Performance Issues of Network - Level Cooperation with Multiple - Relays

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Thesis submitted in partial fulfillment of the requirements for the

Masters' of Science degree in Computer Science

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Abstract

Cooperative communications are widely acknowledged to provide higher communication rates and reliability in a wireless network with time varying channels, due to their ability to overcome fading and signal attenuation. While most cooperative research in this area concern gains achieved by cooperation on the physical layer, recent works suggest that similar gains can be achieved by Network – Level cooperation. By Network – Level cooperation we refer to plain relaying without any physical layer considerations.

In this thesis, we first provide the basic background behind the relay channel which is the basic paradigm of cooperative communications. We present the fundamental cooperative architectures, relaying and multiple access protocols and we discuss the advantages and disadvantages of cooperative systems. Furthermore, we discuss several system tradeoffs that arise and we present some basic application scenarios along with the standardization of new technologies.

In the second part of the thesis, we study the impact of the insertion of a second relay node in a network where the relay nodes relay packets from a number of users to a destination node. We consider the case of a discrete-time slotted system in which the users have saturated queues and random access to the medium. Simultaneous transmission attempts by two or more nodes of the network result in a collision. The two relays do not have packets of their own, but assist the users by relaying their packets when necessary. We obtain analytical expressions for the arrival and service rates of the queues of the two relays and also the stability conditions. In addition, we present a topology of the system in which the users are divided into two clusters and study the impact of the two relay nodes of the two models (with and without clustering) on the aggregate throughput and the throughput per user. We show that the probabilities of the two relays to attempt transmission do not depend on each other when the queues are stable. Another important observation is that the insertion of a second relay in a system generally does not offer higher throughput per user in comparison to a system with one relay, but the system in which the users are divided into two clusters separated by some distance offers significant advantage. Moreover, there is an optimum number of users that maximizes the aggregate throughput of the clustered system. These results could be used to allocate the users among the relays for example in cellular and sensor networks.

In the third part of the thesis, we study a similar model as in the second part, with two relays that relay packets from a number of users to a destination, with the main difference being that the relays and the destination are equipped with multiuser detectors, so that they can decode packets successfully from more than one transmitter at a time (multi-packet reception - MPR capability). We present two variations of a system with two relays, the first in which if both relays receive the same packet from a user, they both store it and forward it to the destination, and the second in which the relay with the smaller queue size stores the packet in its queue and is responsible for forwarding it to the destination. We also, present a topology of the system in which the users are divided into two distant clusters and study the impact on the aggregate and per user throughput compared to the cases of no relay, one relay and two variations (as above) of two relays in the system. Moreover, we find that there is an optimum number of users that maximizes the aggregate throughput of the systems with two relays. We show by extensive simulations that under certain circumstances, the use of two relays offers significant advantage as per aggregate and per user throughput compared to systems with one and no relay. Furthermore, we present a way to verify if the queues of the relays are stable and compare the average queue size and the average delay per packet of all the systems presented. We also show that although the average queue size of the clustered system is higher, the average delay per packet is much lower and in combination with the higher aggregate and per user throughput that it can provide, the clustered system is the most appropriate solution. Finally, we present the conditions under which an interference cancellation technique, in the systems with two relays, can provide higher aggregate throughput and what are the effects of the distance between the two clusters in terms of aggregate throughput.

Περίληψη

Οι συνεργατικές επικοινωνίες είναι ευρέως γνωστό ότι μπορούν να προσφέρουν υψηλότερους ρυθμούς διαμεταγωγής και αξιοπιστία σε ένα ασύρματο δίκτυο με χρονικά μεταβαλλόμενα κανάλια, λόγω της δυνατότητας να αντιμετωπίζουν προβλήματα σκίασης και εξασθένισης του σήματος. Μολονότι τα περισσότερα οφέλη επιτυγχάνονται μέχρι τώρα με τεχνικές συνεργασίας που αφορούν το φυσικό επίπεδο, πρόσφατες έρευνες υποδηλώνουν ότι παρόμοια οφέλη μπορούν να επιτευχθούν με συνεργασία σε επίπεδο δικτύου. Με τον όρο συνεργασία σε επίπεδο δικτύου αναφερόμαστε σε απλή αναμετάδοση χωρίς να λαμβάνουμε υπόψη το φυσικό επίπεδο.

Στο πρώτο μέρος της παρούσας διατριβής παρέχουμε το υπόβαθρο για το κανάλι αναμετάδοσης το οποίο είναι το βασικό μοντέλο των συνεργατικών επικοινωνιών. Παρουσιάζουμε τις θεμελιώδεις αρχιτεκτονικές, τα πρωτόκολλα αναμετάδοσης και πολλαπλής πρόσβασης στο μέσο και αναφέρουμε πλεονεκτήματα και μειονεκτήματα των συστημάτων συνεργασίας. Επίσης, παρουσιάζουμε τους διάφορους συμβιβασμούς που είναι αναγκαίοι σε πολλές περιπτώσεις και παρέχουμε σενάρια εφαρμογής μαζί με την τυποποίηση νέων τεχνολογιών που χρησιμοποιούν συνεργατικές επικοινωνίες.

Στο δεύτερο μέρος της διατριβής, μελετάμε τις επιπτώσεις της εισαγωγής ενός δεύτερου κόμβου αναμετάδοσης σε ένα δίκτυο στο οποίο οι κόμβοι αναμετάδοσης αναμεταδίδουν τα πακέτα ενός αριθμού χρηστών προς έναν κόμβο προορισμού. Θεωρούμε ένα σύστημα διακριτού χρόνου με χρονοσχισμές στο οποίο οι χρήστες έχουν κεκορεσμένες ουρές πακέτων και τυχαία πρόσβαση στο ασύρματο κανάλι. Οι δύο αναμεταδότες δεν έχουν δικά τους πακέτα και απλά βοηθούν τους χρήστες με το να αναμεταδίδουν τα πακέτα τους όταν αυτό είναι απαραίτητο. Ταυτόχρονη προσπάθεια μετάδοσης από δύο ή περισσότερους κόμβους του δικτύου έχει ως αποτέλεσμα τη σύγκρουση και απώλεια των πακέτων. Μελετούμε την ευστάθεια των δύο ουρών των αναμεταδοτών και βρίσκουμε αναλυτικές εκφράσεις για το ρυθμό άφιξης και εξυπηρέτησής τους για την ευστάθεια. Αποδεικνύουμε ότι η πιθανότητα του ενός αναμεταδότη να προσπαθήσει να μεταδώσει ένα πακέτο δεν εξαρτάται από την πιθανότητα μετάδοσης του άλλου αναμεταδότη όταν οι ουρές είναι ευσταθείς. Ακόμη, παρουσιάζουμε μία τοπολογία του συστήματος με δύο αναμεταδότες στην οποία οι χρήστες διαχωρίζονται σε δύο ομάδες και μελετούμε τις επιπτώσεις της όσον αφορά στο ρυθμό διαμεταγωγής ανά χρήστη και το συνολικό ρυθμό. Ακόμη, παρατηρούμε ότι η είσοδος ενός

δεύτερου αναμεταδότη στο σύστημα γενικά δεν προσφέρει υψηλότερο συνολικό ρυθμό διαμεταγωγής σε σύγκριση με συστήματα με έναν ή κανέναν αναμεταδότη, αλλά όταν οι χρήστες είναι χωρισμένοι σε δύο ομάδες και σε κάθε ομάδα αντιστοιχεί ο ένας αναμεταδότης παρέχονται σημαντικά οφέλη. Επίσης, υπάρχει ένας συγκεκριμένος αριθμός χρηστών ο οποίος μεγιστοποιεί το συνολικό ρυθμό διαμεταγωγής του δικτύου όταν οι χρήστες είναι χωρισμένοι σε δύο ομάδες. Τα αποτελέσματα αυτά μπορούν να χρησιμοποιηθούν ώστε να κατανείμουμε τους χρήστες στους διαθέσιμους αναμεταδότες, για παράδειγμα σε δίκτυα κινητής τηλεφωνίας ή σε δίκτυα αισθητήρων.

