay wins contention if it is the first node (and only) whose back-off timer reaches zero. Consider the contending set $\mathcal{N}_c$; node N_i wins contention if all other timers expire after it, hence the probability that N_i wins contention in time slot t is:

$$\begin{aligned}\Pr\{N_i\ wins,\ t \mid N_i \in \mathcal{N}_c\} &= p_{it}(t) \prod_{\substack{N_j \in \mathcal{N}_c,\\ j \neq i}} p_{ja}(t) \\ &= W_i(\mathcal{N}_c, t)\end{aligned} \tag{5.5}$$

Values for $p_{it}(t)$ and $p_{ia}(t)$ depend on the retransmission algorithm used. Example values are derived in Section 5.3. Extending (5.5), the probability that node N_i wins contention in any time slot is:

$$\Pr\{N_i\ wins \mid N_i \in \mathcal{N}_c\} = \sum_{t=0}^{T_{max}-1} W_i(\mathcal{N}_c, t) \tag{5.6}$$

The probability that N_i wins contention, retransmits the data frame to N_d and N_s receives the ACK is therefore:

$$\Pr\{N_i\ succeeds \mid N_i \in \mathcal{N}_c\} = \sum_{t=0}^{T_{max}-1} W_i(\mathcal{N}_c, t) P_D(i, d) P_A(d, s) \tag{5.7}$$

The probability of any contending node (from the contending set $\mathcal{N}_c$) successfully forwarding the frame is:

$$\Pr\{success \mid \mathcal{N}_c\} = \sum_{N_i \in \mathcal{N}_c} \sum_{t=0}^{T_{max}-1} W_i(\mathcal{N}_c, t) P_D(i, d) P_A(d, s) \tag{5.8}$$

Let $\mathcal{S}_c$ be the set of all possible combinations of contending relays and $\mathcal{N}_c$ be a specific contending set, such that $\mathcal{N}_c \in \mathcal{S}_c$. The probability of a specific set $\mathcal{N}_c$ having received the source frame and contending is:

$$\Pr\{\mathcal{N}_c\} = \prod_{N_i \in \mathcal{N}_c} P_D(s, i) \prod_{\substack{N_i \in \mathcal{N}_p,\\ N_i \notin \mathcal{N}_c}} (1 - P_D(s, i)) \tag{5.9}$$

A participating relay may or may not receive the source frame, so the set cardinality is $|\mathcal{S}_c| = 2^{|\mathcal{N}_p|}$. The sum of the probabilities of all contending relay combinations is unity:

$$\sum_{\mathcal{N}_c \in \mathcal{S}_c} \Pr\{\mathcal{N}_c\} = 1. \tag{5.10}$$

From (5.8) and (5.9), the probability that any node from any contending relay set successfully retransmits the frame to the destination and the ACK is successfully received is:

$$\Pr\{success\} = \sum_{\mathcal{N}_c \in \mathcal{S}_c} \sum_{N_i \in \mathcal{N}_c} \sum_{t=0}^{T_{max}-1} W_i(\mathcal{N}_c, t) P_D(i, d) P_A(d, s) \Pr\{\mathcal{N}_c\} \tag{5.11}$$

If $\Pr\{success\} > P_D(s, d)$, then the cooperative retransmission scheme will result in a higher probability of frame delivery compared to a source node ARQ retransmission.

5.2.3 Probability of No Valid Relays

The probability that the contending set is empty (i.e. $|\mathcal{N}_c| = 0$) because no participating relay receives the source frame is:

$$\Pr\{no\ relays\} = \prod_{N_i \in \mathcal{N}_p} (1 - P_D(s, i)) \tag{5.12}$$

By definition, the contending set is non-empty when the source node participates in the retransmission process. This is the typical behaviour for both DAFMAC and Δ-MAC.

5.2.4 Probability of Collision

There is no collision in time slot t if any node timer has expired before this slot, no node timers expire in this slot, or if only one node timer expires in this slot. Hence, the probability of collision is:

$$\Pr\{collision\} = 1 - \Pr\{before\} - \Pr\{none\} - \Pr\{one\} \tag{5.13}$$

where, for a given contending set $\mathcal{N}_c$ and time slot t:

$$
\begin{aligned}
&\Pr\{before,\ t \mid N_i \in \mathcal{N}_c\} \\
&\qquad = 1 - (1 - p_{1b}(t))(1 - p_{2b}(t)) \ldots (1 - p_{|\mathcal{N}_c|b}(t)) \\
&\qquad = 1 - \prod_{i \in \mathcal{N}_c} (1 - p_{ib}(t)) \\
&\qquad = 1 - \prod_{i \in \mathcal{N}_c} (p_{it}(t) + p_{ia}(t)) \qquad (5.14)
\end{aligned}
$$

$$
\begin{aligned}
\Pr\{none,\ t \mid N_i \in \mathcal{N}_c\} &= p_{1a}(t) p_{2a}(t) \ldots p_{|\mathcal{N}_c|a}(t) \\
&= \prod_{N_i \in \mathcal{N}_c} p_{ia}(t) \qquad (5.15)
\end{aligned}
$$

The probability of one relay winning contention is given by (5.6). The total collision probability for all contending sets is therefore:

$$
\begin{aligned}
\Pr\{collision\} = \sum_{\mathcal{N}_c \in \mathcal{S}_c} \sum_{t=0}^{T_{max}-1} \Bigg(&\prod_{N_i \in \mathcal{N}_c} (p_{it}(t) + p_{ia}(t)) \\
&- \prod_{N_i \in \mathcal{N}_c} p_{ia}(t) - \sum_{N_i \in \mathcal{N}_c} W_i(\mathcal{N}_c, t) \Bigg) \Pr\{\mathcal{N}_c\} \qquad (5.16)
\end{aligned}
$$

5.2.5 Probability of Data Retransmission Failure

The probability of any node winning contention then failing to successfully retransmit the data frame to the destination is:

$$
\Pr\{D\ fail\} = \sum_{\mathcal{N}_c \in \mathcal{S}_c} \sum_{N_i \in \mathcal{N}_c} \sum_{t=0}^{T_{max}-1} W_i(\mathcal{N}_c, t)(1 - P_D(i, d)) \Pr\{\mathcal{N}_c\} \qquad (5.17)
$$

5.2.6 Probability of ACK Retransmission Failure

The probability that the destination receives the data frame via retransmission, but the source fails to receive the ACK is:

$$
\Pr\{A\ fail\} = \sum_{\mathcal{N}_c \in \mathcal{S}_c} \sum_{N_i \in \mathcal{N}_c} \sum_{t=0}^{T_{max}-1} W_i(\mathcal{N}_c, t) P_D(i, d)(1 - P_A(d, s)) \Pr\{\mathcal{N}_c\} \qquad (5.18)
$$

5.3 Example Slot Probability Derivation

This section derives example slot time-out probabilities for the non-cooperative 802.11 ARQ, and the CMAC, DAFMAC, Δ-MAC and PRO cooperative relaying schemes. Corresponding algorithm-specific parameters are denoted with the superscripts A, C, D, P, and Δ respectively. These values are used in conjunction with the probability derivations in Section 5.2 to estimate the retransmission performance.

Each retransmission algorithm begins with a uniformly distributed random variable, $X \sim \text{U}[0,1)$ to generate the contention delay. This distribution has the property:

$$\Pr\{X \leq a \mid a \in [0,1)\} = a. \tag{5.19}$$

The random variable is scaled by the relay scoring function to spread the delay, t, over a range of time-out slots:

$$t \in [0, T_{max} - 1]. \tag{5.20}$$

For completeness, the time-out probabilities outside of this range are:

$$p_{ia}(t) = 1, \quad \forall t < 0 \tag{5.21}$$

and:

$$p_{ib}(t) = 1, \quad \forall t > T_{max} - 1. \tag{5.22}$$

5.3.1 ARQ Slot Probability Calculation

The basic 802.11 Automatic Repeat Request (ARQ) algorithm is described in [54]. The ARQ protocol is a non-cooperative retransmission strategy where only the source node retransmits, as shown in Figure 5.1; hence $\mathcal{N}_p^A = \{N_s\}$. This is represented in the model by letting $P_D(s,i) = 1$ (i.e. a perfect channel) while $P_D(i,d)$ remains scenario-specific. The source node generates the uniformly distributed random variable $X_s \sim \text{Un}[0,1)$ to select a random back-off time. T_{max}^A is the upper bound of the contention window size from which t_s is randomly selected:

$$t_s^A = \lfloor X_s T_{max}^A \rfloor \tag{5.23}$$

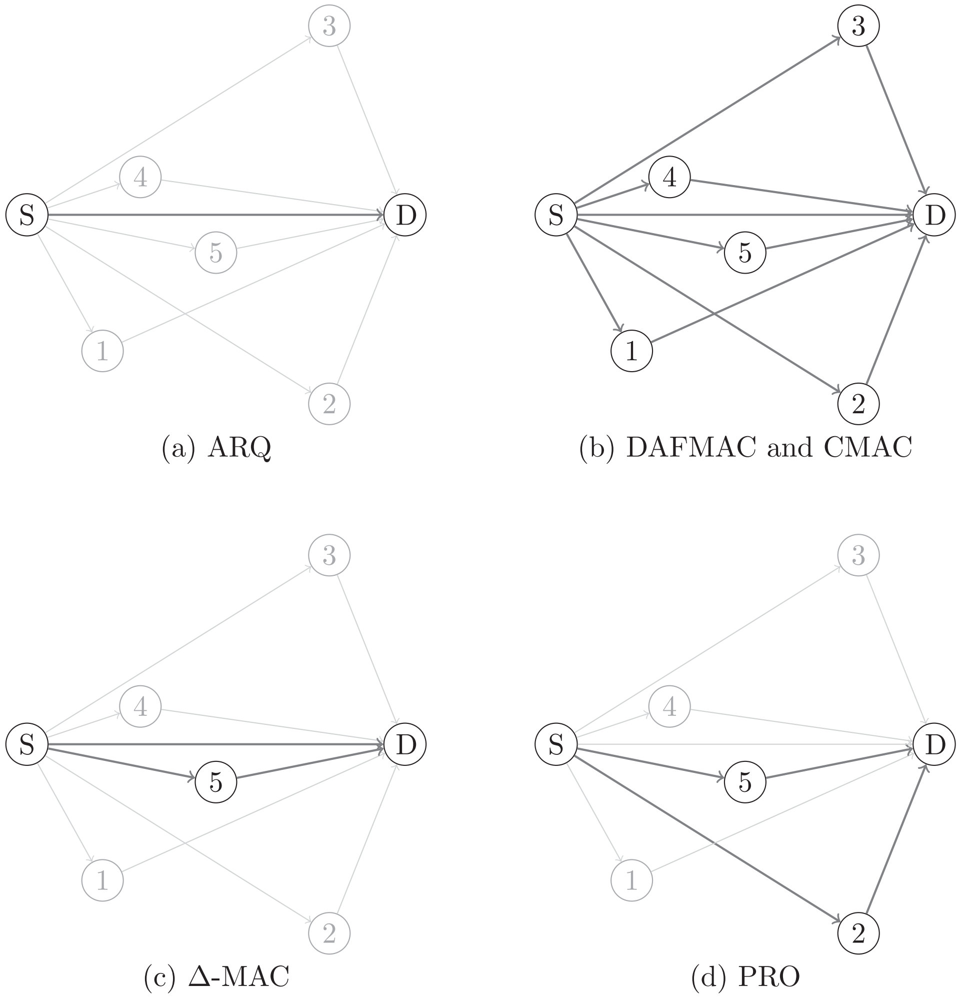

Figure 5.1: Examples of the participating relay set for (a) ARQ, (b) DAFMAC and CMAC, (c) Δ-MAC, and (d) PRO.

Using (5.2) and (5.23), the probability of the ARQ timer t_s^A expiring before time slot t is:

$$\begin{aligned} p_{sb}^A(t) &= \Pr\left\{\left\lfloor T_{max}^A X_s \right\rfloor < t\right\} \\ &= \Pr\left\{T_{max}^A X_s < t\right\} \\ &= \Pr\left\{X_s < \frac{t}{T_{max}^A}\right\} \\ &= \frac{t}{T_{max}^A}. \end{aligned} \tag{5.24}$$

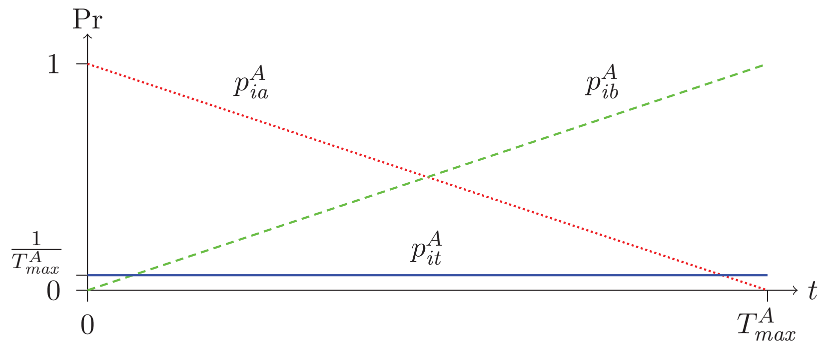

Figure 5.2: Visualisation of the slot probabilities of ARQ derived in (5.24), (5.25) and (5.26), CMAC and Δ-MAC have similar plots

From (5.3), the probability that t_s^A expires after slot t is:

$$\begin{aligned} p_{sa}^A(t) &= \Pr\left\{\left\lfloor T_{max}^A X_s \right\rfloor > t\right\} \\ &= \Pr\left\{T_{max}^A X_s \geq t+1\right\} \\ &= \Pr\left\{X_s \geq \frac{t+1}{T_{max}^A}\right\} \\ &= 1 - \Pr\left\{X_s < \frac{t+1}{T_{max}^A}\right\} \\ &= 1 - \frac{t+1}{T_{max}^A}. \end{aligned} \tag{5.25}$$

From (5.4), (5.24) and (5.25), the probability that t_s^A expires in slot t is:

$$\begin{aligned} p_{st}^A(t) &= 1 - p_{sb}^A(t) - p_{sa}^A(t) \\ &= \frac{1}{T_{max}^A}. \end{aligned} \tag{5.26}$$

These functions are plotted in Figure 5.2.

5.3.2 CMAC Slot Probability Calculation

The CMAC protocol is one of the founding 802.11 cooperative retransmission protocols. CMAC is a "dumb" relay selection algorithm because it does use link quality information to identify the best relay. While CMAC is outperformed by more complex relay selection algorithms, it is included in this comparison to highlight the significant performance benefit of selecting the relay (or random selection from a reduced set) versus randomly selecting any node to act as a relay.

In the event of a retransmission, all relays which overhear and successfully decode the data frame enter a CSMA/CA back-off period to contend for retransmission. The participating set of cooperative relays also includes the source node, $\mathcal{N}_p^C = \{N_s, \mathcal{N}_n\}$. Each contending relay N_i generates a uniformly distributed random variable $X_i \sim \text{Un}[0, 1)$ to select a random back-off time. T_{max}^C is the upper bound of the contention window size from which t_i^C is randomly selected :

$$t_i^C = \lfloor X_i T_{max}^C \rfloor \tag{5.27}$$

Because CMAC uses a randomly generated back-off time, and the contention window is equal for all relays, the slot time-out probabilities are the same as for ARQ. Therefore, the probability of the CMAC timer t_i^C expiring before time slot t is:

$$p_{ib}^C(t) = \frac{t}{T_{max}^C}. \tag{5.28}$$

The probability that t_i^C expires after slot t is:

$$p_{ia}^C(t) = 1 - \frac{t+1}{T_{max}^C}. \tag{5.29}$$

Finally, the probability that t_i^C expires in slot t is:

$$p_{it}^C(t) = \frac{1}{T_{max}^C}. \tag{5.30}$$

5.3.3 DAFMAC Slot Probability Calculation

The DAFMAC relay selection algorithm described in Section 4.2 is a general method for calculating delay values for cooperative retransmission. The default behaviour of this algorithm is to use instantaneous RSS values to rank relays; however, it may use any arbitrary relay scoring function to do so. A key feature of this approach is a random delay component which is added to all delay calculations to avoid repeat collisions from static nodes with similar link quality - this has been shown to reduce contention collisions by approximately 50% in networks with randomly placed nodes. All neighbour nodes participate in cooperative retransmissions, as shown in Figure 5.1.

The general form of the DAFMAC contention delay is:

$$t_i^D = \left\lfloor \left((1 - a_X) \left(\frac{F_i - F_{max}}{F_{min} - F_{max}} \right) + a_X X_i \right) T_{max}^D \right\rfloor \tag{5.31}$$

where a_X is the random delay weighting, X_i is a uniformly distributed random variable in the range $X_i \sim \text{Un}[0,1)$, F_i is the scoring function for node N_i, and F_{min} and F_{max} are the outputs of the scoring function with the lowest and highest expected RSS values, respectively.

The contention delay is comprised of link quality and random components for all scoring functions. Let the link quality component be:

$$L_i^D = (1 - a_X) \left(\frac{F_i - F_{max}}{F_{min} - F_{max}} \right) T_{max}^D, \tag{5.32}$$

which reduces the delay function to:

$$t_i^D = \left\lfloor L_i^D + a_X X_i T_{max}^D \right\rfloor. \tag{5.33}$$

From (5.1) and (5.33), the probability that DAFMAC timer t_i^D expires before slot t is:

$$\begin{aligned} p_{ib}^D(t) &= \Pr\left\{ \left\lfloor L_i + a_X X_i T_{max}^D \right\rfloor < t \right\} \\ &= \Pr\left\{ L_i + a_X X_i T_{max}^D < t \right\} \\ &= \Pr\left\{ X_i < \frac{t - L_i}{a_X T_{max}^D} \right\}. \end{aligned} \tag{5.34}$$

Using the property of (5.19):

$$p_{ib}^D(t) = \frac{t - L_i}{a_X T_{max}^D} \tag{5.35}$$

However, the lower bound of $X_i = 0$ gives a minimum bound such that $p_{ib}^D(t) = 0$ if:

$$\begin{aligned} \frac{t - L_i}{a_X T_{max}^D} &< 0 \\ t &< L_i \end{aligned} \tag{5.36}$$

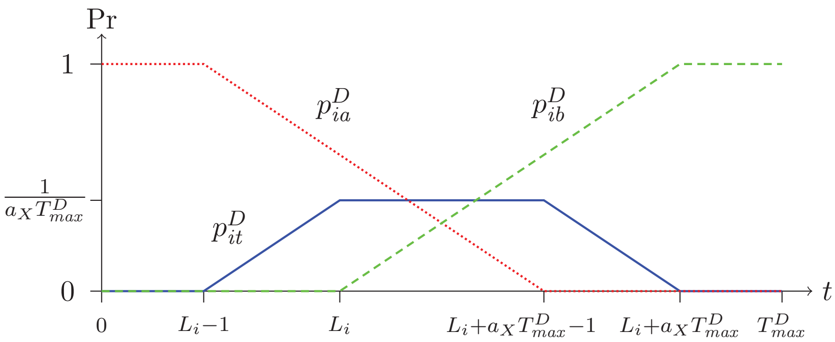

Figure 5.3: Visualisation of the slot probabilities of DAFMAC derived in (5.38), (5.42) and (5.43), where $a_X T^D_{max} > 1$

Similarly, there upper limit of $X_i < 1$ gives a maximum bound such that $p^D_{ib}(t) = 1$ if:

$$\frac{t - L_i}{a_X T^D_{max}} \geq 1$$

$$t \geq L_i + a_X T^D_{max} \tag{5.37}$$

Therefore, a complete definition of $p^D_{ib}(t)$ is:

$$p^D_{ib}(t) = \begin{cases} 0 & \text{if } t < L_i \\ \frac{t-L_i}{a_X T^D_{max}} & \text{if } t \in [L_i, L_i + a_X T^D_{max}) \\ 1 & \text{if } t \geq L_i + a_X T^D_{max}. \end{cases} \tag{5.38}$$

This function is plotted in Figure 5.3.