Τέλος, στο τρίτο μέρος μελετάμε ένα παρόμοιο μοντέλο με αυτό του δευτέρου μέρους, με δύο αναμεταδότες οι οποίοι αναμεταδίδουν τα πακέτα ενός αριθμού χρηστών σε έναν κόμβο προορισμού, με τη βασική διαφορά ότι οι αναμεταδότες και ο τελικός προορισμός είναι εξοπλισμένοι με ανιχνευτές πολλαπλών χρηστών, έτσι ώστε να μπορούν να αποκωδικοποιήσουν πακέτα από περισσότερους από έναν πομπούς ταυτόχρονα. Μελετούμε δύο εκδοχές του συστήματος με δύο αναμεταδότες, στην πρώτη, σε περίπτωση που και οι δύο αναμεταδότες αποκωδικοποιήσουν επιτυχώς ένα πακέτο από τον ίδιο χρήστη το αποθηκεύουν και οι δύο και το αναμεταδίδουν και οι δύο στον τελικό προορισμό. Στη δεύτερη εκδοχή για την ίδια περίπτωση, ο αναμεταδότης με τη μικρότερη ουρά αναλαμβάνει να αποθηκεύσει και να αναμεταδώσει το πακέτο. Επίσης, παρουσιάζουμε μία τοπολογία του συστήματος με δύο αναμεταδότες στην οποία οι χρήστες διαχωρίζονται σε δύο ομάδες και τη συγκρίνουμε με τα συστήματα χωρίς, με έναν και με τις δύο εκδοχές με δύο αναμεταδότες, όσον αφορά στο ρυθμό διαμεταγωγής ανά χρήστη και το συνολικό ρυθμό. Όπως και στο δεύτερο μέρος υπάρχει ένας συγκεκριμένος αριθμός χρηστών ο οποίος μεγιστοποιεί το συνολικό ρυθμό διαμεταγωγής των δικτύων με δύο αναμεταδότες. Με εκτενείς προσομοιώσεις δείχνουμε ότι κάτω από συγκεκριμένες συνθήκες, η χρήση δύο αναμεταδοτών προσφέρει σημαντικά πλεονεκτήματα όσον αφορά στο ρυθμό διαμεταγωγής ανά χρήστη και το συνολικό ρυθμό σε σύγκριση με τα συστήματα χωρίς και με έναν αναμεταδότη. Επιπλέον, παρουσιάζουμε μία μέθοδο για να επαληθεύσουμε αν οι ουρές των αναμεταδοτών είναι ευσταθείς και για να συγκρίνουμε το μέσο μέγεθος και τη μέση καθυστέρηση ανά πακέτο για όλες τις περιπτώσεις που εξετάζουμε. Καταλήγουμε ότι το σύστημα με δύο αναμεταδότες και τους χρήστες ομαδοποιημένους είναι η πιο ενδεδειγμένη λύση. Τέλος, παρουσιάζουμε τις συνθήκες υπό τις οποίες μία τεχνική ακύρωσης των παρεμβολών μεταξύ των δύο αναμεταδοτών μπορεί να προσφέρει υψηλότερο συνολικό ρυθμό διαμεταγωγής στο σύστημα και ποια είναι η επίδραση της απόστασης μεταξύ των δύο ομάδων χρηστών στο συνολικό ρυθμό διαμεταγωγής.

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Στους γονείς μου

To my parents

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Chapter 1

Introduction

In our days, wireless communications have become an important part of our lives due to their ability to provide ubiquitous connectivity. However, in order to provide reliable and high data rate communication over the wireless channel, certain difficulties have to be surpassed. Those are the effects of multipath fading, shadowing and path loss which we encounter in the wireless environment. Those effects may cause high signal attenuation and distortion and also large delays. Thus, in the last two decades the wireless networking community focuses on developing diversity techniques such as time, frequency and space so as to mitigate those effects.

Cooperative communications are acknowledged to be the means to overcome the negative effects of the wireless environment mentioned above. They can help to overcome the effects of fading and signal attenuation, and focus on increasing the data rates across a network and also the reliability of time varying channels. Generally, by cooperative communications we refer to systems in which a communication link between a user and a destination is enhanced by the use of intermediate relays or by other users of the system. Thus, the study of the relay channel, in which between the sender and the receiver lies at least one relay, is of special interest for cooperative communications.

In this chapter we provide the basic background of cooperative communications and the relay channel which constitutes the basic paradigm. We present the fundamental cooperative architectures, relaying and multiple access protocols and we discuss the advantages and disadvantages of cooperative systems. Furthermore, we discuss several system tradeoffs that arise and we present some basic application scenarios along with the standardization of new technologies. We point out the importance of cooperation and we report why we focus on the Network – Level cooperation in this thesis.

1.1 Background on cooperative communications and relay channel

Traditional wireless systems assume that users communicate directly to the base station and vice versa. Instead, cooperative communications provide enhancement of a user's link to the destination, either in a supportive way with relays or by cooperation with other users of the system. This is feasible due to the broadcast nature of wireless environment, which suggests that a signal transmitted to a destination can be overheard by neighboring nodes. The processing and retransmission to the destination of the overheard signal by neighboring nodes, allows single-antenna nodes to share their antennas so as to create spatial diversity and thus create a virtual Multiple Input Multiple Output (MIMO) system [1, 2].

By spatial diversity we mean the transmission of independent copies of a signal from different locations, in order to receive independently faded versions of the signal at the destination [2]. An example that demonstrates the cooperation of two nodes that experience independent fading channels to the destination is presented in Figure 1. The two nodes communicate with the same destination and each has one antenna. It is well known that for a transmission to be successful from a source to a destination the Signal to Noise Ratio (SNR) has to exceed a certain threshold. In a traditional wireless system whenever the SNR of one user falls below the required threshold, communication outage will occur. However, if a cooperation scheme between the two users is deployed in which they relay each other's overheard packets to the destination, we will experience an outage event in case that both users' transmissions fail to reach the destination. In that way, we achieve both spatial diversity and reliability.

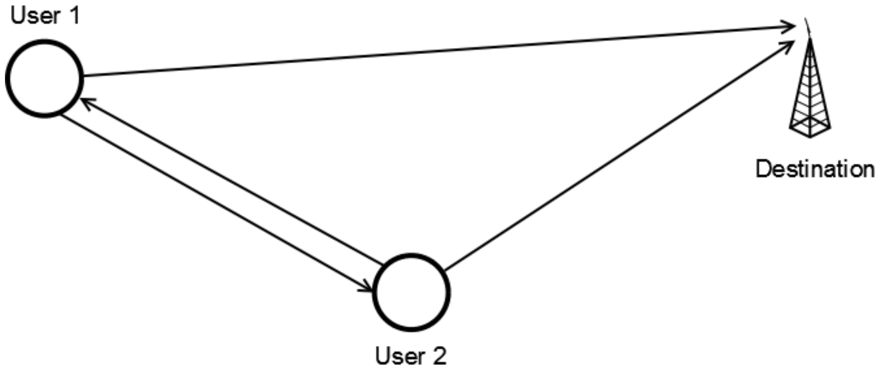

Figure 1: Two user cooperative communication

This basic idea of cooperative communications brings forward numerous challenges to be addressed by system designers. In the rest of this chapter we present some basic definitions, architectures, relaying protocols, medium access methods, advantages and disadvantages and important tradeoffs of cooperative communication systems.