Similarly, from (5.3) and (5.33), the probability that DAFMAC timer t^D_i expires after slot t is:

$$\begin{aligned} p^D_{ia}(t) &= \Pr\left\{\left\lfloor L_i + a_X X_i T^D_{max} \right\rfloor > t\right\} \\ &= \Pr\left\{L_i + a_X X_i T^D_{max} \geq t+1\right\} \\ &= \Pr\left\{X_i \geq \frac{t+1-L_i}{a_X T^D_{max}}\right\} \\ &= 1 - \Pr\left\{X_i < \frac{t+1-L_i}{a_X T^D_{max}}\right\} \\ p^D_{ia}(t) &= 1 - \frac{t+1-L_i}{a_X T^D_{max}} \end{aligned} \tag{5.39}$$

The minimum value of random variable $X_i = 0$ gives a minimum bound such that $p^D_{ia}(t) = 1$ if:

$$\frac{t+1-L_i}{a_X T^D_{max}} < 0$$
$$t < L_i - 1 \tag{5.40}$$

Similarly, there upper limit of $X_i < 1$ gives a maximum bound such that $p^D_{ia}(t) = 0$ if:

$$\frac{t+1-L_i}{a_X T^D_{max}} \geq 1$$
$$t \geq L_i + a_X T^D_{max} - 1 \tag{5.41}$$

Therefore, a complete definition of $p^D_{ia}(t)$ is given by:

$$p^D_{ia}(t) = \begin{cases} 1 & \text{if } t < L_i - 1 \\ 1 - \frac{t+1-L_i}{a_X T^D_{max}} & \text{if } t \in [L_i - 1, L_i + a_X T^D_{max} - 1) \\ 0 & \text{if } t \geq L_i + a_X T^D_{max} - 1. \end{cases} \tag{5.42}$$

Using (5.4), (5.38) and (5.42), the probability that a DAFMAC retransmission delay times out in slot t is:

$$\begin{aligned} p^D_{it}(t) &= 1 - p^D_{ib}(t) - p^D_{ia}(t) \\ &= \begin{cases} 0, & \text{if } t < L_i - 1 \\ \frac{t+1-L_i}{a_X T^D_{max}}, & \text{if } t \in [L_i - 1, L_i) \\ \frac{1}{a_X T^D_{max}}, & \text{if } t \in [L_i, L_i + a_X T^D_{max} - 1) \\ 1 - \frac{t-L_i}{a_X T^D_{max}}, & \text{if } t \in [L_i + a_X T^D_{max} - 1, L_i + a_X T^D_{max}) \\ 0, & \text{if } t \geq L_i + a_X T^D_{max}. \end{cases} \end{aligned} \tag{5.43}$$

There is an important caveat for this result - it is only valid when $a_X T^D_{max} > 1$; a different approach must be used when $a_X T^D_{max} \leq 1$. In this case, there is insufficient random component of t^D_i to spread the delay probability over two or more time slots.

Therefore the probability of the timer expiring before slot t is:

$$\begin{aligned} p_{ib}^{D}(t) &= \Pr\left\{\lfloor L_i \rfloor < t\right\} \\ &= \Pr\left\{L_i < t\right\} \\ &= \begin{cases} 1 & \text{if } t > L_i \\ 0 & \text{if } t \le L_i. \end{cases} \end{aligned} \tag{5.44}$$

Similarly, the probability of the timer expiring after slot t is:

$$\begin{aligned} p_{ia}^{D}(t) &= \Pr\left\{\lfloor L_i \rfloor > t\right\} \\ &= \Pr\left\{L_i \ge t+1\right\} \\ &= \begin{cases} 1 & \text{if } t \le L_i - 1 \\ 0 & \text{if } t > L_i - 1. \end{cases} \end{aligned} \tag{5.45}$$

Finally, the probability of timer t_i^D expiring in slot t is:

$$\begin{aligned} p_{it}^{D}(t) &= \Pr\left\{\lfloor L_i \rfloor = t\right\} \\ &= \Pr\left\{L_i \in [t, t+1)\right\} \\ &= \begin{cases} 0 & \text{if } t > L_i \\ 1 & \text{if } t \in (L_i - 1, L_i] \\ 0 & \text{if } t \le L_i - 1. \end{cases} \end{aligned} \tag{5.46}$$

This special case applies to all scoring functions if $a_X T_{max}^D \le 1$. The modified slot probabilities are illustrated in Figure 5.4. The function and the impact of different scoring function options are discussed in the following subsections.

Nearest Neighbour

The Nearest Neighbour (DAFMAC-NN) scoring function prioritises relays close to N_d by using:

$$F_i^{NN} = RSS_{i,d}. \tag{5.47}$$

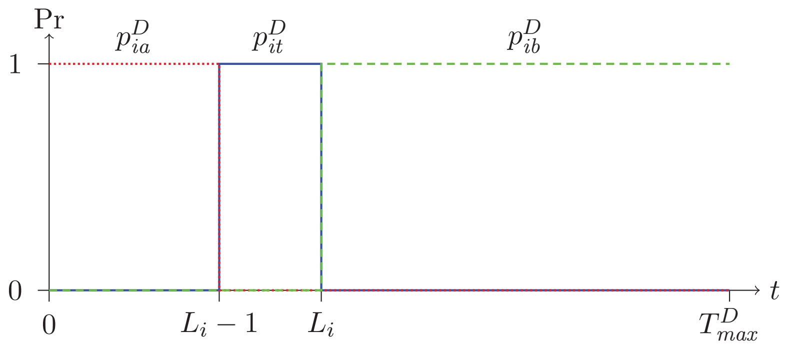

Figure 5.4: Visualisation of the slot probabilities of DAFMAC derived in (5.44), (5.45) and (5.46), where $a_X T_{max}^D \leq 1$

The value of F_{min} is the minimum link quality expected from a useful link and is nominally set to the device receiver sensitivity threshold. F_{max} is the maximum anticipated value of RSS. It may be explicitly specified as part of the algorithm configuration or it may be set dynamically by each node according to the observations stored in its neighbour table. A fixed value is used for the purpose of this comparison.

Minimum Link Quality

The Minimum Link Quality (DAFMAC-ML) scoring function prioritises relays with the smallest path loss to both N_s and N_d by using the function:

$$F_i^{ML} = \min(RSS_{s,i}, RSS_{i,d}). \tag{5.48}$$

The DAFMAC-ML scoring function improves performance when the protocol requires both links of the relay to be as reliable as possible. This is particularly important when only a subset of the potential relays participate in retransmission. However, as shown in Section 4.2.5, it is more challenging to isolate a single relay to retransmit and typically results in a higher collision rate than the Nearest Neighbour scoring function.

As before, F_{min}^{ML} is set to the receiver sensitivity threshold RSS_{Rx}. If $RSS_{s,d} \gg RSS_{Rx}$ the frame will probably be received correctly and retransmission is not required. Conversely, if $RSS_{s,d} \ll RSS_{Rx}$ the source-destination link would be inadequate and the (network layer) routing protocol should define a better path. Therefore, it is assumed that $RSS_{s,d} \approx RSS_{Rx}$. The ideal DAFMAC-ML relay is located mid-way between N_s and N_d, that is $d_{s,i} \approx d_{i,d} \approx 0.5 d_{s,d}$. Assuming a log-normal path loss:

$$RSS_{s,d} \approx RSS_{i,d} + 10n \log\left(\frac{d_{i,d}}{d_{s,d}}\right) \tag{5.49}$$

where n is the path-loss exponent. This value is environment-specific; typically $n \in [2, 4]$ [11]. Therefore,

$$F^{ML}_{max} \approx F^{ML}_{min} + 3n. \tag{5.50}$$

This method is easily extended to the link harmonic average power as used by Bletsas, Lippman, and Reed [21].

5.3.4 Δ-MAC Slot Probability Calculation

The Δ-MAC retransmission algorithm is described in [87]. Δ-MAC is different to the aforementioned retransmission algorithms because the relay is nominated by the source node prior to transmission via a modified RTS frame. All nodes transmit their link status every second and neighbours maintain a two-hop neighbour PDR table similar to PRO. The source node selects the neighbour with the highest joint PDR to itself and the destination as the relay, as shown in Figure 5.1. The relay monitors the frame transaction between source and destination. If the destination does not acknowledge the data frame, and the relay has received it correctly, it will transmit an ACK to the source immediately after the absent destination ACK. Upon receiving this ACK, the source waits for retransmission by the nominated relay and does not attempt an ARQ retransmission. The relay uses a random back-off to contend for access to the channel. The source node overhearing the retransmission accepts this as an acknowledgement of transmission.

A Δ-MAC relay will participate in cooperative retransmission only when it does not already have a frame to send. This model assumes the relay is always available. Additionally, the model assumes that the customised RTS and CTS signalling prior to the data frame transmission always succeeds.

The Δ-MAC participating set is limited to the source and nominated relay, hence $\mathcal{N}_p^{\Delta} = \{N_s, N_r\}$. Let the subscript r or s denote the relay or source, respectively. The contending relay randomly selects a time-out in the range $t_r^{\Delta},\ t_s^{\Delta} \in [0, T_{max}^{\Delta} - 1]$.

The probability of the Δ-MAC timer t_r^{Δ} expiring before time slot t is similar to (5.24):

$$\begin{aligned} p_{rb}^{\Delta} &= \Pr\left\{\left\lfloor T_{max}^{\Delta} X_i \right\rfloor < t\right\} \\ &= \frac{t}{T_{max}^{\Delta}} \end{aligned} \tag{5.51}$$

Similarly to (5.25), the probability that t_r^{Δ} expires after t is:

$$\begin{aligned} p_{ra}^{\Delta} &= \Pr\left\{\left\lfloor T_{max}^{\Delta} X_i \right\rfloor > t\right\} \\ &= 1 - \frac{t+1}{T_{max}^{\Delta}} \end{aligned} \tag{5.52}$$

From (5.4), (5.51) and (5.52), the probability that t_r^{Δ} expires in slot t is:

$$\begin{aligned} p_{rt}^{\Delta} &= 1 - p_{rb}^{\Delta} - p_{ra}^{\Delta} \\ &= \frac{1}{T_{max}^{\Delta}} \end{aligned} \tag{5.53}$$

The time out probability for Δ-MAC follows the same pattern as ARQ which is illustrated in Figure 5.2.

The source node may retransmit frames where the nominated relay is unable to do so. The three scenarios where the source frame may retransmit are: firstly, if the relay correctly receives the source frame, secondly, if the relay has another frame already buffered, and finally, if source node does not receive the ACK sent by the relay. The only case where the source can interact with the relay (and possibly collide) is when the relay receives the data frame but the source node fails to receive the ACK frame.

The source node retransmission behaviour depends on whether or not the relay has received the data frame, therefore the source node time-out probabilities are conditional. If the relay fails to decode the data frame, then the source has an identical contention behaviour as a relay that successfully receives it. Conversely, if the relay receives the source frame, then the source will only contend if it fails to receive the ACK frame sent by the relay. Therefore, the probability that the source Δ-MAC node timer t_s^{Δ} expires before slot t is:

$$p_{sb}^{\Delta} = \Pr\left\{\lfloor T_{max}^{\Delta} X_i \rfloor < t\right\} = \begin{cases} \frac{t}{T_{max}^{\Delta}} & \text{if } N_r \text{ does not decode the data frame} \\ \frac{t(1-P_A(r,s))}{T_{max}^{\Delta}} & \text{if } N_r \text{ decodes the data frame} \end{cases} \tag{5.54}$$

The source does not participate when it receives the relay's ACK frame. This may be modelled as the time-out never expiring. Hence the probability that the source Δ-MAC node times out after slot t is:

$$p_{sa}^{\Delta} = \Pr\left\{\lfloor T_{max}^{\Delta} X_i \rfloor > t\right\} = \begin{cases} 1 - \frac{t+1}{T_{max}^{\Delta}} & \text{if } N_r \text{ does not decode the data frame} \\ \left(1 - \frac{t+1}{T_{max}^{\Delta}}\right)(1 - P_A(r,s)) + P_A(r,s) & \\ & \text{if } N_r \text{ decodes the data frame} \end{cases} \tag{5.55}$$

From (5.4), (5.54) and (5.55), the probability that t_r^{Δ} expires in slot t is:

$$p_{st}^{\Delta} = 1 - p_{rb}^{\Delta} - p_{ra}^{\Delta} = \begin{cases} \frac{1}{T_{max}^{\Delta}} & \text{if } N_r \text{ does not decode the data frame} \\ \frac{1-P_A(r,s)}{T_{max}^{\Delta}} & \text{if } N_r \text{ decodes the data frame} \end{cases} \tag{5.56}$$

This effectively results in the source contention timer never expiring when the cooperative ACK from the relay is received at the source.

5.3.5 PRO Slot Probability Calculation

The PRO algorithm is described in [77]. PRO ranks neighbour nodes using $RSS_{i,d}$, with $RSS_{s,i}$ used to resolve a tie. Relays are added to the participating set until the cumulative joint retransmission probability reaches a set threshold, Th_r. An example of this subset is shown in Figure 5.1. It is assumed that $Th_r = 0.95$ in this scenario, as suggested in [77]. The participating set, $\mathcal{N}_p^P \subseteq \mathcal{N}_n$, is known to all neighbours from control transmissions. PRO uses a uniform random contention period where more highly ranked relays have a smaller contention window T^P_{max}. Let $T^P_{max}(i)$ be the contention window for node N_i:

$$T^P_{max}(i) = 2^{\min\left(\left\lfloor \frac{i+9}{2} \right\rfloor, 10\right)} \tag{5.57}$$

where i is the ordered participating node index (from 1 to $|\mathcal{N}^P_p|$). The contention delay for node N_i is:

$$t^P_i = \left\lfloor T^P_{max}(i) X_i \right\rfloor \tag{5.58}$$

Unlike other contention delay algorithms, individual PRO relays may use different T^P_{max} values. The total range of potential delays is:

$$t^P_i \in \left[0, 2^{\min\left(\left\lfloor \frac{|\mathcal{N}^P_p|+9}{2} \right\rfloor, 10\right)} - 1\right] \tag{5.59}$$

although relays may only use a subset of this range.

The probability of the PRO timer t^P_i expiring before time slot t is similar to (5.24) but bounded to the $T^P_{max}(i)$ contention range:

$$\begin{aligned} p^P_{ib}(t) &= \Pr\left\{ \left\lfloor T^P_{max}(i) X_i \right\rfloor < t \right\} \\ &= \begin{cases} \frac{t}{T^P_{max}(i)} & \text{if } t \in [0, T^P_{max}(i)) \\ 1 & \text{if } t \in [T^P_{max}(i), T^P_{max}(|\mathcal{N}^P_p|)). \end{cases} \end{aligned} \tag{5.60}$$

Similarly to (5.25), the probability that t^P_i expires after t is:

$$\begin{aligned} p^P_{ia}(t) &= \Pr\left\{ \left\lfloor T^P_{max}(i) X_i \right\rfloor > t \right\} \\ &= \begin{cases} 1 - \frac{t+1}{T^P_{max}(i)} & \text{if } t \in [0, T^P_{max}(i)) \\ 0 & \text{if } t \in [T^P_{max}(i), T^P_{max}(|\mathcal{N}^P_p|)). \end{cases} \end{aligned} \tag{5.61}$$

From (5.4), (5.60) and (5.61), the probability that t^P_i expires in slot t is:

$$\begin{aligned} p^P_{it}(t) &= 1 - p^P_{ib}(t) - p^P_{ia}(t) \\ &= \begin{cases} \frac{1}{T^P_{max}(i)} & \text{if } t \in [0, T^P_{max}(i)) \\ 0 & \text{if } t \in [T^P_{max}(i), T^P_{max}(|\mathcal{N}^P_p|)). \end{cases} \end{aligned} \tag{5.62}$$

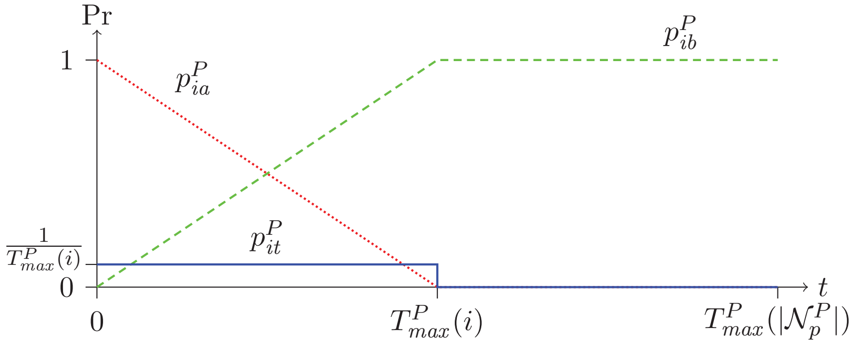

Figure 5.5: Visualisation of the slot probabilities of PRO derived in (5.60), (5.61) and (5.62), illustrated where $i < |N^P_p|$

These functions are plotted in Figure 5.5.

5.4 Preferred Relay Outcome Derivation

As shown in Section 4.4, using a preferred relay can significantly reduce contention collisions while maintaining a low overhead. However, the analytic description is significantly more complex as the system is no longer memoryless. This section describes the retransmission process of a preferred relay algorithm applied to DAFMAC, the Markov model and solution to determine the probability of a relay being preferred, and the modified outcome probabilities.

The probability of any relay gaining and maintaining a preferred status is dependent upon the instantaneous channel properties; the preferred relay probability will change if devices are mobile, channel fading variations are introduced, or the availability of devices to contend for retransmission change.

5.4.1 Introduction to Preferred Relays

The DAFMAC preferred relay model significantly reduces retransmission collisions by allowing previously successful relays to operate in an isolated contention period. If a preferred relay hears a failed frame, it retransmits in time-slot 0, while all other relays contend using the delay algorithms over the reduced interval $t_i \in [1, T_{max} - 1]$.

A relay becomes preferred after a successful retransmission; the relay sets a flag to indicate that it does not need to contend for future retransmissions. No broadcast is necessary when a relay self-identifies as "preferred"; other nodes are normally aware of their non-preferred status, except in exceptional cases which will be discussed later. A relay immediately loses the preferred status if it fails to receive a frame for the given link (by monitoring the sequence numbers of frames), if it hears a retransmission for the same link as it is preferred, or if it fails to retransmit a frame (by not hearing an ACK after retransmission). After losing preferred status, relays participate in subsequent retransmissions via the normal contention algorithm.