1.1.1 Cooperative communications architectures

In Figure 1 we can see the simplest form of cooperative communications with two users. Nevertheless, in a real world system the parameters and architectures that define it can be numerous and with different effects. Architectures and parameters that affect a cooperative system are briefly discussed below.

First of all, it is the way that the relay operates on the source's signal. This aspect is called relaying protocol. Relaying protocols can generally be classified into transparent or regenerative. In general, transparent relaying refers to relays that only amplify or perform simple operations to the signal before retransmitting it to the destination, while regenerative relaying refers to relays that process digitally the received signal before retransmitting it. Certain transparent and regenerative relaying protocols are described in section 1.1.2.

Moreover, relays can be divided into supportive or cooperative. Supportive is a relay that is placed between a source and a destination and just forwards messages received by the source to the destination. Cooperative is a relay that not only forwards messages of other sources, but also its own information can be forwarded by other relays.

Furthermore, the existence or not of a direct link between the source and the destination plays an important role. If this link does not exist only path loss gain can be achieved. If a direct link does exist diversity gain can also be achieved.

Another interesting parameter is the choice of the number of relaying stages for a transmission to reach the final destination. That is dual-hop or multi-hop networks. Figure 2 depicts an example of serial relaying in which the source is connected to the destination by a number N of intermediate relays and Figure 3 depicts an example of parallel relaying in which the source is connected to the destination by N parallel relays that use orthogonal channels so as to relay simultaneously the received information by the source. Also, another type of relaying is space-time, in which the source is connected to the destination by N parallel relays that use space-time encoded channels to relay the received information. Increasing the number of relays that are connected serially, results in an increase of the path loss gain and increasing the number of relays that operate in parallel, results in an increase of the diversity gain [3]. Direct link between the source and the destination may or may not exist.

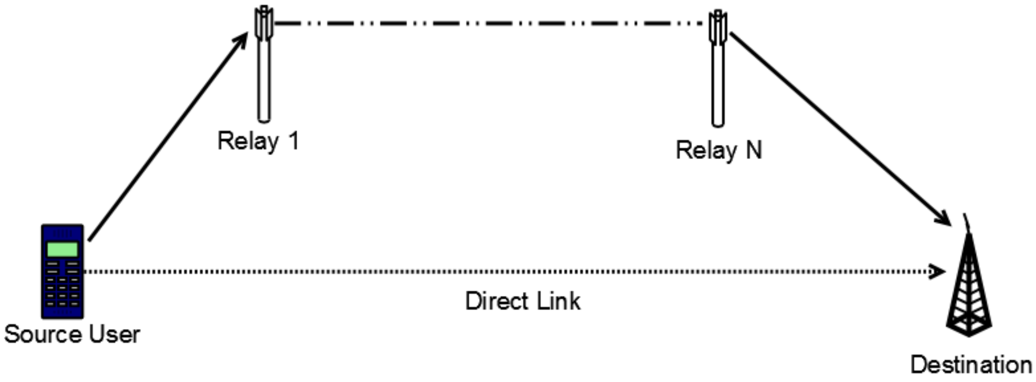

Figure 2: Serial relaying

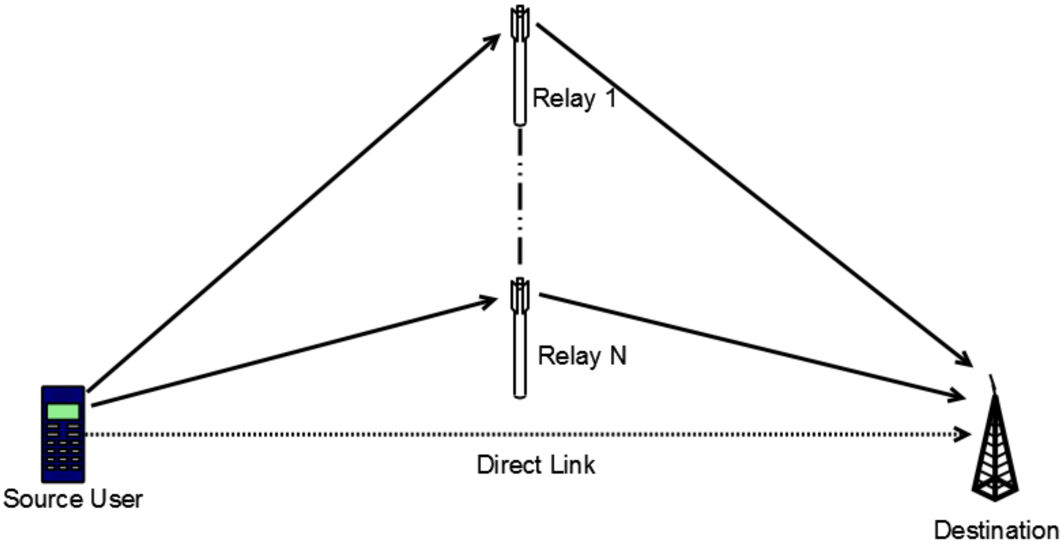

Figure 3: Parallel relaying

1.1.2 Transparent and regenerative relaying protocols

As mentioned in section 1.1.1 there exist two categories of relaying protocols, transparent and regenerative. These protocols define the way the relay handles the information it receives before retransmitting it [3].

Transparent protocols suggest that the information received by the relay is not digitally processed and simple operations such as amplification are performed. The basic transparent relaying protocol is presented below:

- Amplify and Forward (AF): This method was proposed and analyzed by Laneman [4, 5]. The relay receives the signal transmitted by the source, amplifies it and retransmits it to the destination. The destination combines the signals received both by the source and the relay and decides which the transmitted bits are. It is interesting that although the noise of the received signal is amplified at the relay, the destination receives two independently faded versions of the signal and can make better decisions on the detection of information [2].

Regenerative protocols suggest that the signal is digitally modified in the relay before retransmission. Some basic regenerative relaying protocols that perform various modifications of the signal are presented below:

- Decode and Forward (DF): In this protocol the relay detects the signal from the source, decodes it, re-encodes it and retransmits it to the destination [5, 6, 7]. The destination, similarly to the AF method, combines the signals received by the source and the relay so as to make better decisions on the detection of information.
- Estimate and Forward (EF): In this protocol the relay amplifies the analog signal and with some detection algorithms aims at recovering the original representation of the signal. This estimation of the original signal is retransmitted using the same or a different modulation order [3].
- Compress and Forward (CF): This protocol which is similar to the EF protocol implies that the relay detects the signal from the source, decodes it and forwards a quantized, estimated or compressed version to the destination [8]. Instead of decoding perfectly the source signal like DF protocol does, in CF only the information that is most relevant to the decoding at the destination is decoded.
- Coded Cooperation: Coded Cooperation [9, 10], differs from previous protocols in that it integrates cooperation into channel coding. The main idea is that users divide their data into two segments that are augmented with cyclic redundancy check (CRC) code and also the data transmission period for each user is divided into two time segments (frames). In the first frame each user transmits the first segment of his data and attempts to decode the transmission of its partner. If this attempt is successful, in the second frame each user transmits the second segment consisting of the data of its partner. Otherwise, the user transmits its own second segment of his data. We should note that the user and its partner operate over orthogonal channels.

1.1.3 Multiple Access Protocols

In a cooperative communication system with many users and one or more possible relays, proper multiple access protocols should be utilized. We can generally divide multiple access protocols in reservation-based or contention-based, depending on whether the resources are allocated a priori or need to be contended for, prior to communication [3]. Here, we briefly present some basic examples of reservation-based protocols and we provide more details for random access contention-based protocols because we assume random access to the medium in the models studied in this thesis.

Some basic examples of reservation-based multiple access protocols that can be used are: Time Division Multiple Access (TDMA), Frequency Division Multiple Access (FDMA), Code Division Multiple Access (CDMA) and Orthogonal Frequency Division Multiple Access (OFDMA). In TDMA different timeslots are scheduled to every user and every relay while in FDMA different frequency channels. In CDMA different spreading codes are assigned to every user and every relay making it possible for everyone to communicate in the same channel at the same time. Finally, in OFDMA different subsets of subcarriers are assigned to every user and every relay.

In the models we describe in Chapters 2 and 3 we assume random access to the medium with slotted time. Thus, below we present the basic random access contention-based protocols:

- ALOHA: In this protocol [11] when a node receives a new packet in its queue, it transmits it immediately. Thus, slots play no role in plain ALOHA. If there is a collision of simultaneous packet transmissions, each user retransmits the packet after a random delay. ALOHA protocol is rather simple but its efficiency is fairly low.
- Slotted ALOHA: An improvement of ALOHA is slotted ALOHA [12] in which time is divided into equal size slots (equal packet transmission time) and each node transmits a newly arriving packet in the first slot after the packet arrival, thus risking occasional collisions but achieving very small delay if collisions are rare [13]. If there is a collision of simultaneous packet transmissions, each node discovers the collision at the end of the slot and becomes backlogged. Then, each user waits for some random number of slots to retransmit the packet.
- Carrier Sense Multiple Access (CSMA): CSMA [14] is based on the fact that a node can “hear” whether other nodes are currently transmitting, after a very small propagation and detection delay relative to a packet transmission time. Thus, a node that has a packet to transmit first senses the channel to detect idle periods. If an idle period is detected transmission is initiated and if the channel is sensed as busy the node refrains from transmission and tries again at a later moment (depending on the backoff algorithm). Two variations of CSMA are persistent CSMA and non-persistent CSMA [13]. In persistent CSMA all arrivals during a busy slot simply postpone transmission to the end of that slot, thus causing a collision with relatively high

probability. In non-persistent CSMA when a packet arrives at a node while another transmission is in progress, the packet is backlogged and begins transmission with a certain probability after each subsequent idle slot.

- CSMA/CD: In CSMA/Collision Detection, which is a modification of CSMA (used extensively in wire line channels but is difficult to apply to wireless channels), if two nodes start a transmission simultaneously, they will shortly detect a collision and both cease transmission. Then, they try to retransmit after a random time interval. This process of terminating transmissions in case of collision shortens the time required before a retransmission is attempted, leading in reduced channel wastage. This protocol is the basis of IEEE 802.3 networks.
- CSMA/CA: In CSMA/Collision Avoidance, the idea (unlike CSMA/CD) is to prevent collisions before they happen. Each node senses the medium for other transmissions and if the channel is clear it transmits its packet after a random time interval (depending on the backoff algorithm used). This protocol is the basis of IEEE 802.11 networks.

Random Access Model Considered

Some basic assumptions we make in our random access protocol used in Chapter 2 concern a kind of idealized collision-channel model [13] like slotted ALOHA, and are the following:

1. We consider a slotted system in which we assume that all transmitted packets have the same length and that each packet requires exactly one timeslot for transmission. Thus, we assume that all transmitters are synchronized.
2. If two or more nodes send a packet in a given timeslot we have a collision. Only if just one node transmits we may have a successful transmission at the destination.
3. We assume that at the end of each timeslot the receiver provides feedback to the nodes of the system specifying if 0, 1 or more packets were transmitted in that timeslot. Thus, each user knows whether his transmission was the only one in the system.
4. We also assume that each packet involved in a collision must be retransmitted with a certain probability in a later timeslot until it is successfully received by the destination. This “back-off” probability of retransmission is used to reduce the number of collisions.
5. Finally, we assume that the queues of the nodes are saturated (they always have a packet to transmit). However, new arrivals at a node are discarded

and never transmitted. Retransmissions are attempted until the first packet of the queue is successfully received by the destination.

In Chapter 3 we consider a similar model but with the basic difference that the assumption 2 does not apply, that is we assume Multi-Packet Reception (MPR) capabilities for the relay(s) and the destination. In the following we describe the random access models used in Chapters 2 and 3 independently.

1.2 Advantages and disadvantages of cooperation

Cooperative communications offer several advantages, some of them presented in previous sections but, they also have some major disadvantages. Here we summarize the advantages and present the major disadvantages that make the design of a cooperative system a difficult procedure. Certain system tradeoffs (discussed in section 1.3) appear that have to be addressed by the system designer to ensure that cooperation does not deteriorate the overall system performance.

Advantages

First of all, cooperative systems can achieve path loss, diversity and multiplexing gains. Those gains lead to decreased transmission powers, higher capacity or better cell coverage [3].

Another basic advantage is the capability of providing almost equal Quality of Service (QoS) to all users in a cell, even to those who are at the cell edge or in shadowed areas.

Furthermore, the deployment of a system with relays does not require any infrastructure and is relatively easy. Also, it leads to reduced capital and operational costs as shown in [15].

Disadvantages

First of all, the presence of extra relay nodes in a system generates extra interference among the users of the cell and even among other cells. Thus, the path loss, diversity and multiplexing gains should be efficiently handled in order to decrease the transmission power of the relays to decrease interference.

Another disadvantage is the need for more complex schedulers. In a system with many users and relays the data generated by the relays also have to be scheduled resulting in the need for more sophisticated schedulers to perform the extra operations.

The extra traffic generated by the relays results in a decrease of the effective system throughput since more resources should be allocated to the relays. Moreover, the use of relays results in increased overhead, since the need of synchronization and extra security for the extra relayed data flows arise. Tight synchronization is required in the system leading to more expensive hardware and large protocol overheads [3].

Finally, it is the possible increased end-to-end latency, that the procedure of decoding the received signal, re-encoding it and retransmit it to the destination, may cause. This issue is very important for real-time services and should be addressed by novel decoding techniques.

1.3 Cooperative System Tradeoffs

From the advantages and disadvantages presented in section 1.2, it is clear that certain system tradeoffs arise. Those tradeoffs of the system parameters should be taken into account by the system designer so as to ensure that the cooperative scheme does not have any impact on the overall system performance. Some basic system tradeoffs are presented below:

- First, it is the capacity versus coverage tradeoff. It is well known that as a user moves further away of a base station, he achieves successively lower data rates due to the declining signal power received, until the SNR is too low for communication to be achieved. Cooperative systems allow coverage to be traded against capacity, thus the system designer should decide whether to boost the capacity or increase the coverage of the system.
- Second, it is the interference versus performance tradeoff. Decreasing the transmission power of the relays results in decreasing the interference but also in decreasing the capacity/coverage. Respectively, in order to increase the capacity or coverage higher transmit power is required which introduces additional interference in the system.
- The third tradeoff is that of algorithmic versus hardware complexity. Although relays do not require high costs and complexity in hardware in order to increase the coverage or capacity of a system, they require more complex scheduling algorithms as well as synchronization and handover algorithms.

- Finally, we come up against the deployment of the relays and the performance tradeoff. That is, the relays can be deployed in a planned or an unplanned manner. In the planned manner the placement of static relays is examined and given the system's parameters, this placement is optimized. This leads in higher performance but is a complex task. On the other hand, in the unplanned manner the relays can be either static or mobile and their placement is simplified and not extensively examined, resulting in decreased performance compared to the system with planned placed relays.

1.4 Application scenarios

Cooperative communications can be implemented into many real life application scenarios. In this section we present some basic scenarios, either in already established technologies or in novel systems, which reflect the importance of cooperation.