Preferred relays retransmit in time-slot 0, which will result in a collision should two or more relays have preferred status. However, for this to occur, and the first preferred relay would have to miss the source-, retransmission- and ACK frames for a subsequent retransmission with the same sequence number that it has already received. With the exception of high mobility with deep fading, this is highly improbable. Even on the rare occasions when it does occur, system performance is not significantly affected; colliding preferred relays would simply lose their status and participate in regular contention in the following retransmission. Therefore, for the purpose of this model, it is assumed that only one node may be preferred at any time.

5.4.2 DAFMAC Time-out Probability Modifications

When using preferred relays, the contention delay function is modified to:

$$t_i^D = \begin{cases} 0 & \text{if } i \text{ is preferred} \\ \left\lfloor 1 + \left((1 - a_X) \left(\frac{F_i - F_{max}}{F_{min} - F_{max}} \right) + a_X X_i \right) (T_{max}^D - 1) \right\rfloor & \text{otherwise.} \end{cases} \tag{5.63}$$

A preferred relay has no opportunity to collide with another relay, so time-out probabilities are not required. In the case of a non-preferred relay, the link quality component of the delay is:

$$L_i^D = 1 + (1 - a_X) \left(\frac{F_i - F_{max}}{F_{min} - F_{max}} \right) (T_{max}^D - 1). \tag{5.64}$$

Using the same process as (5.38), the probability of a non-preferred relay timing out before slot t is:

$$p_{ib}^D(t) = \begin{cases} 0 & \text{if } t < L_i \\ \frac{t-L_i}{a_X(T_{max}^D-1)} & \text{if } t \in [L_i, L_i + a_X(T_{max}^D - 1)) \\ 1 & \text{if } t \geq L_i + a_X(T_{max}^D - 1). \end{cases} \tag{5.65}$$

From (5.42), the probability of a non-preferred relay timing out after slot t is:

$$p_{ia}^D(t) = \begin{cases} 1 & \text{if } t < L_i - 1 \\ 1 - \frac{t+1-L_i}{a_X(T_{max}^D-1)} & \text{if } t \in [L_i - 1, L_i + a_X(T_{max}^D - 1) - 1) \\ 0 & \text{if } t \geq L_i + a_X(T_{max}^D - 1) - 1. \end{cases} \tag{5.66}$$

Finally the probability of a non-preferred relay expiring during time-slot t is:

$$p_{it}^D(t) = \begin{cases} 0, & t < L_i - 1 \\ \frac{t+1-L_i}{a_X(T_{max}^D-1)}, & t \in [L_i - 1, L_i) \\ \frac{1}{a_X(T_{max}^D-1)}, & t \in [L_i, L_i + a_X(T_{max}^D - 1) - 1) \\ 1 - \frac{t-L_i}{a_X(T_{max}^D-1)}, & t \in [L_i + a_X(T_{max}^D - 1) - 1, L_i + a_X(T_{max}^D - 1)) \\ 0, & t \geq L_i + a_X(T_{max}^D - 1). \end{cases} \tag{5.67}$$

Corresponding changes must also be made to accommodate the special case of $a_X T_{max}^D \leq 1$; this is similar to the process applied in (5.44)-(5.46).

5.4.3 Retransmission Outcome Model

Let π_i be the probability that node N_i is preferred, where π_0 is the probability that no relay is preferred. There is a probability $\pi_i P_D(s,i)$ that preferred relay N_i receives the source frame and retransmits without contention. There is also a probability of $\pi_i(1 - P_D(s,i))$ that N_i fails to receive the source frame and only nodes other than N_i contend for retransmission. This contending set is defined as:

$$\mathcal{N}_{c\bar{i}} \triangleq \{\mathcal{N}_p \cap \{N_i\}\}'. \tag{5.68}$$

The probability of retransmission success is the summation:

$$\begin{aligned}\Pr\{pref\ \ success\} \triangleq\ & \pi_0 \Pr\{success\} \\ & + \sum_{N_i \in \mathcal{N}_p} \pi_i P_D(s,i) P_D(i,d) P_A(d,s) \\ & + \sum_{N_i \in \mathcal{N}_p} \pi_i (1 - P_D(s,i)) \Pr\{success \mid \mathcal{N}_{c\bar{i}}\}.\end{aligned} \tag{5.69}$$

The probability of data frame failures with preferred relays is:

$$\begin{aligned}\Pr\{pref\ \ D\ fail\} \triangleq\ & \pi_0 \Pr\{D\ fail\} \\ & + \sum_{N_i \in \mathcal{N}_p} \pi_i P_D(s,i)(1 - P_D(i,d)) \\ & + \sum_{N_i \in \mathcal{N}_p} \pi_i (1 - P_D(s,i)) \Pr\{D\ fail \mid \mathcal{N}_{c\bar{i}}\}.\end{aligned} \tag{5.70}$$

The probability of ACK frame failures with preferred relays is:

$$\begin{aligned}\Pr\{pref\ \ A\ fail\} \triangleq\ & \pi_0 \Pr\{A\ fail\} \\ & + \sum_{N_i \in \mathcal{N}_p} \pi_i P_D(s,i) P_D(i,d)(1 - P_A(d,s)) \\ & + \sum_{N_i \in \mathcal{N}_p} \pi_i (1 - P_D(s,i)) \Pr\{A\ fail \mid \mathcal{N}_{c\bar{i}}\}.\end{aligned} \tag{5.71}$$

The probability for a contention collision is only non-zero for non-preferred retransmissions, that is:

$$\Pr\{pref\ \ coll\} \triangleq \pi_0 \Pr\{coll\} + \sum_{N_i \in \mathcal{N}_p} \pi_i (1 - P_D(s,i)) \Pr\{coll \mid \mathcal{N}_{c\bar{i}}\}. \tag{5.72}$$

Finally, the probability of retransmission failure because no relay has received the source frame remains the same as (5.12).

5.4.4 Preferred Relay as a Markov Process

The preferred relay process is a state machine, where one state corresponds to a network with no preferred relay and $|\mathcal{N}_p|$ states represent the situation when each node has assumed the role of preferred relay. The state transition probabilities are a function of the

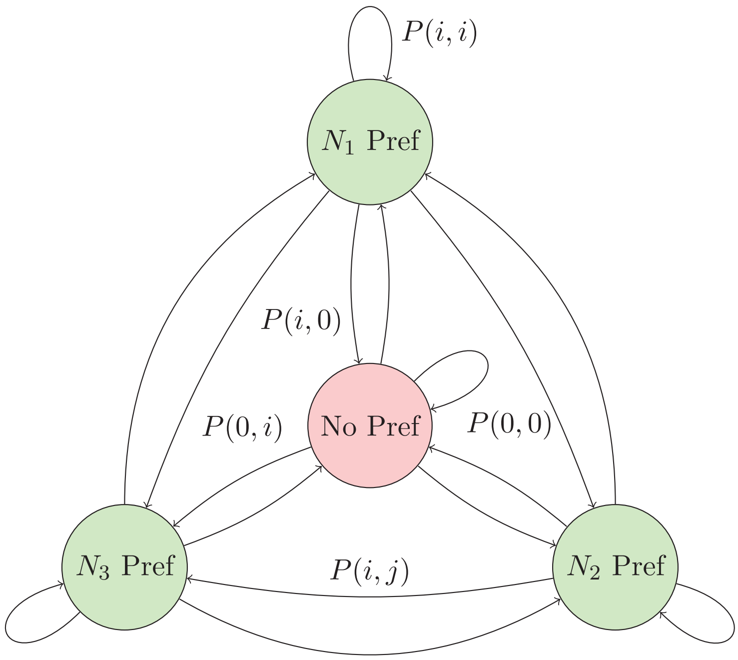

Figure 5.6: State diagram and transitional probability notation for a three node system

link quality parameters and are assumed to be constant for the duration of a retransmission attempt. The state machine is a Markov process because it is memoryless and time-homogeneous. The state probability is calculated by solving the Markov process.

An example preferred relay state machine is shown in Figure 5.6 for a system with three participating nodes. There are five unique preferred relay state transitions: stay with preferred relay i, switch from no preferred relay to some preferred relay i, change preferred relay from i to j, switch from preferred relay i to no preferred relay, or stay with no preferred relay. The probabilities of each transition are denoted as $P(i,i)$, $P(0,i)$, $P(i,j)$, $P(i,0)$, and $P(0,0)$ respectively. These transition probabilities are derived in the following subsections.

5.4.5 Preferred Relay State Transition Probability

A flow chart illustrating the operation of retransmission using the preferred relay scheme is shown in Figure 5.7. The preferred status is gained or maintained with successful data frame retransmission; the ACK frame does not need to succeed in order for the relay to

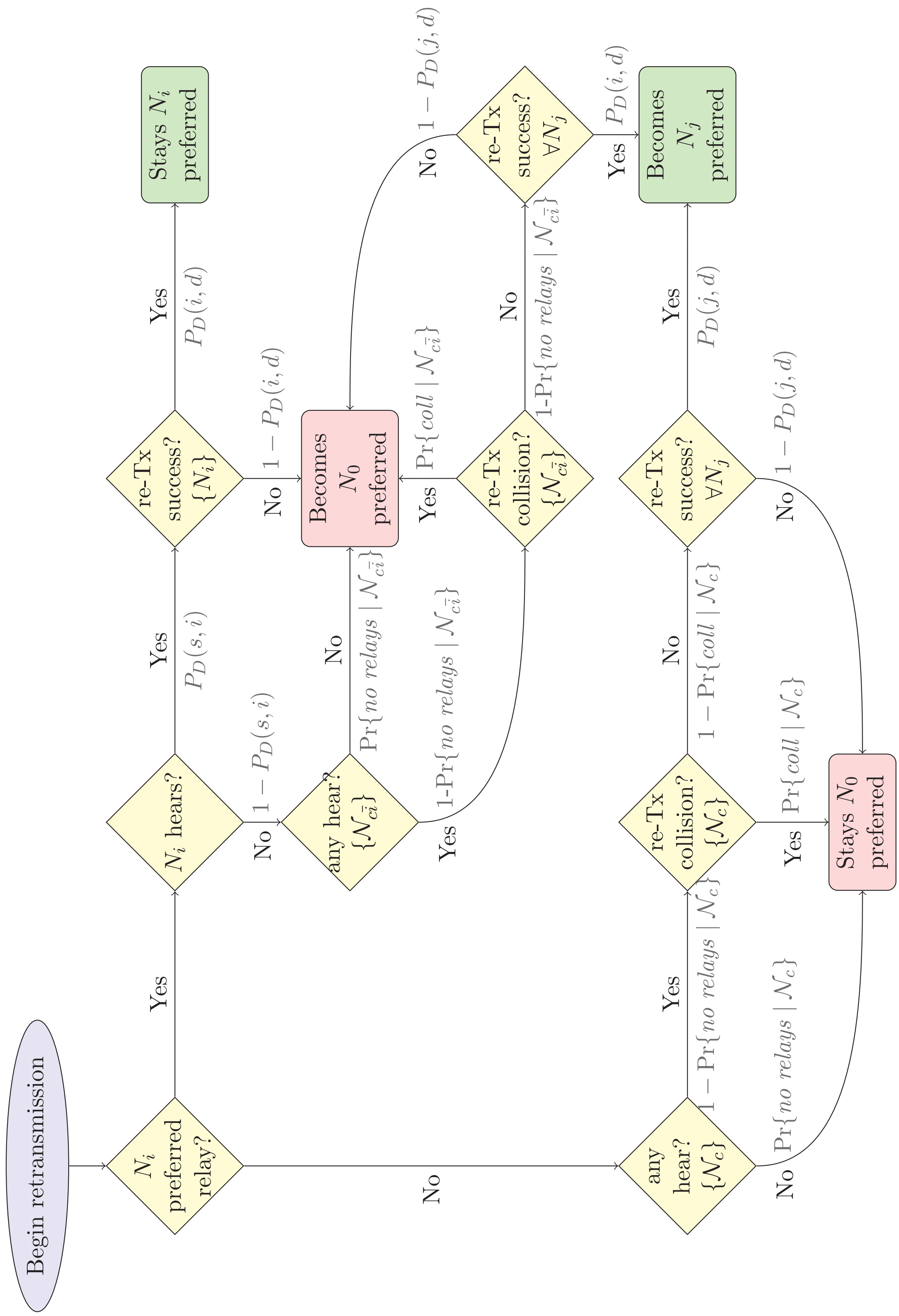

Figure 5.7: Retransmission process with a potential preferred relay

be useful. The state change from a to b during a retransmission attempt is denoted as $P^c_\pi(a,b)$.

A preferred relay may lose its status by missing any frame on the preferred link, even when the destination successfully receives the frame. This must be accounted for in order to ensure the analytic model accurately reflects actual algorithm behaviour.

The state change from a to b during a non-cooperative frame is denoted as $P^n_\pi(a,b)$. The total state transition probability is the weighted sum of the probabilities:

$$P_\pi(a,b) = (1 - P_D(s,d))P^c_\pi(a,b) + P_D(s,d)P^n_\pi(a,b) \tag{5.73}$$

Transition Probability $P^c_\pi(i,i)$

The preferred node N_i must receive the source frame and successfully retransmit it to the destination to maintain its preferred status. The probability of this is:

$$P^c_\pi(i,i) = P_D(s,i)P_D(i,d) \tag{5.74}$$

Node N_i must receive the frame to maintain preferred status:

$$P^n_\pi(i,i) = P_D(s,i) \tag{5.75}$$

Hence, the total probability of N_i keeping preferred status is:

$$P_\pi(i,i) = (1 - P_D(s,d))P_D(s,i)P_D(i,d) + P_D(s,d)P_D(s,i) \tag{5.76}$$

Transition Probability $P^c_\pi(0,i)$

By definition, N_i must receive the source frame to become preferred. Node N_i must then win contention ahead of any other node and successfully retransmit the data frame to the destination. Let $\mathcal{N}_{c\bar{i}}$ be the set of contending relays excluding N_i, and $\mathcal{S}_{c\bar{i}}$ be the set of all possible contending relays excluding N_i. Therefore:

$$P^c_\pi(0,i) = P_D(s,i)P_D(i,d) \sum_{\mathcal{N}_{c\bar{i}} \in \mathcal{S}_{c\bar{i}}} \sum_{t=0}^{T_{max}-1} W_i(\mathcal{N}_c, t)\Pr\{\mathcal{N}_{c\bar{i}}\} \tag{5.77}$$

A node cannot gain preferred status without retransmitting the frame, therefore:

$$P_\pi^n(0,i) = 0 \tag{5.78}$$

The total probability is:

$$P_\pi(0,i) = (1 - P_D(s,d))P_D(s,i)P_D(i,d) \sum_{\mathcal{N}_{c\bar{i}} \in \mathcal{S}_{c\bar{i}}} \sum_{t=0}^{T_{max}-1} W_i(\mathcal{N}_c, t)\Pr\{\mathcal{N}_{c\bar{i}}\} \tag{5.79}$$

Transition Probability $P_\pi^c(i,j)$

For the relay preference to transfer to another node, the original preferred relay must fail to receive a frame at the same time as another node successfully receives it, contends with other nodes, and retransmits to the destination. Assume N_i is the preferred relay at the beginning of the transmission and N_j becomes the new preferred relay. Let $\mathcal{N}_{c\bar{i}\bar{j}}$ denote the set of contending nodes but excluding N_i and N_j. Let set $\mathcal{S}_{c\bar{i}\bar{j}}$ denote all possible combinations of contending nodes other than N_i and N_j. The probability of transferring preference from N_i to N_j is:

$$P_\pi^c(i,j) = P_D(s,j)(1 - P_D(s,i))P_D(j,d) \sum_{\mathcal{N}_{c\bar{i}\bar{j}} \in \mathcal{S}_{c\bar{i}\bar{j}}} \sum_{t=0}^{T_{max}-1} W_j(\mathcal{N}_{c\bar{i}}, t)\Pr\{\mathcal{N}_{c\bar{i}\bar{j}}\} \tag{5.80}$$

Preferred status cannot transfer from one node to another without retransmission, so:

$$P_\pi^n(i,j) = 0 \tag{5.81}$$

The total probability is:

$$\begin{aligned} P_\pi(i,j) = (1 - P_D(s,d))P_D(s,j)(1 - P_D(s,i))P_D(j,d) \\ \times \sum_{\mathcal{N}_{c\bar{i}\bar{j}} \in \mathcal{S}_{c\bar{i}\bar{j}}} \sum_{t=0}^{T_{max}-1} W_j(\mathcal{N}_{c\bar{i}}, t)\Pr\{\mathcal{N}_{c\bar{i}\bar{j}}\} \end{aligned} \tag{5.82}$$

Transition Probability $P_\pi^c(i,0)$

There are four possibilities for a retransmission sequence to begin with a preferred relay and result in no preferred relay. These are: the preferred relay fails to retransmit the data frame successfully, no relay receives the source frame, and, the preferred relay does not receive the source frame and the remaining contending nodes collide or fail to retransmit successfully. The total probability is given by:

$$\begin{aligned} P^c_\pi(i,0) &= P_D(s,i)(1-P_D(s,i)) \\ &\quad + \Pr\{no\ relays\} \\ &\quad + (1-P_D(s,i))P_D(s,j)(1-P_D(j,d)) \sum_{\mathcal{N}_{c\bar{i}\bar{j}} \in \mathcal{S}_{c\bar{i}\bar{j}}} \sum_{t=0}^{T_{max}-1} W_j(\mathcal{N}_{c\bar{i}}, t)\Pr\{\mathcal{N}_{c\bar{i}\bar{j}}\} \\ &\quad + (1-P_D(s,i))\Pr\{coll \mid \mathcal{N}_{c\bar{i}}\} \end{aligned} \tag{5.83}$$

This is more easily solved using the property that the total probability flux out of any state is 1, therefore:

$$P^c_\pi(i,0) = 1 - P^c_\pi(i,i) - \sum_{N_j \in \mathcal{N}_{c\bar{i}}} P^c_\pi(i,j) \tag{5.84}$$

There is a finite probability that a node will lose preferred status after a direct transmission if the preferred node does not receive the frame:

$$P^n_\pi(i,0) = (1 - P_D(s,i)) \tag{5.85}$$

The total transition probability is therefore:

$$\begin{aligned} P_\pi(i,0) = (1-P_D(s,d)) &\left(1 - P^c_\pi(i,i) - \sum_{N_j \in \mathcal{N}_{c\bar{i}}} P^c_\pi(i,j)\right) \\ &+ P_D(s,d)(1-P_D(s,i)) \end{aligned} \tag{5.86}$$

Transition Probability $P^c_\pi(0,0)$

The system stays with no preferred relay after a transmission attempt if no relays receive the source frame, if there is a collision, or if there is a data failure after contention. The probability is:

$$P^c_\pi(0,0) = \Pr\{no\ relays\} + \Pr\{D\ fail\} + \Pr\{coll\} \tag{5.87}$$

This is more easily solved as:

$$P_\pi^c(0,0) = 1 - \sum_{N_i \in \mathcal{N}_c} P(0,i) \tag{5.88}$$

This value is not required to solve the Markov process.