Cellular Networks

Cellular is a network that is comprised of adjacent cells, each served by a base station (BS). Each cell uses a different set of frequencies from neighboring cells, to avoid interference and provide guaranteed bandwidth within each cell. Today's cellular standards include GSM (Global System for Mobile Communications, originally Groupe Spécial Mobile) which was developed for second generation (2G) digital cellular networks used by mobile phones, and UMTS (Universal Mobile Telecommunications System) which is a third generation (3G) mobile cellular system. Recent standards in cellular networks are 3GPP LTE and WiMAX, in which cooperative communication and relay technologies will be widely used. Cooperation using relays in those two standards is briefly described in section 1.5.

The basic challenges of cellular networks are the increase of capacity and coverage as well as the decrease of interference. This can be achieved by the use of relays between the communication of a mobile station (MS) to the BS, as explained in the following bullets [16]:

- Capacity: Since each cell, for a given transmit power level, can provide sufficient capacity for a given number of users, the increase of the users connecting to a BS results in capacity reduction. Thus, a solution would be the increase of the density of the base stations. However, that will result in higher deployment costs and higher inter-cell interference. On the other hand, using relays confronts this problem and is also more cost effective.

- Coverage: Since the transmit power level of the BS is limited, MSs at the cell edge or in coverage holes may not receive sufficient power levels in order for communication to be achieved. However, the use of relays between MSs and the BS helps communication in such situations to become feasible.
- Interference: While the deployment of relays in a cell helps to increase the coverage and/or capacity, that should be properly used to lead in the decrease of the BS transmission power and hence the decrease of inter-cell interference. But, the inter-cell and intra-cell interference caused by the extra transmissions of the relays should be taken into account in order for the deployment of the relays to provide the desirable results.

Wireless Sensor Networks (WSN)

In recent years, these networks have attracted the wireless communications community attention and many proposals appeared which address the numerous challenges that came up [17-20]. Cooperative techniques with the use of relays may provide the solution to the problems that arise from the deployment of these networks [21-24].

Generally, a wireless sensor network is a network of sensor nodes which intend to sense/monitor physical or environmental phenomena such as temperature, humidity, sound etc. These sensor nodes are battery operated devices which have limited energy, limited processing capabilities and transmission range. Two are the major factors of the power consumption in a sensor node due to its electronics. The first is the amount of data to be transmitted and the second is the distance between the sensor node that transmits and its destination. The higher the amount of data and the transmission distance, the higher the power consumption required. The data generated by each sensor are gathered by a usually fixed BS. For sensor nodes that are further away from the BS, the intermediate nodes are used to forward the data to the BS.

Sensor nodes which relay data of other sensor nodes consume more energy because they need to transmit data in higher rates. An approach to solve this issue is the proper placement of relay nodes, whose task is only to relay the data generated by the sensor nodes to the BS. In that way, the lifetime of the network is prolonged because the load of the sensor nodes is decreased (hence less power consumption of the sensors is required). Moreover, the distance between a sensor and the destination is “shortened” resulting in less power consumption, because of the insertion of the relay node, which becomes responsible to relay the data to the BS.

The relay nodes which are also battery operated, can either have the same capabilities as the sensor nodes or higher capabilities in terms of transmission range, data processing and initial energy. A special category of sensor networks is the cluster-based sensor networks [25-28] in which the relay nodes have higher capabilities compared to the sensors and take the role of cluster heads [29]. A network with two clusters and two relay nodes is depicted in Figure 4. The sensors belong only in one cluster and send their data only through the relay of their cluster to the BS. The relays of each cluster help the sensors that cannot reach efficiently the BS to succeed that and also to avoid the long haul transmissions resulting in less power consumption.

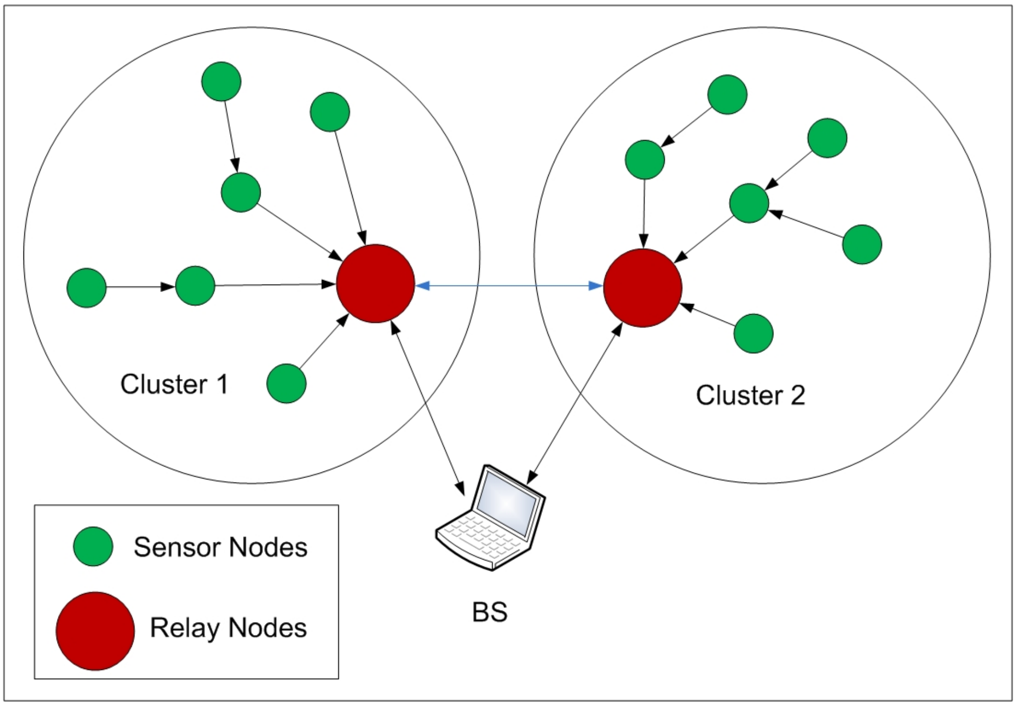

Figure 4: Wireless sensor network with two clusters and two relay nodes

Wireless Local Area Networks (WLAN)

In our days, WLANs which are based on the IEEE 802.11 standards are widely used in homes, offices, cafes, airports etc. As in cellular networks, many cooperative techniques and novel protocols have been proposed in order to boost capacity and increase the coverage of WLANs [30-35]. The optimum placement of the relays and the number of the hops (for which there is evidence that is only two on average) between a user and the access point (AP) is an open field for the research community.

Vehicle-to-Vehicle Communication

An emerging technology in the field of automobiles is Vehicle-to-Vehicle (V2V) communication. This technology implies that the moving vehicles exchange information, such as speed, position, traffic information etc, with each other and/or with roadside infrastructure. This information can be used primarily for safety reasons (warning for obstacles, intersections, accidents etc) but also for traffic management, driver assistance systems (parking the vehicle, lane keeping etc) and many more [36-40]. The cooperation between the vehicles can be enhanced by cooperative techniques which will offer higher reliability and link stability [41-44].

1.5 Standardization of cooperative communication

The idea of cooperation in a network has been adopted in recent standards such as IEEE 802.16j, Long Term Evolution (LTE)-Advanced and ETSI Cooperative Intelligent Transport Systems (C-ITS). In the following paragraphs we briefly discuss the use of relays and cooperation in general, proposed in those standards.