5.4.6 Creating and Solving the Markov Model

The state transition probabilities are used to create the infinitesimal generator matrix, $\mathbf{Q}$, to solve the Markov process [95]. For the example network with three potential relays:

$$\mathbf{Q} = \begin{pmatrix} -\sum_{i=0,i\neq 0}^{3} P_\pi(0,i) & P_\pi(0,1) & P_\pi(0,2) & P_\pi(0,3) \\ P_\pi(1,0) & -\sum_{i=0,i\neq 1}^{3} P_\pi(1,i) & P_\pi(1,2) & P_\pi(1,3) \\ P_\pi(2,0) & P_\pi(2,1) & -\sum_{i=0,i\neq 2}^{3} P_\pi(2,i) & P_\pi(2,3) \\ P_\pi(3,0) & P_\pi(3,1) & P_\pi(3,2) & -\sum_{i=0,i\neq 2}^{3} P_\pi(3,i) \end{pmatrix} \tag{5.89}$$

At present, there is insufficient information to determine a unique solution. However, we know that the sum of all probabilities must be 1:

$$\sum_i \pi_i = 1 \tag{5.90}$$

Therefore, this can be placed in the the lower row of the transposed matrix. Now:

$$\mathbf{Q}_n^T = \begin{pmatrix} -\sum_{i=0,i\neq 0}^{3} P_\pi(0,i) & P_\pi(1,0) & P_\pi(2,0) & P_\pi(3,0) \\ P_\pi(0,1) & -\sum_{i=0,i\neq 1}^{3} P_\pi(1,i) & P_\pi(2,1) & P_\pi(3,1) \\ P_\pi(0,2) & P_\pi(1,2) & -\sum_{i=0,i\neq 2}^{3} P_\pi(2,i) & P_\pi(3,2) \\ 1 & 1 & 1 & 1 \end{pmatrix} \tag{5.91}$$

which has the unique solution vector of:

$$\mathbf{e}_n = \begin{pmatrix} 0 & 0 & 0 & 1 \end{pmatrix}'. \tag{5.92}$$

Therefore, solving the linear equation:

$$\mathbf{Q}_n^T \boldsymbol{\pi} = \mathbf{e}_n \tag{5.93}$$

for the $\boldsymbol{\pi}$ vector computes the proportion of the time spent in each state, hence the probability that any given node is preferred. The values for π_i are then substituted into into equations (5.69)-(5.72) to calculate the retransmission outcome probability for DAFMAC with preferred relays.

In practice, the Markov chain is most easily numerically solved using tools like MATLAB [79] or SciPy [86]. The solution complexity increases with the size of the contending set, however, the solution time for a practical network size is several orders of magnitude shorter than a full QualNet simulation.

5.5 Model Validation

This section validates the analytic cooperative retransmission model through QualNet simulations and Monte Carlo analysis. An example scenario is described and is used to demonstrate that the analytic model accurately reproduces an integrated PHY/MAC layer QualNet simulation [85]. The same scenario is then evaluated using a Monte Carlo simulation, which is shown to converge to the results predicted by the analytic model.

5.5.1 Link Quality Relationship

The analytic retransmission model is specifically designed to be independent of the propagation or physical layer model. For model verification, the required RSS-PDR relationship is obtained from a QualNet simulation.

The simulated hardware parameters are based on the Senao IEEE 802.11b device [88]. Data frames contained a 1400 byte payload and are transmitted at 11 Mb/s. ACK frames are sent at the same transmission rate as data frames to illustrate the potential

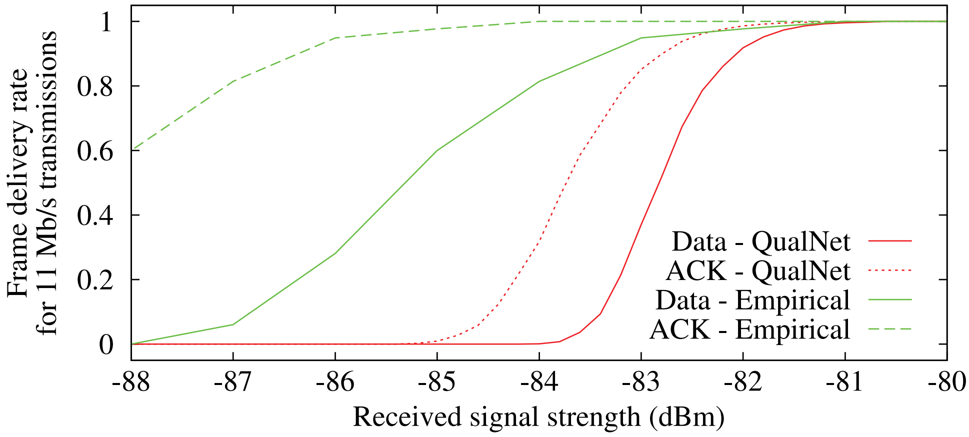

Figure 5.8: The RSS-PDR relationship obtained from QualNet for IEEE 802.11b.

influence of ACK failures. The simulation used 10^5 frame transmissions for each of 10^3 seeds. The transmission reliability of data and ACK frames are measured individually. The resulting RSS-PDR relationships are shown in Figure 5.8. It is noted that the results from the QualNet simulation are more compressed in comparison to the empirical results obtained by Judd and Steenkiste from a physical test-bed [59].

The empirical RSSI results only include values for frames which are successfully decoded (see Section 2.5.2). The ACK frame performance estimate in Figure 5.8 is assumed to be a 3 dBm offset from the data frame performance results.

5.5.2 Scenario Configuration

The scenario contains one source node, one destination node, and between one and five relay candidates placed as previously shown in Figure 5.1. This configuration is a pathological case for DAFMAC because relays 2, 3 and 5 have identical RSS values, which will deliberately induce retransmission collisions. As such, this scenario should not be taken as a reflection of algorithm performance; rather it shows how the analytic retransmission model successfully predicts collision probabilities. The RSS and PDR values for all links are given in Table 5.1.

Table 5.1: Scenario link RSS and transmission PDR values

Node	$RSS_{s,i}$ (dBm)	$P_D(s,i)$	$RSS_{i,d}$ (dBm)	$P_D(i,d)$
N_s	0	1.0	-83	0.5
N_1	-72	1.0	-82	0.79
N_2	-83	0.40	-78	1.0
N_3	-83	0.40	-78	1.0
N_4	-71	1.0	-81	0.99
N_5	-73	1.0	-78	1.0

5.5.3 QualNet Simulation Comparison

The QualNet simulation used between one and five relays to illustrate the changing behaviour as more relays are added to the retransmission process. This increases the probability that a relay is able to retransmit, while also increasing the probability of collisions. Relays are always added to the system sequentially, so the set of three participating relays is $\mathcal{N}_3 = \{N_1, N_2, N_3\}$. Each relay set configuration is simulated using 10^3 random seeds to provide a statistically meaningful result.

The analytic retransmission model produces results nearly identical to the QualNet simulation, as shown in Figure 5.9. The median QualNet result is presented as a histogram. The confidence intervals (which are so tight as to be barely visible in most cases) represent the central 90% and are typically limited to within of 1% of the median. The diamond shaped point represents the corresponding analytically-generated result and is consistently inside the 90% confidence interval of the QualNet simulation.

5.5.4 Preferred State Convergence

A Monte Carlo simulation is configured with four nodes as per Figure 5.1; the fifth node is omitted to facilitate transitions between node preference. Between 10^4 and 10^{10} sample frames are retransmitted in the Monte Carlo simulation, and the variation between the preferred node state probability π_i in the analytic model and the simulation is shown in Figure 5.10.

The Monte Carlo simulation converges to the analytic result, validating the Markov model and its solution presented in Section 5.4.

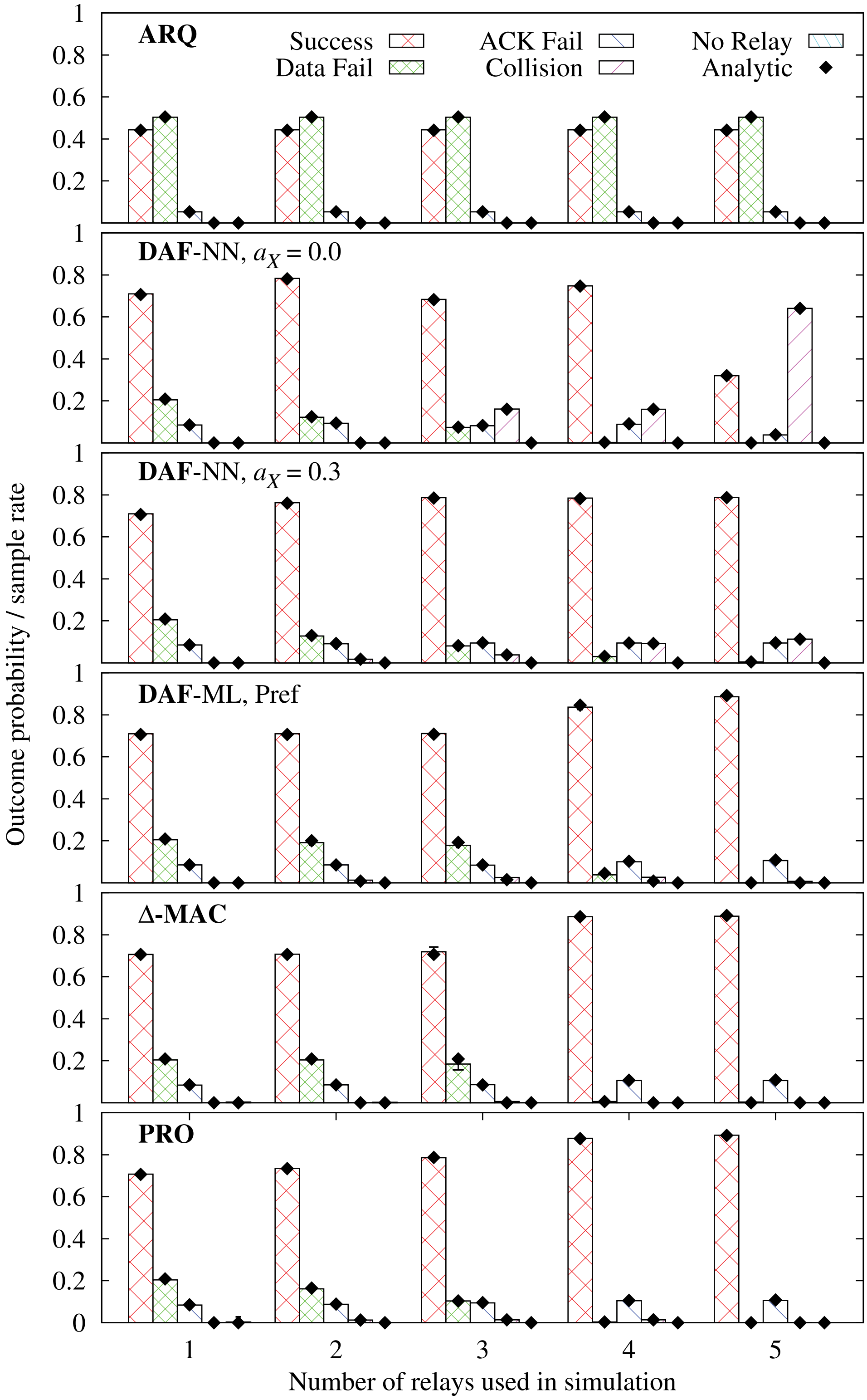

Figure 5.9: The analytic model predicts nearly identical retransmission probabilities as observed in an equivalent QualNet simulation using 1 to 5 neighbours - the 90% confidence intervals are barely visible due to the narrow spread of the results

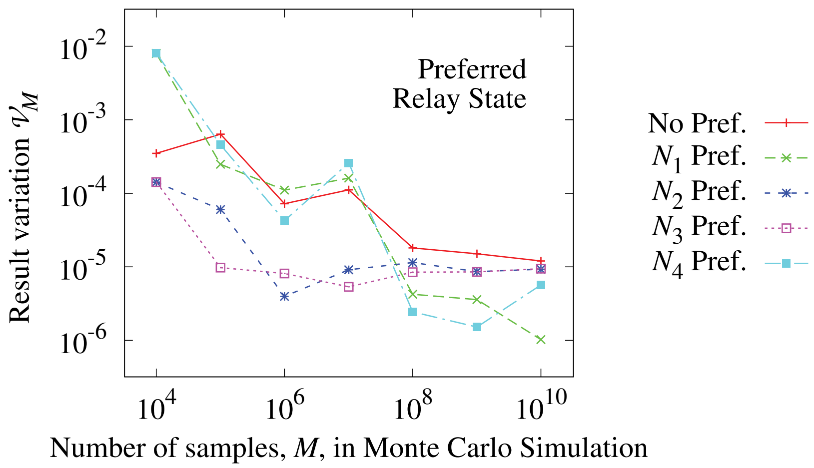

Figure 5.10: The variation in preferred state probability between the analytic model and Monte Carlo simulation reduces as $M \to \infty$.

The preferred state value converges more slowly than expected. This is caused by the relatively infrequent state changes despite the large number of frames being retransmitted. That is, the probability that no relay is preferred is approximately 1.2%, meaning only 1.2% of the retransmissions require a decision to select a relay. The Monte Carlo simulation converges to the analytic result, but is approximately two orders of magnitude behind the expected convergence rate, which is consistent with the reduction in the frequency at which a relay is selected using the preferred relay scheme.

5.5.5 Monte Carlo Simulation Convergence

This section shows that the Monte Carlo simulation converges to the predictions of the retransmission model.

The Monte Carlo simulation used the aforementioned network configuration and node parameters with all five possible relays. Frame transmission success is determined using a random variable $X \sim \mathrm{U}[0,1)$, where a transmission is successful if $X < P(a,b)$ and a failure otherwise. The full Monte Carlo algorithm is shown in Algorithm 5.1.

The simulation used $M \in [10^4, 10^{10}]$ samples to calculate the retransmission success rate. The variation between the analytic and simulation result for M samples is:

$$\varepsilon_M(k) = \left| \Pr\{outcome\, k\} - \tfrac{1}{M} \sum_{m=1}^{M} x_k \right| \tag{5.94}$$

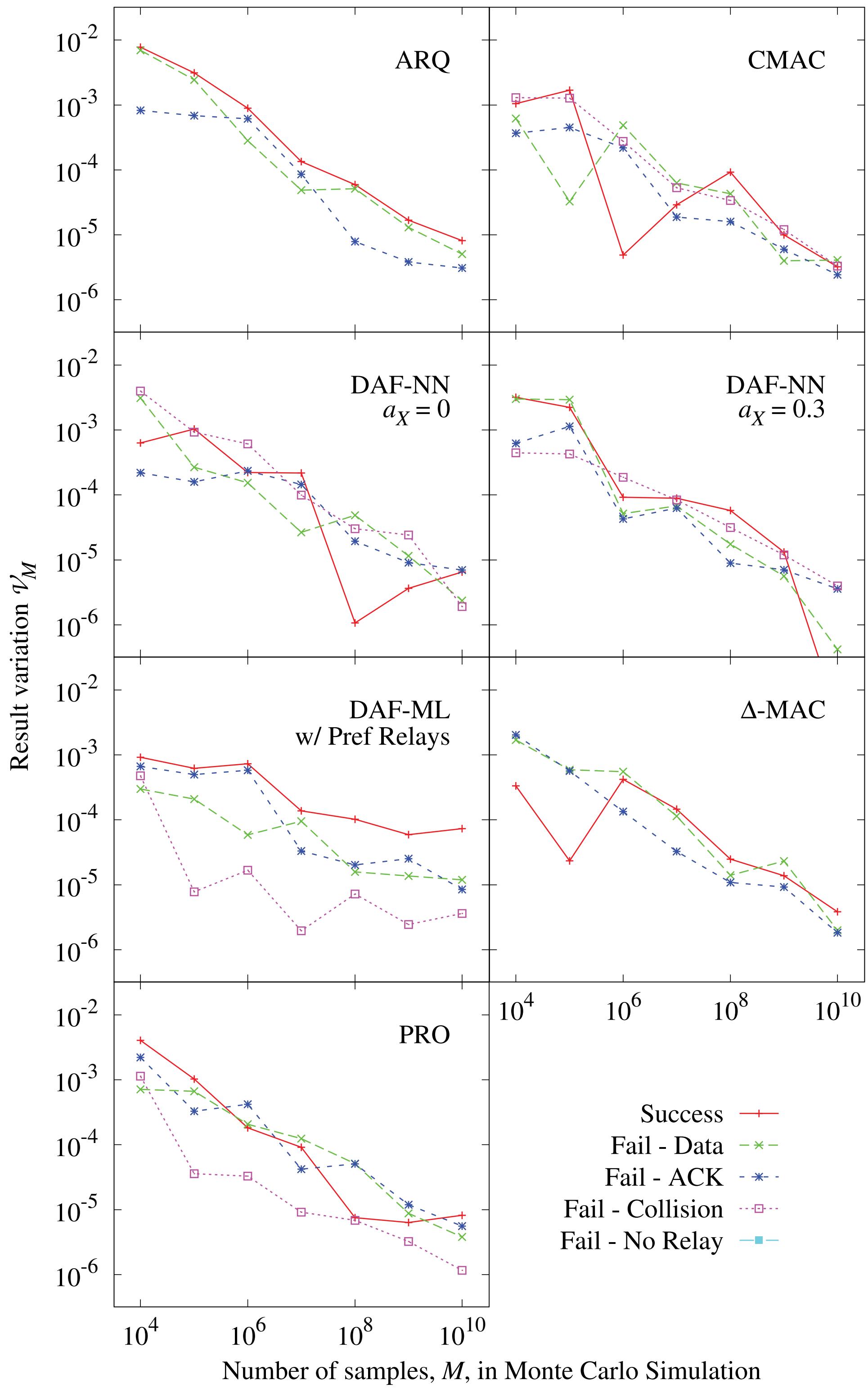

Figure 5.11: The Monte Carlo simulation converges to the analytic result as the sample size increases.

Algorithm 5.1: Simulation of the cooperative retransmission

```
Input: Neighbour relay set $\mathcal{N}_n$
Input: Relay RSS values to both source $RSS(i, s)$ and destination $RSS(i, d)$
Input: Relay PDR values to both source $P_D(i, s)$ and destination $P_D(i, d)$
Input: Destination to source ACK success probability $P_A(d, s)$
Output: The sample rate of contention outcomes
Determine participating set $\mathcal{N}_p$
$t_{min} \leftarrow T_{max}$
for $m$ in sample size $M$ do
    /* Identify which nodes receive the source frame, calculate their
       contention delay                                              */
    $num_{best} \leftarrow 0$
    for node $N_i$ in set $\mathcal{N}_p$ do
        $t_i \leftarrow T_{max}$
        if $X < P_D(i, s)$ then
            Calculate $t_i$
            if $t_i < t_{min}$ then
                $t_{min} \leftarrow t_i$
                $num_{best} \leftarrow 1$
                $r \leftarrow i$
            if $t_i == t_{min}$ then
                $num_{best} \leftarrow num_{best} + 1$
    /* Identify the outcome of the retransmission attempt, increment
       the counter                                                   */
    if $t_{min} == T_{max}$ then
        $x_{none} \leftarrow x_{none} + 1$
    else
        if $num_{best} > 1$ then
            $x_{coll} \leftarrow x_{coll} + 1$
        else
            if $X < P_D(r, d)$ then
                if $X < P_A(d, s)$ then
                    $x_{success} \leftarrow x_{success} + 1$
                else
                    $x_{A\,fail} \leftarrow x_{A\,fail} + 1$
            else
                $x_{D\,fail} \leftarrow x_{D\,fail} + 1$
```

where $x_k = 1$ if the retransmission outcome is k and $x_k = 0$ otherwise. Figure 5.11 shows the simulation converges to the analytic result as $M \to \infty$ for each of the ARQ, CMAC, DAFMAC, Δ-MAC, and PRO models.

5.6 Re-examination of DAFMAC Collisions with Random Component Weighting

The collision model derived in Section 4.3 is an approximation for the collision probability. This section re-examines the relay performance with different random weightings by adjusting the value of a_X in a representative scenario using the analytic retransmission model.

5.6.1 Re-creation of Previous Analytic Model Results

The scenario consists of source and destination nodes are placed 130 m apart in the centre of a 250 m $\times$ 250 m area, as shown in Figure 5.12. Using the aforementioned device parameters, the direct transmission probability is $P_D(s, d) \approx 0.5$. Fifteen neighbour nodes are randomly placed in the area and the retransmission outcome probability is calculated for 10^4 random node placements for a range of values of a_X.

The collision probability using a value of a_X is between 0 and 0.3 is shown in Figure 5.13. The collision rate exhibits the same general trend as the previous result shown in Figure 4.5, however, the increase in collision rate previously predicted occurs more slowly using the analytic retransmission model. The new model suggests that the optimal random component weighting is in the range $a_X \in [0.15, 0.25]$ where $s_{max} \in [20, 50]$.

5.6.2 Detailed Retransmission Outcome

The purpose of the model derived in Section 4.3 is to identify the value for a_X which minimises the collision rate. However, the actual objective is to maximise the retransmission success.

The previous scenario uses 15 neighbour nodes, as this is the value used in Section 4.3. This is a higher node density than other scenarios presented elsewhere in this chapter. Additionally, the contention window size is nominally set to 32 time slots to be consistent

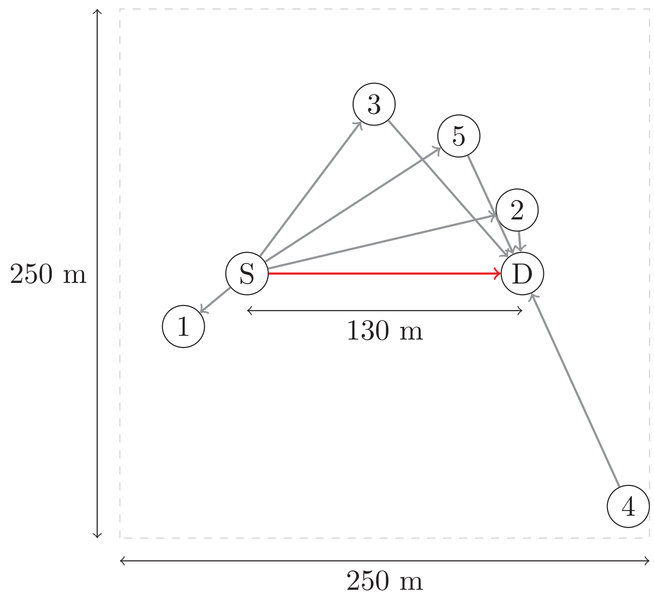

Figure 5.12: Example scenario with fixed source and destination nodes with five randomly placed neighbours

with 802.11 ARQ and PRO. Therefore, the following scenario uses the prior configuration but modifies the s_{max} to be 32, and uses five neighbour nodes. The analysis is conduct with and without preferred relays.

Again, collision probability has a minimum value for the range $a_X \in [0.15, 0.25]$, as shown in Figure 5.14. Enabling preferred relays results in a continual decrease in collision probability as the random delay component increases. However, the data failure error rate consistently increases with the random delay component. This is caused by relays winning contention although they have a larger path loss to the destination; the larger the random component, the greater the probability that a relay with insufficient link quality wins contention and transmits first. Therefore, the random delay weighting should be limited to $a_X \approx 0.1$ for this scenario.

5.7 *Analytic Comparison of Example Retransmission Protocols*

This section presents a brief analytic comparison between the ARQ, CMAC, DAFMAC, Δ-MAC, and PRO retransmission algorithms in a more general scenario, obtained using the analytic model.

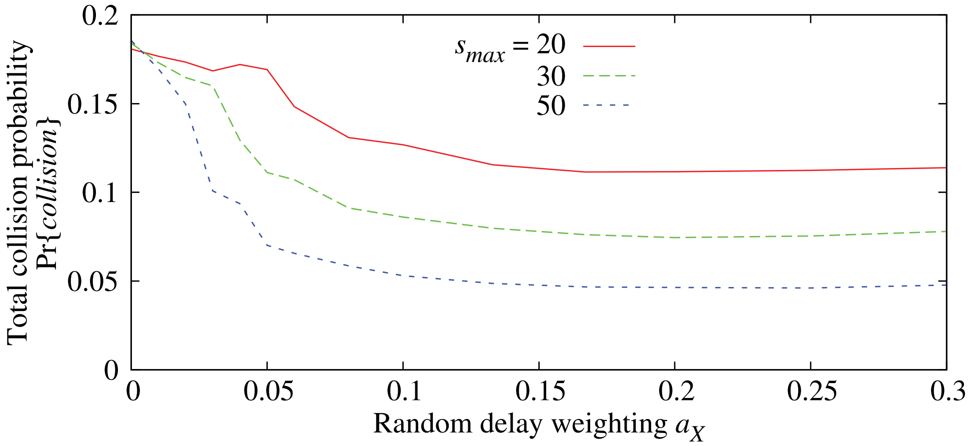

Figure 5.13: The collision probability with the analytic model exhibits a similar general trend to the simple derivation shown in Figure 4.5, although the comprehensive model shows that the collision rate increases more slowly for larger values of a_X

5.7.1 Configuration

The scenario is a similar configuration to that previously described in Section 5.6. However, the ARQ, CMAC, DAFMAC, Δ-MAC, and PRO protocols are evaluated for between one and five randomly placed relays, using 10^4 randomly placed node sets at each density.

Each protocol used a contention window of 32 time slots. DAFMAC assumes that $F_{min} = -85$ dBm for the QualNet decoder model and $F_{min} = -88$ dBm for Judd and Steenkiste's empirical model. DAFMAC also assumes $F_{max} = F_{min} + 16$ and uses the *nearest neighbour* relay ranking scheme. PRO uses a cooperative threshold of 0.95 to select the contending relay set.

5.7.2 QualNet Receiver Model

The experiment used log-normal fading to generate the path loss between nodes. The parameters are: $RSS_0 = -82.83$ dBm, $n = 2.6$, $d_0 = 130$ m.

The mean retransmission outcome probability from the random placements is shown in Figure 5.15. Retransmission failures due to the source not decoding the ACK frame are independent of the cooperative protocol and are omitted from the figure.

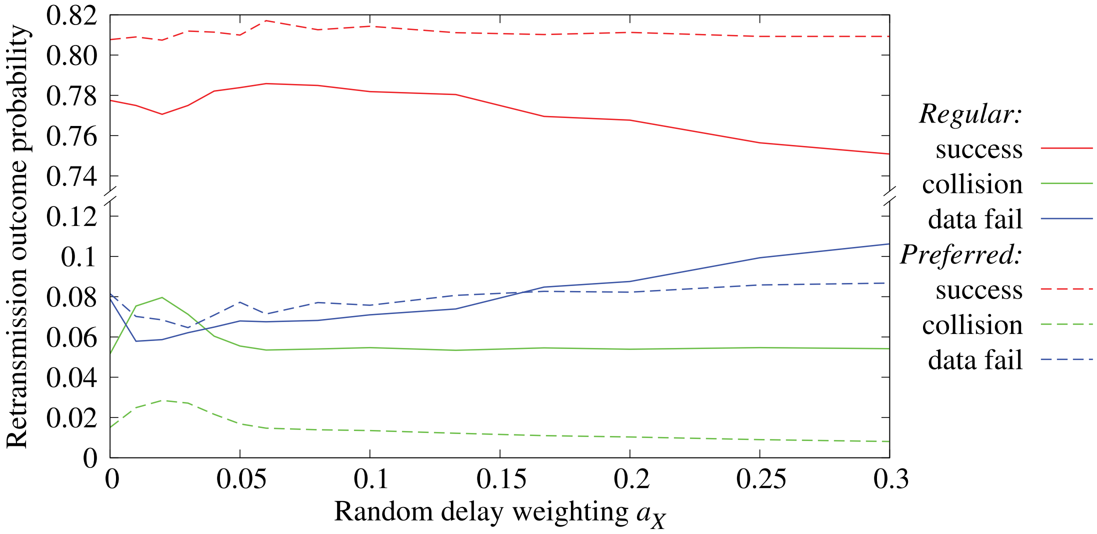

Figure 5.14: While using a larger value for a_X reduces the collision rate, it increases the data failure rate, therefore the optimal value for success remains as $a_X \approx 0.1$

The DAFMAC selection algorithm has a high probability of successfully forwarding frames and generally outperforms PRO, which is in agreement with the simulation results obtained in Section 4.5. The DAFMAC collision rate using different algorithm parameters gives an interesting and unexpected result; the collision rate with a zero random component is lower than that with a non-zero random component. However, as the node density increases, the non-zero random component is shown to achieve a lower collision rate which justifies the previous design decisions.

PRO has a significant probability of being unable to retransmit because there no valid relay is available. In this case, performance is simply a function of the specific locations of the randomly placed relays. DAFMAC, ARQ, CMAC, and Δ-MAC are not subject to this failure mode because the source node itself functions as a potential relay candidate in these respective algorithms.

Δ-MAC effectively represents the ideal single-relay cooperative scheme and has the highest probability of successfully opportunistically forwarding the data frame. However, this retransmission probability model does not include the overhead required to negotiate the cooperative relay, which is quite significant as discussed in Chapter 3.

Finally, the low retransmission success probability of CMAC clearly illustrates the advantage of selecting relays based on the link quality. While CMAC has a comparable collision

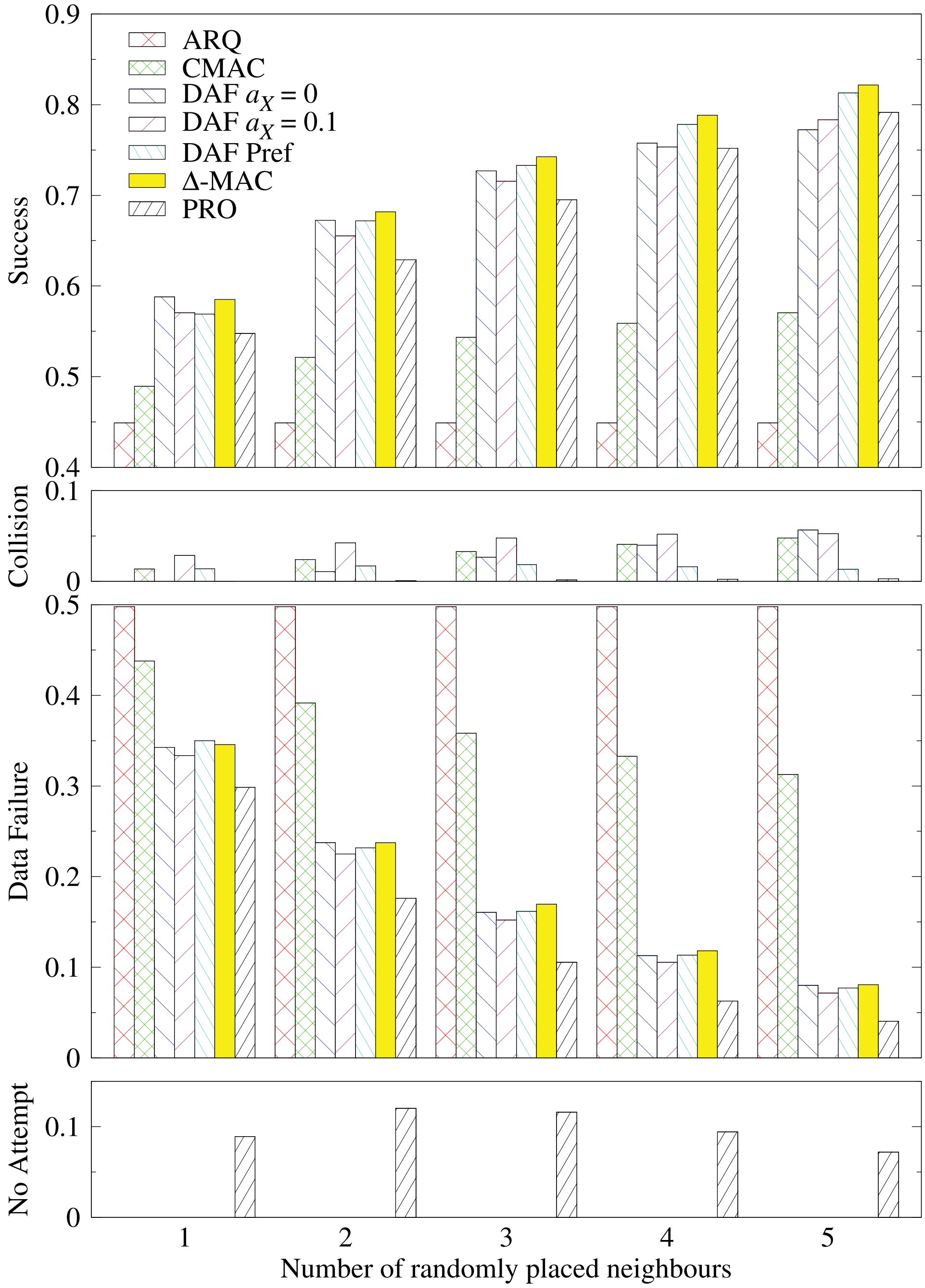

Figure 5.15: The retransmission outcome probabilities using a random neighbour layout and the QualNet receiver probability model

rate to DAFMAC, a randomly selected relay (without regard to the relay-destination link quality) produces a significantly higher rate of retransmission data frame decoding errors than DAFMAC produces. CMAC does provide a cooperative diversity gain over ARQ retransmissions, however, DAFMAC outperforms CMAC by more than 40% with five potential neighbours in the current scenario.

5.7.3 Judd and Steenkiste's Receiver Model

A key feature of the analytic retransmission model is it does not depend on specific path loss or receiver decoding models. The QualNet receiver model is useful for validating the retransmission performance, but it may not accurately reflect the decoding performance of a practical commodity wireless interface. Judd and Steenkiste empirically determined the probability that the receiver successfully decodes a frame for a given RSS value using an accurate and repeatable transmission emulation platform [59]. Their results exhibit a wider transition range than the QualNet model (as shown in Figure 5.8), which will affect the behaviour and performance of the relay selection algorithm.

The scenario is normalised such that the probability of decoding the frame with a node separation of 130 m is approximately 0.5. This is achieved with the log-normal path loss parameters of $RSS_0 = -85.3$ dBm, $n = 2.6$ and $d_0 = 130$ m. The empirical results only include the data frame decoding performance; it is assumed that the ACK frame decoding behaves similarly but with a 3 dB offset.

The mean retransmission outcome probability from the random placements is shown in Figure 5.16. Again, retransmission failures due to the source not decoding the ACK frame are independent of the cooperative protocol and are omitted from the figure.

It is observed that the empirical decoder model significantly impacts on relay selection algorithm performance. The DAFMAC collision rate is higher, particularly when no random component is used. This is because there is greater variability as to whether frames are correctly received or not, which results in a greater number of combinations of contending relay sets. However, the overall DAFMAC retransmission success rate is found to be higher when the empirical decoding model is used rather than that derived from QualNet. In particular, using five randomly placed neighbour nodes, the DAFMAC

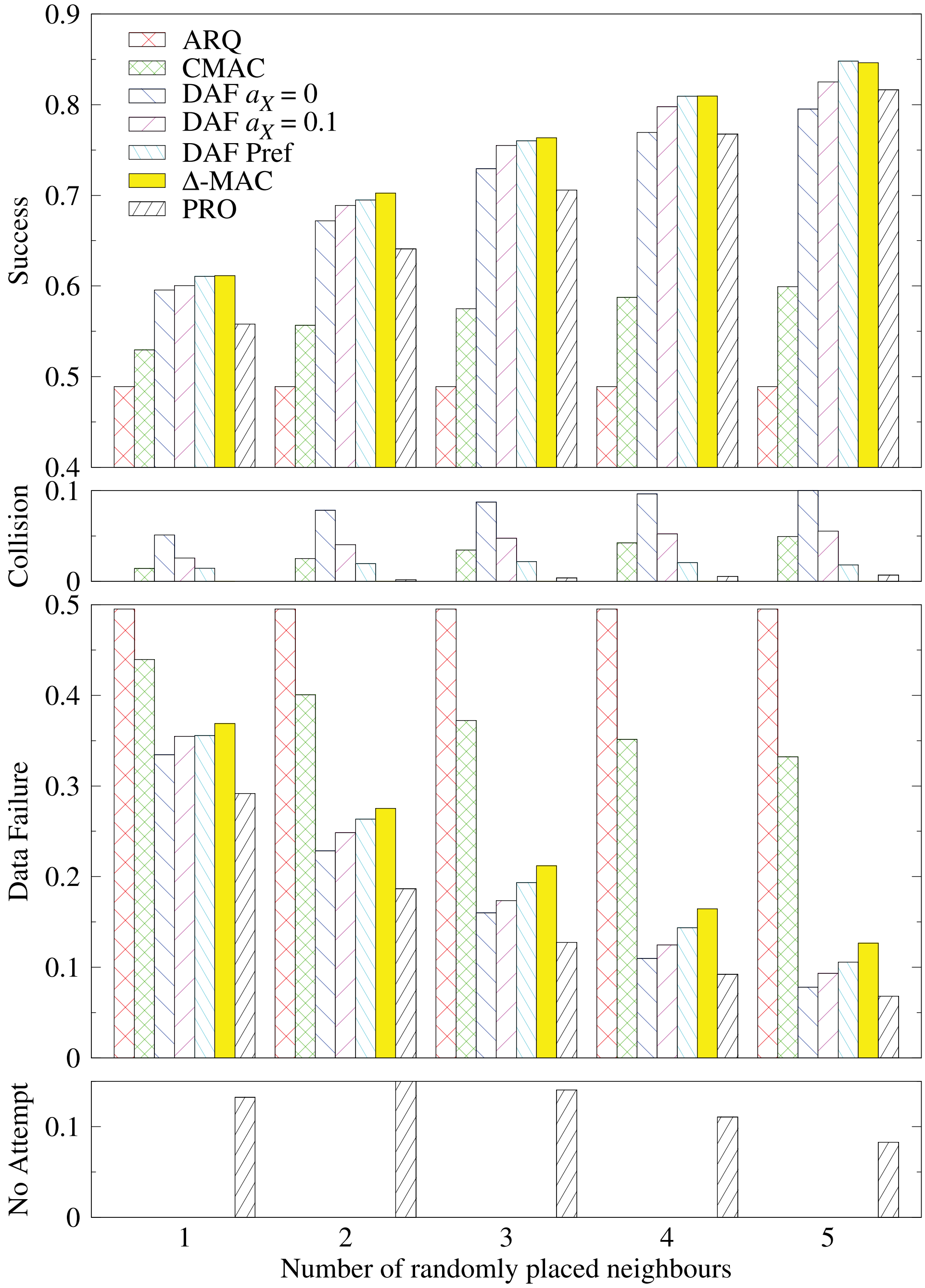

Figure 5.16: The retransmission outcome probabilities using a random neighbour layout and Judd and Steenkiste's empirically derived receiver probability model [59]

retransmission success probability is higher than Δ-MAC, which is effectively an ideal case using a single relay.