More specifically, IEEE 802.16j [45] incorporates relay capabilities in the foundation of IEEE 802.16e-2005 Worldwide Interoperability for Microwave Access (WiMAX) standard [46]. Its purpose is to expand previous single-hop 802.16 standards to include multi-hop capabilities. The relays used are divided in two categories: transparent and nontransparent. Transparent are the relays that serve the Mobile Stations (MSs) which are in range of the BS and can decode the control information of the BS. Thus, transparent relays are not required to transmit control information. Nontransparent relays serve MSs that cannot decode the control information from the BS because they are located at the edge of the cell. Thus, nontransparent relays have to transmit control information to the MS while the MS supposes that the relay is the BS [47]. Eventually, the use of relays may offer increment of the throughput for users at the cell edge and extension of the coverage in IEEE 802.16j systems.

In LTE-Advanced [48], which is specified by the 3rd Generation Partnership Project (3GPP), the relays are classified into inband or outband. Inband relays communicate to the base station (called eNB) and to the end user (called User Equipment, UE) over the same carrier frequency while outband relays do not. Moreover, relays are classified in transparent and nontransparent (like in IEEE 802.16j) depending on whether the UE is aware of communicating with the network via a relay or not. Furthermore, depending on the relay strategy, a relay may be part of the donor cell or control cells of its own. Eventually, the LTE-Advanced standard reckons that relaying is a tool to improve the coverage of high data rates, temporary network deployment, group mobility and throughput of users at the cell edge.

Finally, the standardization of vehicle-to-vehicle communication is in progress by ETSI organization with the project of C-ITS [49]. The basic characteristic of C-ITS is the sharing of data between vehicles and/or with roadside infrastructure as mentioned in section 1.4 This technology will lead to greater transport efficiency and increased safety also with major economic benefits.

Overall, the use of relays and generally cooperative communication technology in promising emerging wireless networks evince the advantages that cooperation may provide.

1.6 History of cooperative communications

The classical relay channel which is the main idea behind cooperative communications was introduced in 1968 by van der Meulen [50, 51]. In his work, communication channels with three terminals are considered and upper and lower bounds of the capacity of the relay channel are obtained. In 1979, Cover and Gamal [52] determined general lower and upper bounds to the capacity for various communication scenarios such as the degraded, reversely degraded and feedback relay channels. It is interesting to note that the capacity of such network configurations exceeds the capacity of a simple direct link and up till today many of these results cannot be superseded. However, the capacity of the general relay channel still remains unknown.

In 1981, Gamal [53] extends the previous work in order to derive the capacity of deterministic relay networks with no interference and in 1982 in [54] he presents the capacity of the semideterministic relay channel. Since then and up to the mid 1990s the activity in the relay channel area has decreased probably due to implementation problems.

In 1996, the concept of Opportunity Driven Multiple Access (ODMA) was introduced by European Telecommunication Standards Institute (ETSI) and in 1999 the UMTS Concept Group Epsilon proposed ODMA as a potential 3rd generation (3G) candidate [55]. The main target of ODMA as a communications relaying protocol is to increase the high data rate coverage of a cell using relays located within the cell. The proposal of ODMA did not get much of attention, despite the gains that were demonstrated, primarily due to the authorization required by the users to provide their own resources and the fact that it could not function as a standalone, always available, high capacity 3G system [56].

In 1998, Sendonaris [57] introduced the concept of cooperative relaying, that is the cooperation of in-cell users. A simple cooperation protocol is proposed that leads to an increase in capacity and to a more robust system. Extensions of this proposal by the same authors are, [6] in which a cooperation strategy for a conventional Code-Division Multiple-Access (CDMA) system is proposed and [7] in which practical issues related to the implementation of the system are investigated. The results of these works indicate that cooperation leads to the increase of the system throughput and cell coverage as well as to the decrease of the sensitivity to channel variations.

In 2000, Laneman [58] extended the work of [57] by developing energy-efficient transmission protocols based on decoding-and-forwarding and amplifying-and-forwarding relaying techniques. Those protocols exploit spatial diversity created by antenna sharing and offer diversity and outage gains. All previous works as well as Laneman's and his coworkers' later works [4, 5] in 2001 and 2004, made it clear that by using relay nodes in a wireless network we can exploit spatial diversity and thus obtain better data transmission from a source to a destination node. As a consequence, the area of cooperative communications started to flourish and many new cooperative schemes were proposed since then. Furthermore, the contributions of the Multiple Input Multiple Output (MIMO) systems and coding techniques have been fundamental for the growth of the cooperative communications research area.

The use of MIMO systems in a wireless communication network provides increased spectral efficiency (total number of information bits per second per Hertz transmitted) for a given total transmit power. That is achieved by introducing additional spatial channels that are exploited by using space-time coding [59]. Major contributions in the area of MIMO systems constitute the works by Foschini [60] and Telatar [61]. In these works it is shown that multi-antenna systems provide significant advantages over single antenna systems given the fact that the fades and noises at different receiving antennas are independent (uncorrelated and of different strength). The basis of the construction of coding techniques to be used in MIMO systems, are the works of Alamouti [62] and its mathematical enhancement by Tarokh [63] in which space-time block coding is introduced. Further studies in space-time coding schemes are [64-66] in which spatial diversity and coding gain is demonstrated.

1.7 Motivation – Network Level Cooperation

Most cooperative techniques studied so far concern gains that can be achieved on the physical layer. However, recent works [67-70], suggest that similar gains can be achieved with network-layer cooperation (or packet-level cooperation). By network-layer cooperation we refer to plain store-and-forward relaying without any physical layer considerations and processing.

Our work in this thesis focuses at the network-layer cooperation while taking into account the physical layer properties (fading and attenuation) and the MAC layer. More specifically, we consider two cases of cooperation which are briefly described in the following paragraphs.

- In the first case (analyzed in Chapter 2), we consider a network with N users-sources, two relay nodes and a common destination node. The users transmit packets to the destination with the cooperation of the two relays. The relays and the destination are equipped with single transceivers, so that they can decode packets successfully only from one transmitter at a time. That is, simultaneous transmission of two or more nodes of a network results in a collision (slotted ALOHA – collision model [12]). We obtain analytical expressions for the arrival and service rates of the queues of the two relays and we show that the probabilities of the two relays to attempt transmission do not depend on each other when the queues are stable. We study the impact of the deployment of the second relay node in terms of aggregate and per user throughput. We also present a topology of the system in which the users are divided into two clusters, and show its advantages in terms of aggregate and per user throughput. Moreover, we show that there is an optimum number of users that maximizes the aggregate throughput of the clustered system.
- In the second case (analyzed in Chapter 3), we again consider a network with N users-sources, two relay nodes and a common destination node with the difference that the relays and the destination have multi-packet reception (MPR) capabilities. That is, they are equipped with multiuser detectors, so that they can decode packets successfully from more than one transmitter at a time. It is known that a transmission is successful if the received signal to interference plus noise ratio (SINR) is above a certain threshold γ. We study three variations of the systems with two relays and show that all systems with two relays offer significant advantage as per aggregate and per user throughput, compared to the systems with one and no relay when the SINR threshold $\gamma>1$. We also show that there is an optimum number of users that maximizes the aggregate throughput of the systems with two relays.

1.8 Outline of thesis

This thesis is organized in two parts as follows:

In Chapter 2, we investigate the impact of the deployment of a second relay node in a cooperative communication scheme. The relay nodes relay packets from a number of users to a destination node. We assume that the two relays do not have packets of their own and the users have saturated queues and random access to the medium with slotted time. We consider the collision channel model which suggests that simultaneous transmission attempts by two or more nodes (source-users or relays) result in a collision. We obtain analytical expressions for the arrival and service rates of the queues of the two relays and the stability conditions. We also study a model of the system, in which the users are divided into two clusters. We quantify the above, analytically and through simulations, for different number of users and we indicate the conditions under which the deployment of a second relay in the system provides significant advantages.