PRO's retransmission performance is relatively inferior compared to DAFMAC using the empirical receiver model. The PRO collision rate is higher because there is a greater uncertainty in the frame decoding, which results in more relays being included in the contending set and creating more opportunities for collisions. The PRO 'no retransmission attempt' rate is also higher because the greater variability in the decoding probability means there is a greater probability that no valid relay receives the source frame.

The Δ-MAC relay selection, although approaching the optimal single-relay result, is still subject to receiver limitations. In this case, retransmission performance is limited by the selected relay not successfully receiving and forwarding the frame. DAFMAC outperforms Δ-MAC because DAFMAC is able to leverage any available relay for retransmission, and results in a higher retransmission probability even considering retransmission collisions.

The empirical receiver model has no significant impact on the CMAC performance; DAFMAC outperforms CMAC by more than 40% with five potential neighbour nodes.

The key result of this section is that the relay selection algorithms are materially affected by the receiver decoding model. Therefore, the independence between this analytic retransmission model and the receiver (or path loss) model is a significant advantage when evaluating and comparing protocols in a range of scenarios.

5.7.4 Protocol Performance Discussion

It is important to recognise what the cooperative retransmission model is, and is not. The model evaluates the probability of each outcome for a single retransmission attempt. It makes many assumptions, including:

- transmission probabilities are independent;
- partial channel state information (RSSI and PDR) is accurate;
- no other flow attempts to access the channel during the cooperative retransmission attempt; and,

- all neighbour nodes are idle and available for cooperation.

Additionally, the retransmission model does not consider either the per-retransmission signalling overhead (RTS and CTS, plain or customised) or the periodic coordination overhead.

Therefore, ignoring the coordination overhead discussed in Section 3.3.4, Δ-MAC becomes the *ideal* single relay selection. That is, the Δ-MAC relay selection algorithm chooses the candidate node with the highest joint PDR to both source and destination, therefore has the highest probability of retransmission success. Additionally, if the relay does not receive the source frame, the source node will retransmit. In summary, the retransmission probability model shows the best attributes of Δ-MAC without showing the significant impact the overhead has on the maximum throughput capacity.

Similarly, the PRO retransmission model ignores both the relay selection coordination overhead, and the significant performance reduction when the contending relays are not idle (as shown in the reduced performance in Section 4.5). Therefore, the PRO model is somewhat idealised and indicates a better performance than a full simulation would produce.

Conversely, DAFMAC does require inter-relay coordination, so no assumptions are made which improve performance over reality. The model does assume accurate (quantised) RSSI values, however, a similar assumption is made for PRO. Furthermore, the random delay component in the DAFMAC relay selection algorithm is generally large enough to allow relays with a range of RSSI values to contend for retransmission. Therefore, the assumptions made by the analytic model do not increase the probability of retransmission success for DAFMAC as it does for PRO and Δ-MAC.

Despite the obvious advantages to PRO in the retransmission model, DAFMAC has a greater probability of retransmission success than PRO in all tested scenarios. The cause for this is the relatively high probability that no contending relay is suitably placed to retransmit. To be considered for contention, a PRO relay must have a higher RSS than the direct link, and the source node does not attempt retransmission if any other node is added to the contending set. Therefore, in this relatively low node density scenario, it is possible that a contending set with only one or two relays has a lower success rate than the direct ARQ retransmission. However, in the same network configuration, DAFMAC would still permit the source node to retransmit with a contention delay based on the value of the source-destination RSS. While the DAFMAC source retransmission has a failure rate of greater than 0.5, it still increases the success probability compared to not attempting retransmission at all.

More significantly, DAFMAC matches the Δ-MAC retransmission success rate when using Judd and Steenkiste's empirical receiver model. The Δ-MAC algorithm approximates the ideal single-relay selection because it uses the relay with the best joint-PDR to both source and destination nodes. That is, with a zero-coordination relay selection algorithm, DAFMAC is able to match the retransmission success performance of the ideal single-relay selection. When the coordination signalling and the per-transmission relay management is considered, the DAFMAC performance is far superior to Δ-MAC.

Therefore, the results of the analytic retransmission model show that DAFMAC provides a high probability of retransmission success without explicit relay coordination. In addition to DAFMAC offering the best total performance, as shown in Section 4.5, the relay selection algorithm is comparable to the ideal single relay selection.

5.8 Conclusion

This chapter has proposed a general retransmission performance model. The proposed model is suitable for evaluating any independent, distributed, slot-based contention algorithm for MAC-layer opportunistic retransmission. The slot time-out probabilities are derived for ARQ, CMAC, DAFMAC, Δ-MAC, and PRO retransmission schemes.

A Markov model is developed to represent the state machine used by DAFMAC with preferred relays enabled. The state probabilities for the Markov model are then numerically solved, using the link quality and decoding probability parameters, to determine the probability that each relay is operating as a preferred relay at any given time. The DAFMAC slot time-out probabilities are then re-calculated using the preferred relay probability and the total retransmission outcome probability is evaluated.

The analytic model is validated by a direct comparison to a QualNet simulation, which shows that the predicted outcome probabilities are typically within $\pm 1\%$ of the simulated result. The analytic result is also validated through Monte Carlo simulation, which is shown to converge to the analytic result as the sample size increases, when using the same receiver decoding probability model.

The key contribution of this model is that it enables a direct comparison of the retransmission attempt outcome probabilities between cooperative retransmission protocols, relay selection algorithms and specific parameter configurations, without the need for a comprehensive implementation in a state-based simulator such as QualNet or ns2. To demonstrate this capability, the retransmission performance of ARQ, CMAC, DAFMAC, Δ-MAC, and PRO are compared using this model with a random relay node placement.

A further powerful feature of the analytic retransmission model is its independence to the path loss and receiver decoding models. This is evaluated by implementing the empirically-derived receiver decoding model of Judd and Steenkiste. The results of applying the proposed analytic retransmission model demonstrate that cooperative protocol performance is dependent on the receiver model. In this case, the greater variability in received signal strength introduced by the empirical model decreases the retransmission efficacy of the Δ-MAC and PRO protocols, while relatively improving the performance of DAFMAC.

Finally, the analytic model shows that DAFMAC provides a high quality relay selection which is comparable to the ideal single-relay selection using Δ-MAC. This is raw retransmission probability, which is effectively *prior* to including the relay coordination signalling of PRO and Δ-MAC, and the assumptions made which favour the performance indicated by the model.

There are several interesting opportunities for further development of the cooperative retransmission model:

- At present, the model only considers static nodes; however, it can potentially be extended to mobile nodes. Assuming no channel fading, all that is required is a "history" of link quality for protocols which use historical values, such as the PDR used by PRO and Δ-MAC, and the current node positions. This will provide an accurate estimate for a retransmission attempt in the current configuration, which can be extended for a series of node location sets to identify the distribution of the retransmission probabilities.

- The model may also be extended to incorporate fading channels. This can potentially be realised using a new receiver model which includes the effect of fading on path loss, and hence on the corresponding probability of decoding the frame. This requires a fundamentally different approach to the ACK path; it would no longer be independent of the forward path. That is, the reverse channel is approximately reciprocal to the forward channel, therefore while the forward channel exhibits a large frame-to-frame variation in the probability of successful frame delivery due to instantaneous channel fading, the reverse channel will be strongly correlated to the given forward path. The retransmission outcome result will become a distribution of results based on the instantaneous channel fading.

- The model currently assumes all devices are homogeneous, but it may be extended to include heterogeneous devices. This is a straightforward modification to include both device-to-device variations transmission power and receiver sensitivity. This is a logical continuation of the work already performed with Judd and Steenkiste's empirical receiver model, extended to include heterogeneous transmission power. The outcome may be expressed as a distribution of results using a series of random and independent device configurations.

Chapter 6

OPPORTUNISTIC RETRANSMISSIONS IN MULTI-HOP NETWORKS

6.1 Introduction

MAC protocols in isolation normally only provide single-hop communications - even in cooperative systems, where a single hop may be assisted by intermediate nodes. In practice, large-scale multi-node networks require some form of layer 3 routing protocol to forward multi-hop traffic flows through the network. It is therefore necessary to demonstrate the value of cooperative MAC protocols and DAFMAC in particular when used in conjunction with ad hoc / mesh routing protocols.

With constantly varying channel conditions resulting from node and/or interferer mobility, a routing protocol must constantly maintain or repair routes to maximise packet delivery rates. This process necessitates the use of control signalling, which consumes a portion of network capacity. Since cooperative retransmission schemes increase the reliability of each hop, it is hypothesised that dynamic routing protocols will enjoy improved stability while reducing the required network overheads. This is expected to result in both greater and more fairly distributed throughput, reduced jitter and lower energy consumption.

This chapter provides a performance evaluation of two representative ad hoc / mesh routing protocols when used with plain 802.11 ARQ and the DAFMAC and PRO cooperative MAC protocols. The key contributions and results of this chapter are:

- Integration of DAFMAC and PRO with two well-known representative reactive and proactive ad hoc / mesh routing protocols (Section 6.2); and

- Simulation evaluation of combined cooperative MAC protocols with these routing protocols (Section 6.3).

This chapter does not attempt to draw conclusions on the relative performance of routing protocols, as this is not the subject of this Thesis. Instead, the focus is on the relative performance of the MAC layer for a given routing protocol. The simulations in this Chapter use the same basic MAC-layer and network configurations as in previous chapters; nothing has been explicitly optimised for either routing protocol.

6.2 Overview of Routing Protocols

There are two fundamental ad hoc routing strategies: *reactive* and *proactive*.

Reactive protocols initiate a route discovery from the source to the destination on demand. This design reduces unnecessary route establishment and management, thereby reducing the complexity of the route management, at the cost of some initial delay to packet delivery.

The *Ad-hoc On-demand Distance Vector* protocol (AODV) [83] is a well established reactive routing protocol, and is used as a representative of reactive protocols in this experiment. A key design advantage for AODV is that it does not use a fixed forwarding path and may therefore adapt more rapidly to highly dynamic scenarios [3]. However, in the event of a transient link failure, it may also trigger an expensive route (re)discovery process, introducing significant transmission latency.

Conversely, *proactive* protocols establish routes from each participating node to all other nodes (or clusters of nodes) in the network. This routing information is stored locally at each node, which reduces the transmission latency because an optimised path is already known prior to transmission. However, this comes at the cost of additional network capacity being consumed to maintain the routing table, particularly for infrequently used routes.

The *Optimised Link State Routing* protocol (OLSR) [33] is a classic example of a proactive protocol, and is used in this experiment. An interesting feature of OLSR is that it incorporates multi-point relays (MPRs) to act as local routing supernodes to significantly reduce routing complexity.

Both DAFMAC and PRO are MAC protocols, operating at the data link layer. Although they both provide cooperative retransmission capabilities to leverage spatial diversity after failed direct transmissions, they are designed as extensions to the base 802.11 MAC. It is expected that under high-density network conditions, where most direct transmissions succeed, routing protocol performance should be similar to 802.11. Under sparse network conditions, it is expected that the use of cooperative protocols provides a significant improvement in routing protocol stability and performance compared with basic 802.11 ARQ, due to their ability to recover lost packets before routing protocols time out.

6.3 Performance Analysis

6.3.1 Simulation Configuration

Performance is evaluated for AODV and OLSR using plain 802.11, DAFMAC, and PRO as the underlying MAC protocols. The transmission rate is fixed at 11 Mb/s. A light total traffic load of 0.5 Mb/s is used to evaluate the individual link throughput, jitter and end-to-end delay. A heavier load of 2 Mb/s is used to evaluate the total throughput, link fairness and energy efficiency. A load of 2 Mb/s effectively saturates the network because of the half-duplex nature of the multi-hop channel.

To evaluate individual link throughput, jitter and end-to-end delay, uniformly-distributed random network topologies consisting of 100 nodes are constructed in a square simulation area of 400 m $\times$ 400 m. The mean distance between adjacent nodes is 36 m. QualNet's radio range function suggests the transmission range is approximately 70 m. Therefore, this configuration generally results in a fully connected network.

Total throughput, link fairness and energy efficiency are measured using a series of progressively larger square simulation areas with side lengths of $d \in [300, 500]$ m to illustrate routing performance in a potentially partially disconnected network.

CBR network traffic is equally distributed amongst nine data flows between fixed node pairs as shown in Figure 6.1. Each data flow uses a fixed data payload size of 1400 bytes, with source-destination distance increasing linearly from flow 1 to flow 9. The frame transmission interval is set to either 200 ms or 50 ms to generate a total traffic load of 0.5 Mb/s or 2 Mb/s respectively. The data flow is measured over a 600 second period.

The AODV experiment uses the following configuration:

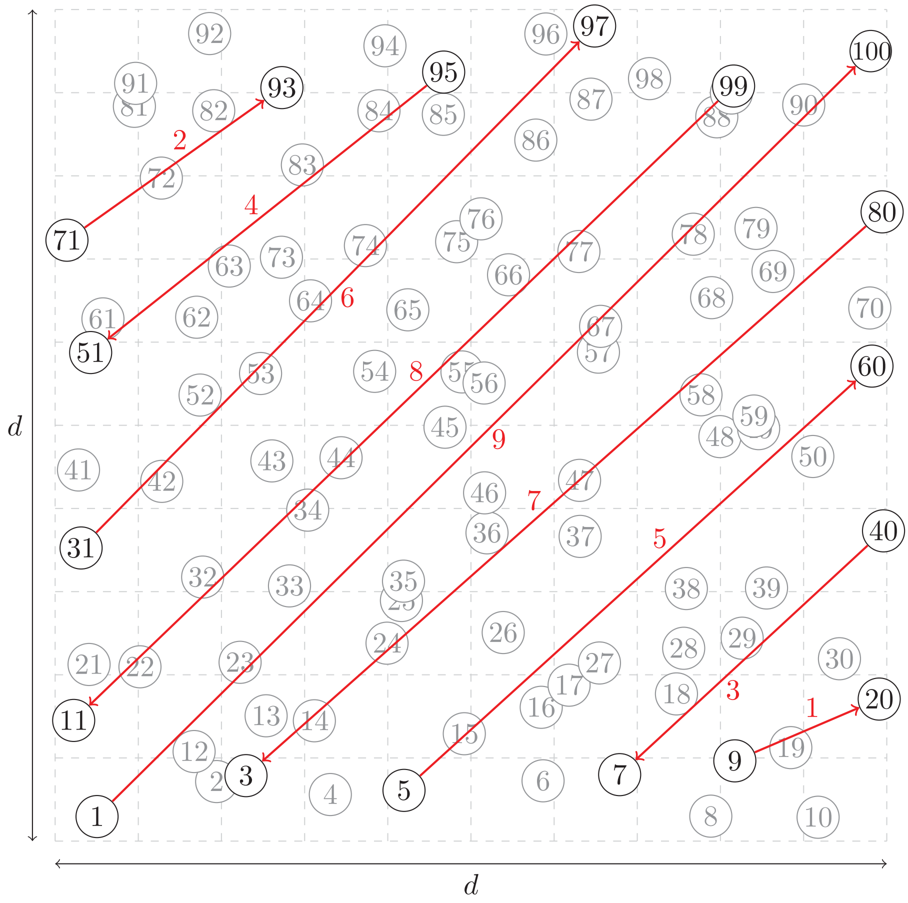

Figure 6.1: 100 uniformly randomly placed nodes with nine (potentially multi-hop) flows

- `HELLO` interval is set to 1 second;
- Active route time-out is set to 3 seconds;
- The expanded ring route request retry limit is 2; and
- The maximum network diameter is 35 hops.

OLSR is configured with the following parameter values:

- `HELLO` interval is set to 2 seconds;
- TC interval is set to 5 seconds;

- Refresh time-out interval is set to 2 seconds;
- Neighbour hold time is set to 6 seconds; and
- Topology hold time is set to 15 seconds.

Proactive protocols require time to establish routes and stabilise; if insufficient time is allowed for initial routing table convergence, the simulation result will not be an accurate indication of actual steady state behaviour. A simple experiment is performed in Section 6.3.4 to determine an appropriate settling time for OLSR in this work. Note that the settling time is prior to starting the commencement of data flows and is in addition to the 600 second simulation time. This settling period is also included in AODV simulations to ensure the channel conditions are consistent between protocols.

All MAC protocols are configured with settings based on default 802.11b timing parameters. The initial contention window size is 32 slots, the transmission limit is 7 attempts, and RTS/CTS signalling is disabled. DAFMAC uses the nearest neighbour scoring function, the retransmission contention window is 32 time slots, the random delay weighting is 0.1, and preferred relays are enabled. PRO uses a retransmission contention window of 32 time slots, and has a total cooperation threshold of 0.95.

The channel is configured to use Rician fading, with a K-factor of 5 and a maximum fading velocity of 5 m/s. No object shadowing is used and the path loss exponent is 2.6. These settings are similar to previous simulation studies in this Thesis and are based on realistic indoor values.

The result presented is the mean of 100 random seeds. The same 100 seeds are used for all configurations to ensure consistency in the node placement and channel fading characteristics between protocol configurations. Error bars shown on histograms represent the central 90% of the results.

Simulations are conducted using QualNet 4.5 [85] with the default AODV and OLSR implementations that are included in the Wireless Model Library.

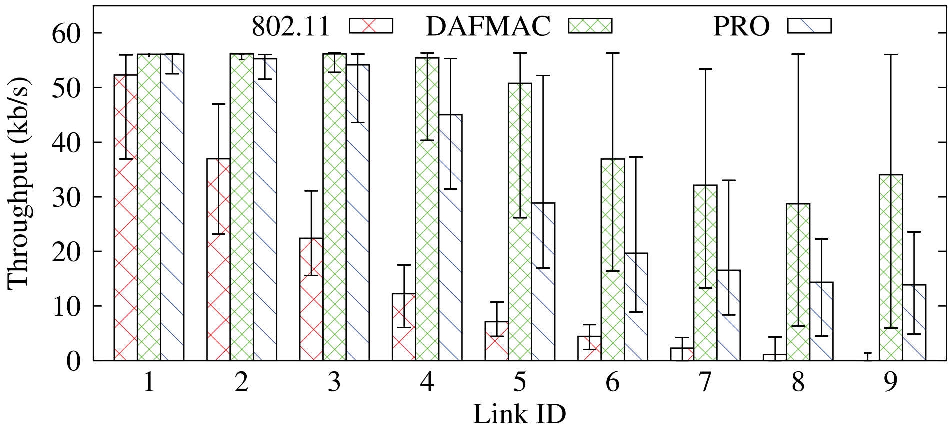

Figure 6.2: DAFMAC provides higher per-flow AODV throughput compared to PRO and plain 802.11

6.3.2 AODV - Light Load

The individual link throughput, end-to-end transmission time and jitter time for AODV are evaluated using a fixed 400 m × 400 m simulation area and a total network load of 0.5 Mb/s.

The throughput of the nine individual links are shown in Figure 6.2. Plain 802.11+AODV throughput falls away quickly as the node separation increases; link 1 has a higher throughput than the combined throughput of links 3 to 9. The cooperative MACs significantly improve the link throughput as the node separation increases. DAFMAC+AODV provides the highest throughput for each link and maintains a minimum throughput rate of at least half the requested load. PRO+AODV improves the individual link performance but does not match DAFMAC's throughput, even with a light network load.

Both DAFMAC and PRO significantly reduce the end-to-end transmission latency for all flows, as shown in Figure 6.3. For short to moderate transmission distances, both DAFMAC and PRO reduce the end-to-end transmission time by more than half when compared to the plain 802.11 MAC. The 802.11 MAC becomes unreliable at longer total transmission distances; the results only show the average of the frames that are actually delivered to the destination. This misrepresents the performance by producing a relatively short end-to-end latency for the plain 802.11 MAC, when in reality this flow

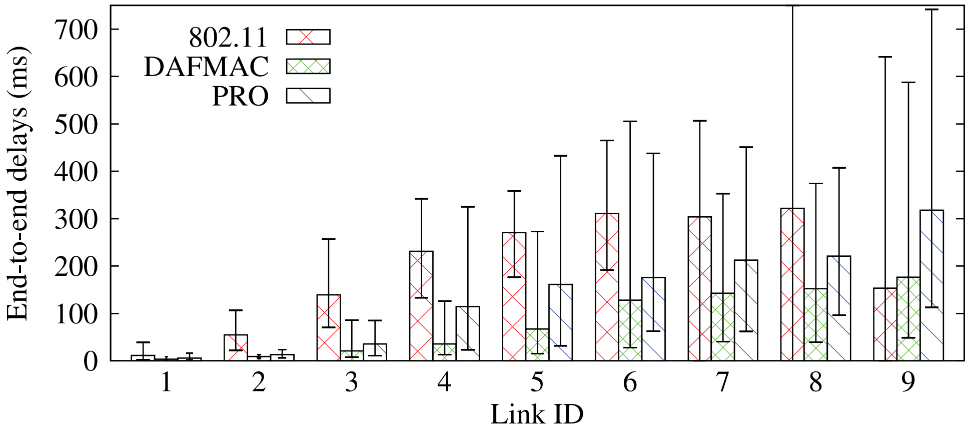

Figure 6.3: DAFMAC provides lower AODV end-to-end transmission latency compared to PRO and plain 802.11

would be unusable due to the high loss rate. Again, DAFMAC maintains a significant end-to-end transmission time advantage over PRO in a lightly loaded AODV network.

Jitter represents the variation in the link transmission time. It has already been established in previous Chapters that cooperative MACs significantly reduced one-hop jitter. The same result is evident in an end-to-end flow with a reactive routing protocol: DAFMAC provides the lowest jitter for all AODV simulations as shown in Figure 6.4. As previously stated, the result for the plain 802.11 MAC misrepresents its observed jitter because only a small number of frames traverse the network; those frames that do succeed exhibit only a small variation in transmission time and therefore have a small jitter.

Therefore, cooperative MACs significantly improve the AODV transmission performance with a light network load. Specifically, DAFMAC+AODV outperforms PRO+AODV in the individual link throughput, end-to-end transmission time and jitter.

6.3.3 AODV - Heavy Load

The total network throughput, throughput fairness and energy efficiency are evaluated for AODV using a range of simulation areas (hence node densities) and a total network load of 2 Mb/s.

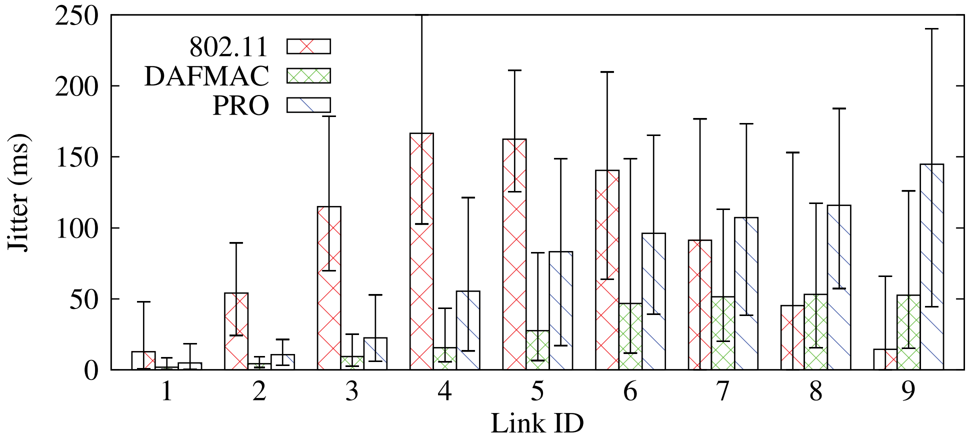

Figure 6.4: DAFMAC provides lower AODV jitter compared to PRO and plain 802.11

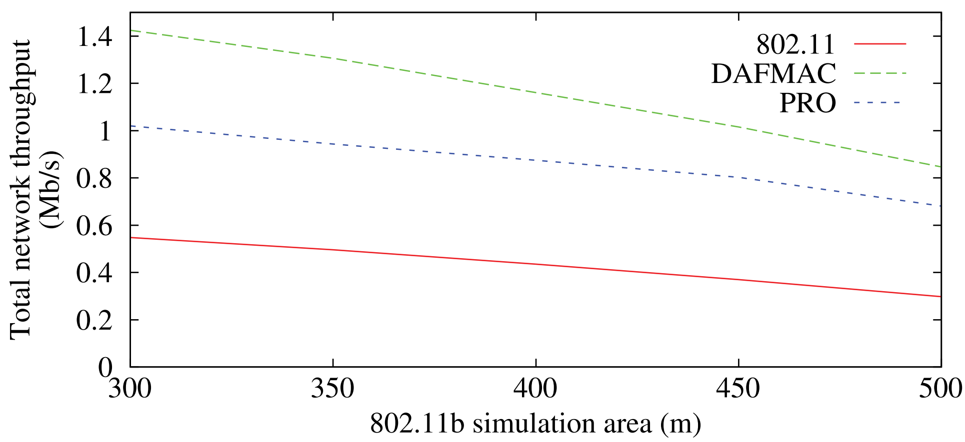

Figure 6.5: DAFMAC provides better AODV throughput over all simulation areas compared to PRO and plain 802.11

DAFMAC significantly increases the saturated AODV network throughput over all tested node densities, as shown in Figure 6.5. DAFMAC+AODV maintains almost three times the total throughput of plain 802.11+AODV, while PRO+AODV generally doubles the plain 802.11+AODV network throughput.

The 802.11 MAC results in over 60% of the total throughput delivered to just two of the nine data flows, even when the simulation area is relatively small. This corresponds to a poor link fairness, as measured using Jain's Fairness Index [56], which is shown in Figure 6.6. DAFMAC maintains a significantly higher fairness index than 802.11 or PRO

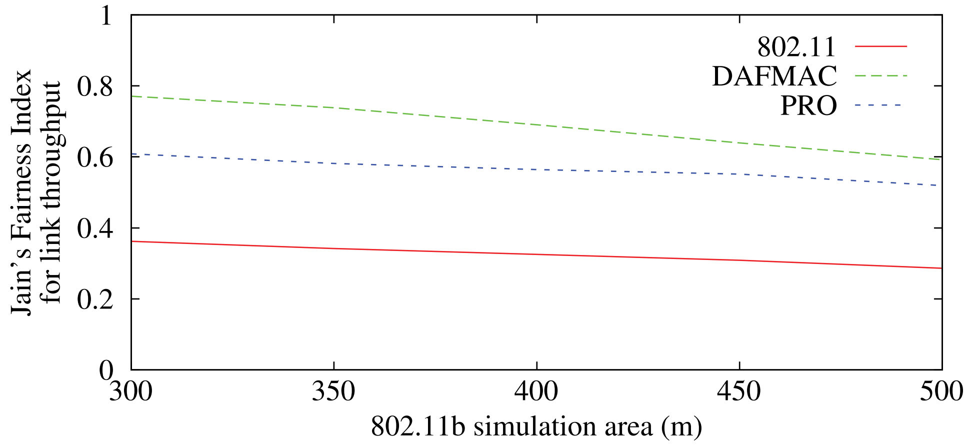

Figure 6.6: DAFMAC provides more fairness in throughput across all AODV data flows over all simulation areas compared to PRO and plain 802.11

at all node densities, although PRO does provide a significantly more fair distribution of link throughput than plain 802.11.

In addition to increasing the multi-hop throughput of AODV, DAFMAC reduces the energy required to successfully transmit each bit (aggregated over all links) by more than 60%. This is shown in Figure 6.7. PRO also reduces the energy per delivered bit, however the improvements are smaller than for DAFMAC. These results include the AODV route exploration frames that do not contribute to the throughput but do use energy. The energy efficacy is calculated using the same method as previously described in Section 4.6.

These results confirm that incorporating a cooperative MAC significantly increases the total throughput, link throughput fairness, and successful transmission energy efficiency for a saturated AODV network. Furthermore, DAFMAC+AODV outperforms PRO+AODV in all evaluated metrics in a saturated network.

6.3.4 OLSR - Settling Time

A brief simulation is used to estimate OLSR's initial convergence time in the simulated network in order to ensure that the routing table has time to stabilise prior to starting the simulation proper. The scenario uses a fixed 300 m $\times$ 300 m simulation area with the same nine data flows and a 0.5 Mb/s CBR load (started once the network has been

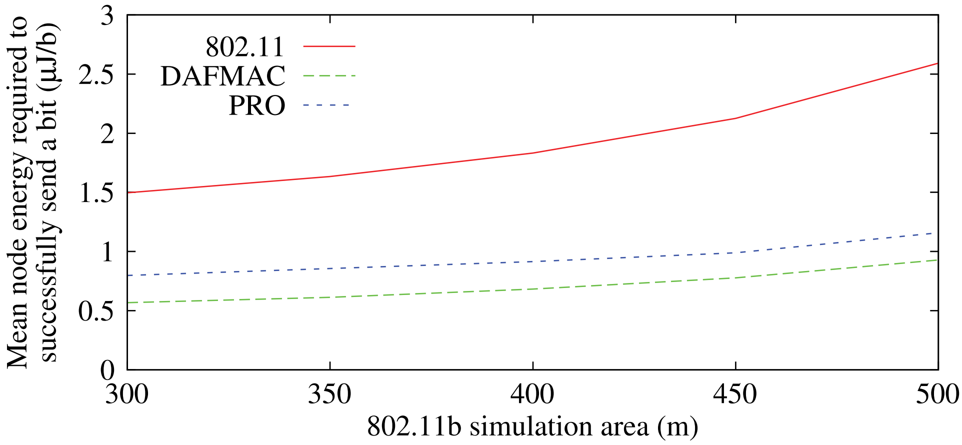

Figure 6.7: Use of DAFMAC results in less energy being consumed per bit successfully delivered using AODV over all simulation areas compared to PRO and plain 802.11

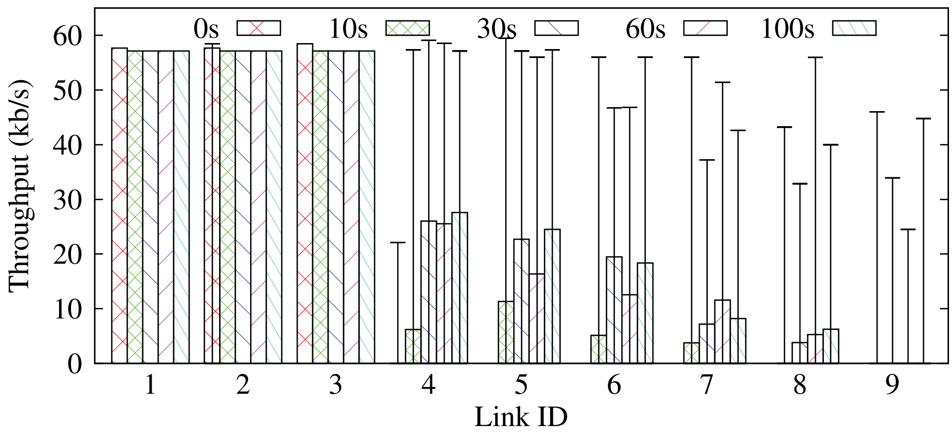

Figure 6.8: OLSR routing performance converges after approximately 30 seconds

given allowed to converge for the specified time). End-to-end throughput is measured over a period of 10 seconds after allowing OLSR to discover routes during an initial data-traffic-free period of between 0 and 100 seconds. The standard 802.11 MAC is used for consistency, and no channel fading is applied such that the channel is time-invariant. The sample consists of 100 random seeds.

Figure 6.8 shows that after 30 seconds, no further improvement in throughput is observed; therefore, a 30 second period is used to establish the routing table (prior to starting traffic flows and measuring performance) to ensure a consistent result over the entire sampling period, while also minimising the simulation run-time.

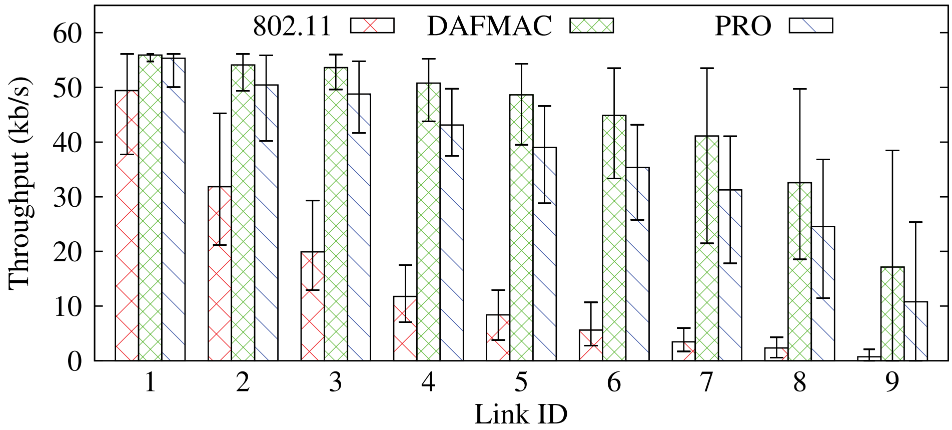

Figure 6.9: DAFMAC provides higher per-flow OLSR throughput compared to PRO and plain 802.11

6.3.5 OLSR - Light Load

The individual link throughput, end-to-end transmission time and jitter time for OLSR are evaluated using a fixed 400 m × 400 m simulation area and light network load of 0.5 Mb/s CBR traffic.

Similarly to AODV, individual link throughput performance with OLSR deteriorates as node separation increases and multi-hop forwarding is required to traverse the link. Figure 6.9 shows that both DAFMAC+OLSR and PRO+OLSR significantly outperform the individual link throughput of plain 802.11+OLSR as the node separation increases. DAFMAC consistently offers a higher throughput than PRO, with an average advantage of more than 20%.

OLSR end-to-end transmission latency is difficult to evaluate because of the small number of samples at the greater node separation. However, as shown in Figure 6.10, DAFMAC consistently provides lower transmission latency compared to PRO across all flows.

Similarly, the 802.11 jitter results are somewhat misleading due to the small sample size. However, a direct comparison of the cooperative MAC jitter shows that DAFMAC provides an average 40% less jitter than PRO. This result is shown in Figure 6.11.

These results confirm that cooperative MACs significantly increase the per-flow throughput in a lightly loaded OLSR network. Furthermore, DAFMAC+OLSR outperforms

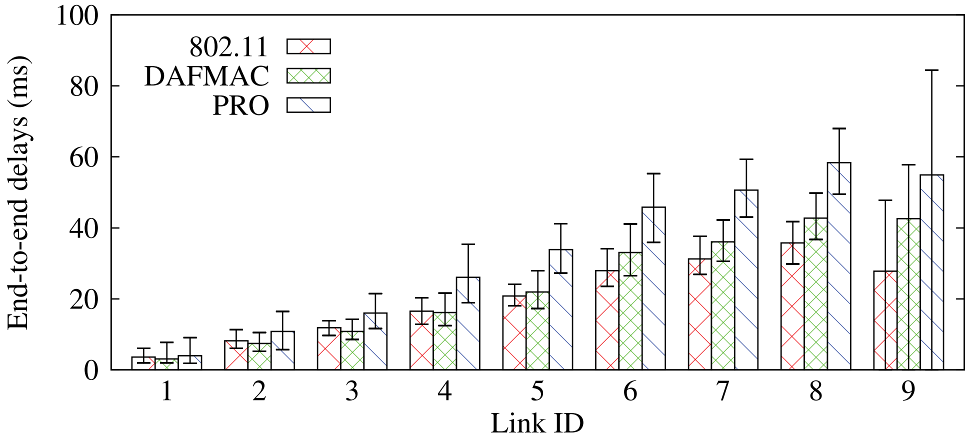

Figure 6.10: DAFMAC provides a lower OLSR end-to-end transmission latency than PRO

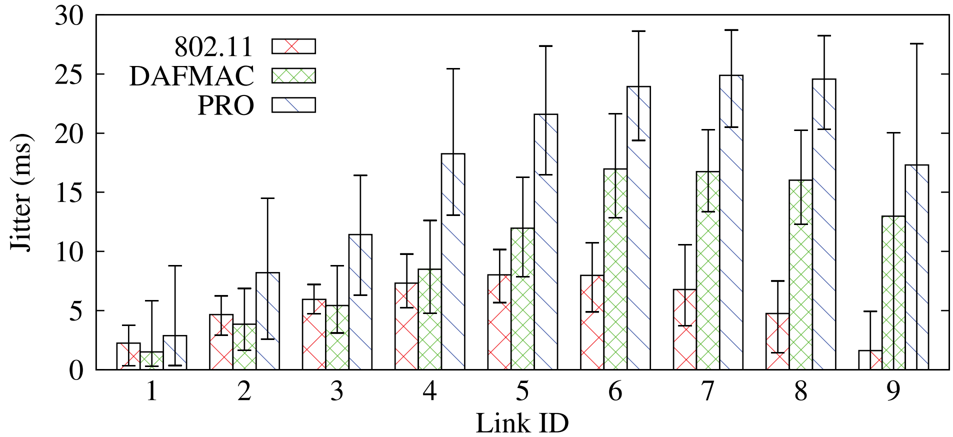

Figure 6.11: DAFMAC provides a lower OLSR jitter compared to PRO and plain 802.11

PRO+OLSR in each of the individual link throughput, end-to-end transmission time, and jitter time.