In Chapter 3, we study a similar model as in the second part, with two relays that relay packets from a number of users to a destination, with the main difference being that the relays and the destination have Multi-Packet Reception (MPR) capabilities. We present three variations of a system with two relays and compare them with systems with no and one relay in terms of aggregate and per user throughput, average queue size (for the cases with relays) and average delay per packet. Finally, we examine under what conditions an interference cancellation technique can provide significant advantages in terms of aggregate throughput and what are the effects of the distance of the two clusters in terms of aggregate throughput.

Chapter 4 presents the conclusions of this thesis and our future work plans.

Chapter 2

Performance Issues of Multiple-Relay Cooperation

2.1 Introduction

In recent years, the study of the relay channel has gained a lot of interest in the wireless communications community. The relay channel which was initially introduced by van der Meulen [51] is the basic paradigm of cooperative communications, which are widely acknowledged to provide higher communication rates and reliability. The first information theoretic formulations were presented in [52]. While most works in this area concern gains achieved by cooperation on the physical layer (as we discussed in Chapter 1), recent works [67-70] suggest that similar gains can be achieved by network-layer cooperation. By network-layer cooperation we refer to plain relaying without any physical layer considerations.

More specifically, in [67, 68] cognitive cooperation is proposed in which the cognitive relay senses idle time slots to transmit. In [67], the impact of cooperative communications at the multiple-access layer with TDMA is studied. The cognitive relay tries to utilize the periods of source silence to cooperate with other users in the network. When the relay senses an empty slot forwards the packets of the users that were lost in previous transmissions. In [68], the secondary transmitter (of the cognitive system with two single-user links, the licensed and the unlicensed) acts as a "transparent" relay for the primary link. That is, packets that are not received correctly by the destination but are decoded correctly by the secondary transmitter are queued and forwarded to the destination by the secondary transmitter. While in [67] an extra relay is introduced which cooperates with the other users, in [69] it is the users that relay packets for other users, and it is shown that substantial performance improvement can be achieved without the cost of an extra node. Moreover, in [70] a three-node network with two users unicasting to a common destination over erasure channels is studied and a cooperative strategy is proposed. The stability region and the throughput region are characterized under scheduled access and random access and also network coding at the relay is performed for which is shown that does not lead to additional performance gains.

In [71] the impact of a single relay node on per user and aggregate throughput is investigated in a system in which the relay relays packets from a number of users to a destination node. Analytical expressions for the arrival and service rate of the relay's queue, the stability condition and the average length of the queue as functions of the probabilities of transmissions and the outage probabilities of the links are obtained.

In this Chapter, we investigate the impact of the insertion of a second relay node in a network where the relay nodes relay packets from a number of users to a destination node, and is an extension of [71]. We consider the case of a discrete-time slotted ALOHA (as we described in section 1.1.3) system [13] which represents the classical analysis of random multiple access schemes.

We make the assumptions mentioned in Chapter 1, namely that the users have saturated queues and random access to the medium with slotted time. The transmission of a packet takes the duration of exactly one time slot. Simultaneous transmission attempts by two or more nodes of the network result in a collision. The two relays do not have packets of their own, but assist the users by relaying their packets when necessary. The wireless link between any two nodes of the network is modeled as a Rayleigh narrowband flat-fading channel with additive Gaussian noise.

In order to obtain analytical expressions for the arrival and service rates of the queues of the two relays and also the stability conditions, we use the stochastic dominance technique [72]. That is because the two queues are coupled (i.e., the service process of each queue depends on whether the other queue is empty or not).

In addition, a topology of the system in which the users are divided into two clusters is presented. In this model the users of one cluster do not interfere with the users and the relay of the other cluster (of course, the relays are interfering with each other). This corresponds to the case of having the users in two distant areas, each area served by one relay. We study the impact of the two relay nodes of the two models (with and without clustering) on the aggregate throughput and the throughput per user when the queues of the two relays are stable.

We show that the probabilities of the two relays to attempt transmission do not depend on each other when the queues are stable. Also, the insertion of the second relay offers significant advantage when the users are divided into clusters and each cluster is assigned to a relay.

In section 2.2 we describe the system model. In section 2.3 we derive analytical expressions for the arrival and service rate of the relays' queues, the stability conditions of the queues, the stability region and the equation of the throughput per user along with the upper and lower bounds. In section 2.4 we present the analysis of the model with the users divided into two clusters and derive the expressions for the upper and lower bounds for the throughput per user. Finally, in section 2.5 we present arithmetic and simulation results and our conclusions are given in section 2.6.

2.2 System Model

2.2.1 Network Model

We consider a network with N source users, two relay nodes R1 and R2 and a common destination node d, as depicted in Figure 5 (with N = 2 users). The sources transmit packets to the destination with the cooperation of the two relays. We assume that the queues of the two users are saturated. The users have random access to the medium with no coordination among them. The channel is slotted in time and the transmission of a packet takes the duration of exactly one time slot. The acknowledgements (ACKs) of successful transmissions are instantaneous and error free.

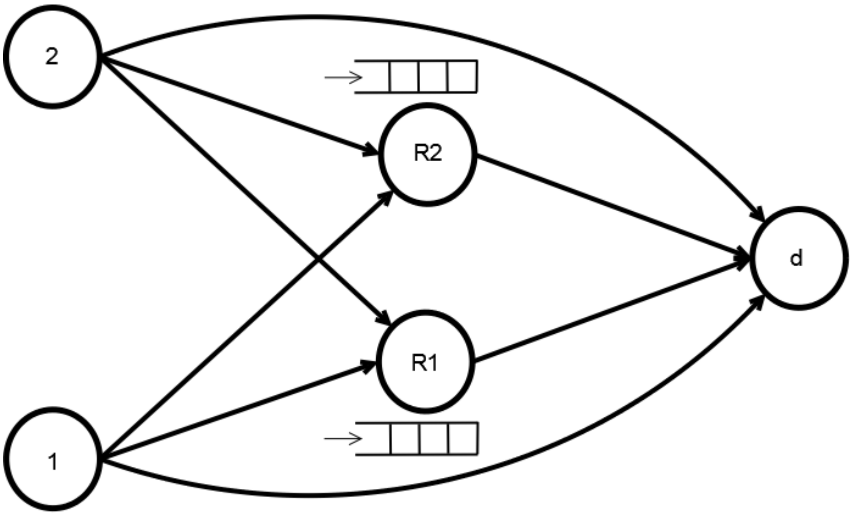

Figure 5: Two relay nodes with N=2 user nodes

The two relays do not have packets of their own. If a transmission of a user's packet to the destination fails, the relays store it in their queues and try to forward it to the destination at a next time slot. In case that both relays receive the same packet from a user, they choose randomly and with equal probability which will store it in its queue for subsequent transmission. We also assume that each node has a single transceiver and simultaneous transmission attempts by two or more nodes (source-users or relays) result in a collision.

The notation we consider throughout Chapter 2 is the following: The users and the relays (when they have packets in their queues) attempt to transmit with probabilities q_i, where $i = 1,2,...,N,R1,R2$. The relays transmit when their queues are not empty, and the probability that a relay node attempts transmission at time slot t is given by $q_{Ri}P(Q_{Ri}^t > 0)$, where $i = 1,2$.

2.2.2 Physical Layer Model

We model the link between two nodes i and j of the network as a Rayleigh narrowband flat-fading channel with additive Gaussian noise. Thus, the link has a specific outage probability which is derived as follows [73]:

The received SNR_{ij} for the link between nodes i and j is given by:

$$SNR_{ij} = \frac{|h_{ij}|^2 r_{ij}^{-\alpha} P}{n_0} \tag{1}$$

where, $|h_{ij}|^2$ is the square of the magnitude of the channel gain and has an exponential distribution with unity mean, P is the transmission power, r_{ij} is the distance between i and j, α is the path loss exponent and n_0 is the power of the additive white Gaussian noise.