6.3.6 OLSR - Heavy Load

Finally, the total network throughput, throughput fairness and energy efficiency are evaluated for OLSR using a saturated combined load of 2 Mb/s over a range of simulation areas.

OLSR with the plain 802.11 MAC increases the total throughput performance compared to AODV. However, DAFMAC+OLSR generally doubles the combined throughput of

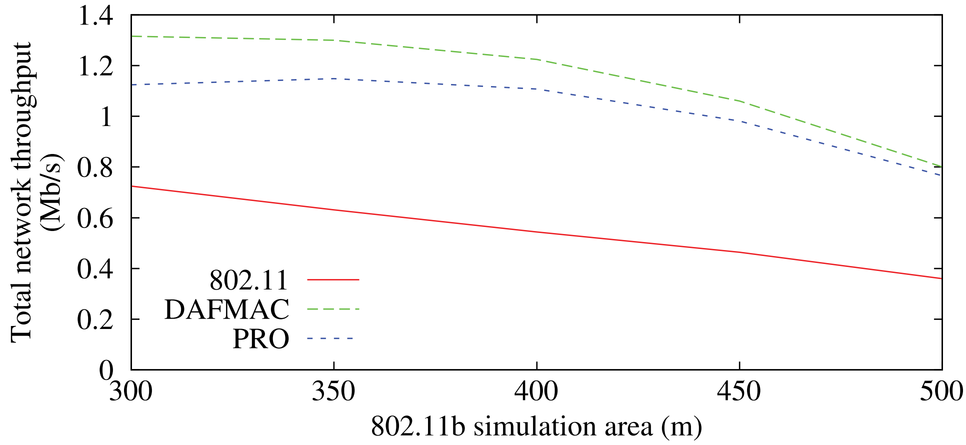

Figure 6.12: DAFMAC provides the maximum throughput improvement in OLSR routes over all simulation areas

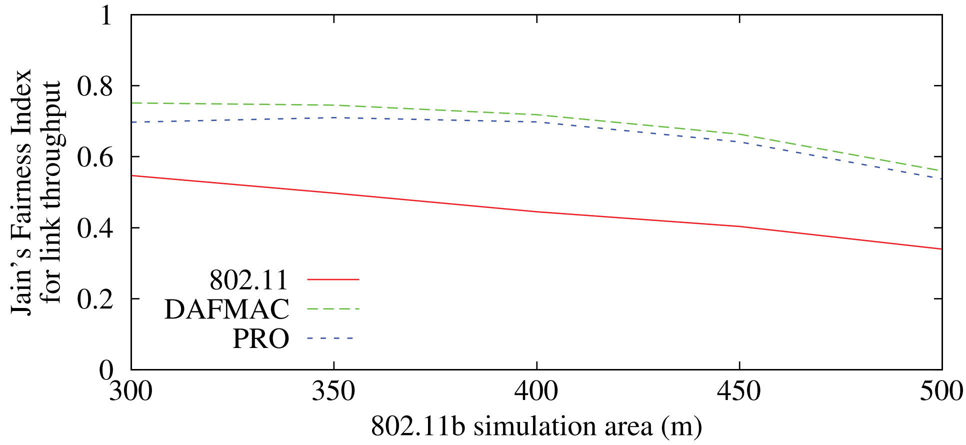

Figure 6.13: DAFMAC provides the fairest throughput for each OLSR data flow over all simulation areas

802.11+OLSR, as shown in Figure 6.12. PRO+OLSR also significantly improves the total saturated throughput, although it is consistently outperformed by DAFMAC+OLSR.

OLSR also provides fairer flow throughput than the saturated AODV network. Figure 6.13 shows that both DAFMAC+OLSR and PRO+OLSR significantly increase the flow throughput fairness, as measured using Jain's Fairness Index. DAFMAC+OLSR offers marginally better fairness than PRO+OLSR for all tested node densities.

Cooperative MACs require less energy to successfully transmit frames across a saturated OLSR network than the plain 802.11 MAC. Figure 6.14 shows that DAFMAC+OLSR

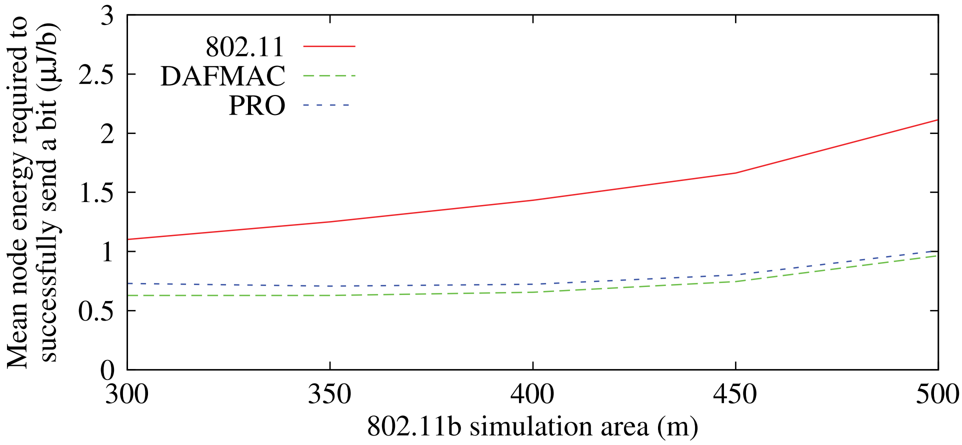

Figure 6.14: DAFMAC provides the lowest energy consumed per bit successfully transmitted using OLSR over all simulation areas

has a slight energy efficiency advantage over PRO+OLSR, and typically requires half of the energy used by 802.11+OLSR to successfully deliver packets to the destination node. In general, the OLSR energy utilisation is higher than AODV because OLSR is a proactive routing protocol which requires additional signalling to establish and maintain links between *all* node pairs, even when no useful data flows between them.

Therefore, both DAFMAC+OLSR and PRO+OLSR increase the total network throughput, link throughput fairness, and successful transmission energy efficiency compared to plain 802.11+OLSR in saturated networks at all tested node densities. DAFMAC+OLSR offers a slight advantage over PRO+OLSR in all tested metrics.

6.3.7 Protocol Comparison Discussion

DAFMAC clearly proides significant improvements across a wide variety of performance metrics when combined with both AODV and OLSR routing protocols. However, DAFMAC provides relatively greater benefits (compared to PRO) in dense networks than in sparsely populated networks, and DAFMAC provides a larger performance increase (than PRO) to AODV than to OLSR. This section discusses the cause of this performance differential.

Firstly, DAFMAC outperforms PRO by a larger margin in densely populated networks than it does in sparse networks. DAFMAC uses each available relay to contend during each retransmission contention period, and prioritises cooperative retransmissions over direct transmissions. Conversely, PRO uses a subset of the available relays, and nodes only cooperate when they are idle. The case exists where a single PRO relay provides sufficient gain to meet the cooperation threshold (set to 0.95 in this scenario [77]), and if this relay is not idle then no PRO relay will attempt a cooperative retransmission. Therefore, DAFMAC can provide a larger benefit than PRO in dense, saturated networks. As the network becomes more sparse, the PRO relay selection algorithm accepts a greater portion of the available relays into the contention set (because it is less probable that one relay can meet the cooperation threshold) and thus PRO performance converges to that of DAFMAC. DAFMAC performance necessarily decreases in sparse networks because there are fewer relays available to cooperate. Hence, the DAFMAC performance appears to decrease more quickly than PRO as network density decreases.

Secondly, DAFMAC offers a more significant gain compared to PRO in AODV networks than with OLSR. OLSR appears to rely upon cooperation when it is available; OLSR generates approximately 20% more cooperative retransmissions than AODV for a normalised network load. That is, OLSR includes the link reliability increase from cooperative retransmissions in the calculations when planning a route; because MAC-layer cooperation is transparent to the network layer, OLSR *expects* to leverage opportunistic cooperation. However, this temporary link is less reliable than a dedicated OLSR relay path, therefore this configuration is sub-optimal.

This observation highlights an opportunity to further increase performance. It is anticipated that a reliable route, which requires fewer opportunistic retransmissions, will exhibit a higher performance than the system as tested. Reducing the reliance on cooperative transmissions, while maintaining a cooperative MAC for transient channel fading, will maximise total performance. Such modifications are outside the scope of this initial investigation and require substantial simulation development and testing.

6.4 Conslusion

This chapter briefly examines the impact of cooperative MACs on multi-hop ad hoc / mesh routing protocols. The results show that both DAFMAC and, to a lesser extent, PRO offer significant benefits to individual link throughput, end-to-end transmission latency, jitter, combined throughput with a saturated load, link fairness when saturated, and energy required to successfully transmit a frame across the network. Furthermore, DAFMAC outperforms PRO in every tested metric for both AODV and OLSR.

There are several opportunities for further research in incorporating cooperative MACs into mesh routing protocols, including:

- Tuning both cooperative MAC protocol configuration and ad hoc networking protocols via comprehensive simulation studies to optimise the combined performance;
- Evaluating the DAFMAC cooperative MAC with more mesh networking protocols, specifically including the 802.11s hybrid protocol as a single cross-layer protocol; and
- Evaluating the performance of DAFMAC with routing protocols in highly mobile scenarios, such as a vehicular network.

Chapter 7

CONCLUSIONS AND FUTURE RESEARCH OPPORTUNITIES

7.1 Summary of Results and Contributions

7.1.1 Literature Review

A comprehensive literature review was undertaken to identify the highest performing cooperative retransmission MAC protocols and relay selection algorithms. This search showed that of the existing published protocols and algorithms, PRO and Δ-MAC are the most comprehensively defined, and have been successfully implemented in commodity hardware in practical test-beds.

This literature review revealed four opportunities to improve the performance of cooperative MAC protocols:

- Avoiding coordination signalling between contending neighbour nodes by using a relay selection algorithm which requires only partial link state information already available at the MAC layer;
- Optimising the relay selection algorithm to select a single relay without increasing the computational complexity at the node;
- Developing an accurate cooperative retransmission outcome model which evaluates the cooperative protocol and relay selection algorithm performance without needing to implement the entire protocol in a simulator; and
- Evaluation of the performance gains created by using cooperative MAC protocols in conjunction with ad hoc / mesh routing protocols.

7.1.2 DAFMAC Cooperative Retransmission Protocol

A new cooperative MAC protocol is initially justified by demonstrating that both PRO and Δ-MAC consume a significant portion of the channel capacity in coordination signalling overhead. Therefore, there is an opportunity for a zero-signalling protocol which uses only the partial channel state information available to the relay candidate to schedule its own retransmission.

The total cooperative coordination overhead of PRO and Δ-MAC is evaluated as a function of both the broadcast coordination frames and the cooperative retransmission collision rate. The cooperative coordination overhead is expressed as an equivalent retransmission collision rate, which is used as a comparative metric to assess the feasibility of other potential retransmission protocols and relay selection algorithms.

DAFMAC is introduced as a novel cooperative retransmission protocol that does not require explicit coordination. A relay selection algorithm is proposed that uses only link quality information already available at the MAC layer. Preliminary Monte Carlo simulations show that DAFMAC improves retransmission performance by approximately 70% over non-cooperative ARQ retransmissions in random network configurations. The initial DAFMAC retransmission collision rate is less than 8%, which suggests that DAFMAC's design is feasible when compared to PRO's equivalent overhead of 5–20% and Δ-MAC's overhead of approximately 50%. DAFMAC is thus established as a viable protocol; however, there is still a significant opportunity to increase the retransmission performance and optimise the relay selection algorithm.

7.1.3 DAFMAC Relay Selection Algorithm

The DAFMAC relay selection algorithm is introduced a general method for calculating delay values for cooperative retransmission. The default behaviour of this algorithm is to use instantaneous RSS values to rank relays; however, it may use any arbitrary relay scoring function to do so.

A critical factor in DAFMAC's performance is the cooperative retransmission collision rate. The relay selection algorithm is optimised via four incremental contributions:

- Identifying that the outer weighted relay scoring function is the most effective at isolating a single relay;
- Incorporation of a small random component, which adds a small number of additional random collisions but reduces repeated failures from relays with equal scoring function values;
- Deriving effective scoring function parameters; and
- Introducing a preferred relay scheme to re-use successful relays.

This results in a DAFMAC relay selection algorithm that achieves a very low retransmission collision rate. Further, it is also significantly less computationally complex than the PRO relay ranking algorithm.

DAFMAC's retransmission effectiveness is evaluated against the traditional non-cooperative ARQ retransmission and the PRO cooperative retransmission protocol using a comprehensive set of simulations. The key results of which show DAFMAC:

- Improves the total network saturated throughput;
- Improves the relative fairness of individual link throughput;
- Reduces the network-wide energy consumption per successfully received bit;
- Reduces the frame jitter; and,
- Improves the throughput performance in mobile scenarios.

7.1.4 General Cooperative Retransmission Model

A general analytic performance model for a wide range of decode-and-forward cooperative retransmission protocols is proposed. The model is suitable for evaluating any independent, distributed, slot-based contention algorithm for MAC layer opportunistic retransmission. The slot time-out probabilities are derived for each of the ARQ, CMAC, DAFMAC, Δ-MAC, and PRO retransmission schemes.

A Markov model is developed to represent the state machine used by DAFMAC with preferred relays enabled. The state probabilities for the Markov model are then numerically solved, using the link quality and decoding probability parameters, to determine the probability that each relay is operating as a preferred relay at any given time. The DAFMAC slot time-out probabilities are then re-calculated using the preferred relay probability and the total retransmission outcome probability is evaluated.

The analytic model is validated by a direct comparison to a QualNet simulation, which shows that the predicted outcome probabilities are typically within $\pm 1\%$ of the simulated result. The analytic result is also validated through Monte Carlo simulation, which is shown to converge to the analytic result as the sample size increases, when using the same receiver decoding probability model.

The key contribution of this model is that it enables a direct comparison of the retransmission attempt outcome probabilities between cooperative retransmission protocols, relay selection algorithms and specific parameter configurations, without the need for a comprehensive implementation in a state-based simulator such as QualNet or ns2. To demonstrate this capability, the retransmission performance of ARQ, CMAC, DAFMAC, Δ-MAC, and PRO are compared using this model with a random relay node placement.

A further powerful feature of the analytic retransmission model is its independence to the path loss and receiver decoding models. This is evaluated by implementing the empirically-derived receiver decoding model of Judd and Steenkiste. The results of applying this model demonstrate that cooperative protocol performance is significantly dependent on the receiver model. In this case, the greater variability in received signal strength introduced by the empirical model decreases the retransmission efficacy of the Δ-MAC and PRO protocols, while relatively improving the performance of DAFMAC.

The analytic model predicts that DAFMAC retransmission success probability is comparable to an optimal single-relay cooperative scheme. That is, although DAFMAC avoids the explicit coordination signalling used by PRO and Δ-MAC, DAFMAC provides a similar retransmission efficacy to Δ-MAC and exceeds that of PRO.

7.1.5 Opportunistic Retransmissions in Multi-hop Networks

The initial results clearly show that DAFMAC cooperative retransmissions are capable of enhancing the operation of the AODV and OLSR routing protocols, providing significant improvements to individual flow throughput, end-to-end transmission latency, jitter, combined throughput with a saturated load, link fairness under saturation conditions, and energy required to successfully transmit frames across the network. Furthermore, DAFMAC outperforms PRO in each tested metric for both AODV and OLSR; PRO is shown to provide some benefits to both routing protocols but these improvements are smaller than those achieved with DAFMAC.

7.2 Future Work

This thesis has exposed a number of interesting opportunities for future work in both the DAFMAC protocol and in the analytic retransmission model.

7.2.1 DAFMAC Protocol Development and Evaluation

Heterogeneous links present a challenge to link protocols because, in general, the assumption of *link* reciprocity (as opposed to *channel* reciprocity) is not a valid due to considerable variability in transmitter power and receiver performance. Simulation-based studies evaluating performance with heterogeneous transceivers will reveal how resilient DAFMAC is to this asymmetry. The DAFMAC protocol may then be extended to accommodate variations in device behaviour to maintain retransmission performance.

The random waypoint mobility model provides a simple method to evaluate the protocol response to varying topology (which affects potential relay availability) and channel gain (link quality to neighbours, including distance path loss, fading and shadowing). However, it is not representative of a real-world node mobility pattern. The promising simulation results for DAFMAC strongly indicate that it will improve network performance in scenarios with varying channel quality and is therefore suitable for deployment in mobile environments. The performance gain can be quantified through extensive mobile simulations, including realistic vehicular and pedestrian mobility models.

Simple preliminary analysis shows that DAFMAC reduces the per-successful-transmission energy cost, both for the sender and for the network as a whole. This result is important because it disproves the intuitive expectation that participation in relaying represents a cost to the potential relay with no apparent benefit. There is a significant opportunity to extend these results using an economic game theoretic method to maximise the network up-time in an energy constrained scenario. In particular, few studies consider the change in game equilibrium when resources are allocated heterogeneously, such as fully charged nodes entering an established network.

A brief simulation has shown that combining DAFMAC with ad hoc / mesh network layer routing protocols can significantly improve the multi-hop networking performance. However, there is a significant opportunity to enhance the synergy between DAFMAC and the routing protocol through cross-layer interaction. The first step is to identify the factors that limit the DAFMAC performance in ad hoc / mesh networks, and then to create configurable DAFMAC parameters which can be tuned to maximise performance for specific scenarios and routing protocols.

7.2.2 Analytic Retransmission Model

At present, the model only considers static nodes, but it can potentially be extended to mobile nodes. Assuming no channel fading, all that is required is a "history" of link quality for protocols which use historical values, such as the PDR used by PRO and Δ-MAC, and the current node positions. This will provide an accurate prediction for the result of a retransmission attempt in the current configuration, which can be extended to a series of node location sets to identify the distribution of the retransmission probabilities.

The model may also be extended to incorporate channel fading. This can potentially be realised using a new receiver model which includes the effects of fading on path loss, and hence the corresponding probability of successfully decoding the frame. This requires a fundamentally different approach for the ACK path; it would no longer be independent of the data frame path. That is, the reverse channel is approximately reciprocal to the forward channel - therefore, while the forward channel exhibits a large variation in the probability of decoding a frame due to instantaneous channel fading, the reverse channel will exhibit a much smaller decoding variation for the given forward path loss. The retransmission outcome result will become a distribution of results based on the instantaneous channel fading state.

The model currently assumes all devices are homogeneous, but it may be extended to include heterogeneous devices. This is a straightforward modification to include a different transmission power and receiver decoding model for each device. Again, the retransmission outcome is only valid for the exact combination of devices in the given configuration. Alternatively, the outcome can be expressed as a distribution of results using a series of random and independent device configurations.

7.3 Conclusions

Opportunistic user cooperation is an effective and resource efficient method of reducing the link outage rate in wireless networks. Although the predominant research efforts in cooperative MAC protocols focus on coordinating information between contending devices to reduce or avoid retransmission collisions, this Thesis shows that an effective relay selection algorithm produces a lower total cooperative overhead and outage loss and therefore retains a greater share of the channel capacity for general use.

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