We denote an outage event between nodes i and j operating with an SNR threshold equal to γ by:

$$O_{ij} = \{h_{ij} : SNR_{ij} < \gamma\} = \{h_{ij} : |h_{ij}|^2 < \gamma n_0 r_{ij}^{-\alpha} / P\} \tag{2}$$

And the probability of an outage in the link between nodes i and j with an SNR threshold equal to γ, is given by:

$$\Pr(O_{ij}) = \Pr(SNR_{ij} < \gamma) = 1 - \exp(-\gamma n_0 r_{ij}^{-\alpha} / P) \tag{3}$$

So, by p_{ij} we denote the success probability of a transmission between nodes i and j, which is given by:

$$p_{ij} = \Pr(\overline{O}_{ij}) = \exp(-\gamma n_0 r_{ij}^{-\alpha} / P) \tag{4}$$

2.3 Analysis

In this section we first demonstrate that the stability analysis of the system is difficult (because of the fact that the queues of the two relays are coupled). Next, using the stochastic dominance technique [72] we obtain analytical equations for the arrival and service rate of the two relays and also the stability region of the system. Finally, we derive the equation of the throughput per user.

2.3.1 Computation of Arrival and Service Rate

The service rate seen by relay $R1$ depends on whether Q_{R2} is empty or not.

- If $Q_{R2} = 0$ the service rate seen by relay $R1$ is:

$$P(Q_{R2} = 0) q_{R1} p_{R1d} \prod_{i=1}^{N} (1 - q_i) \tag{5}$$

- If $Q_{R2} \neq 0$ the service rate seen by relay $R1$ is:

$$P(Q_{R2} \neq 0)(1 - q_{R2}) q_{R1} p_{R1d} \prod_{i=1}^{N} (1 - q_i) \tag{6}$$

Thus, the average service rate seen by relay $R1$ is given by:

$$\mu_{R1} = q_{R1} p_{R1d} \prod_{i=1}^{N} (1 - q_i)[1 - q_{R2} P(Q_{R2} \neq 0)] \tag{7}$$

where, by Little's theorem [74], $P(Q_{R2} \neq 0) = \frac{\lambda_{R2}}{\mu_{R2}}$

This is true because we have removal of a packet from the queue of the relay $R1$, if it attempts to transmit and the transmission at the destination is successful, and all users as well as relay $R2$ remain silent.

Similarly, the average service rate seen by relay $R2$ is given by:

$$\mu_{R2} = q_{R2} p_{R2d} \prod_{i=1}^{N} (1 - q_i)[1 - q_{R1} P(Q_{R1} \neq 0)] \qquad (8)$$

where, $P(Q_{R1} \neq 0) = \frac{\lambda_{R1}}{\mu_{R1}}$

From Eq. 7 and 8 we can see that the average service rate of each queue depends on whether the other queue is empty or not, which makes the stability analysis difficult. So, we use the stochastic dominance approach to address this problem.

The stochastic dominance approach implies the construction of two hypothetical dominant systems. In the first system, denoted by $S1$, the relay $R1$ reverts to the transmission of "dummy packets" with the same probability, when its queue is empty. All the other characteristics and assumptions of the original system remain exactly the same. Similarly, in the second system $S2$ the relay $R2$ reverts to the transmission of "dummy packets" with the same probability, when its queue is empty.

Dominant System S1: Relay R1 transmits "dummy packets"

The service rate of relay $R1$ is given by Eq. 7. There is an arrival at the queue of relay $R1$ if relay $R2$ is silent, only one user transmits, and its transmission is successfully received by $R1$ but not by the destination and it is decided that $R1$ will keep the packet if both $R1$ and $R2$ receive it successfully. Thus, the arrival rate at relay $R1$ is given by:

$$\lambda_{R1} = \sum_{i=1}^{N} q_i p_{iR1} (1 - p_{id})(1 - q_{R1})(1 - q_{R2} \frac{\lambda_{R2}}{\mu_{R2}}) \prod_{j=1, j \neq i}^{N} (1 - q_j)[(1 - p_{iR2}) + \frac{1}{2} p_{iR2}] \qquad (9)$$

The service rate of relay $R2$ is given by:

$$\mu_{R2} = q_{R2} p_{R2d} (1 - q_{R1}) \prod_{i=1}^{N} (1 - q_i) \tag{10}$$

In order to obtain the arrival rate at relay $R2$ we follow the procedure described in [71]. The arrival rate of relay $R2$ depends on whether its queue is empty or not. If the queue is empty the arrival rate is denoted by $\lambda_{R2,0}$ and by $\lambda_{R2,1}$ if it is not. Thus, the mean arrival rate λ_{R2} is given by:

$$\begin{aligned} \lambda_{R2} &= P(Q_{R2} = 0)\lambda_{R2,0} + P(Q_{R2} > 0)\lambda_{R2,1} = \\ &= P(Q_{R2} = 0)\lambda_{R2,0} + (1 - P(Q_{R2} = 0))\lambda_{R2,1} \end{aligned} \tag{11}$$

If the queue of the relay $R2$ is empty then arguing as in Eq. 9 we can easily show that the probability of arrival $\lambda_{R2,0}$ is:

$$\lambda_{R2,0} = \sum_{i=1}^{N} q_i p_{iR2} (1 - p_{id})(1 - q_{R1}) \prod_{j=1, j \neq i}^{N} (1 - q_j)[(1 - p_{iR1}) + \frac{1}{2} p_{iR1}] \tag{12}$$

If the queue is not empty then the arrival rate is:

$$\lambda_{R2,1} = (1 - q_{R2})\lambda_{R2,0} \tag{13}$$

Figure 6 shows the Discrete Time Markov Chain with infinite states which describes the queue evolution of relay $R2$.

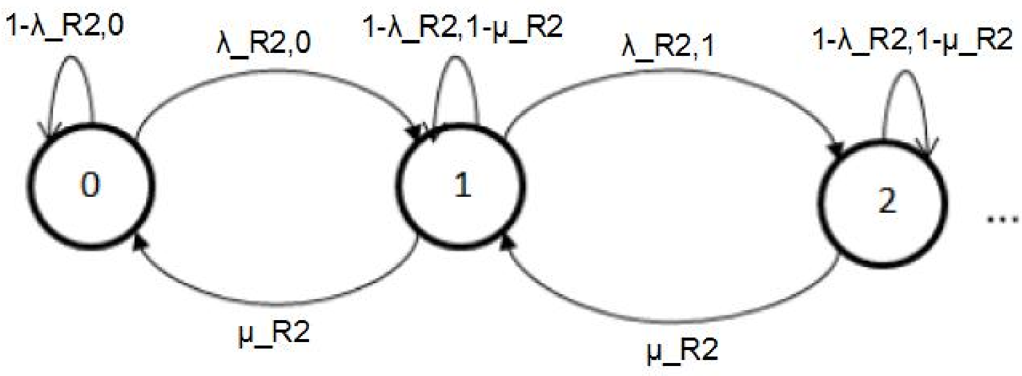

Figure 6: Markov Chain model of the queue of relay R2

By following exactly the same steps of [71] (with the appropriate symbols) we compute the probability that the queue of the relay $R2$ is empty. We use the balance equations as described in [74] in order to compute the stationary distribution π of the Markov Chain, with $\pi(i)$ denoting the probability of state i when the chain is in the steady state. As is well-known, the balance equations reflect the fact that the rate of entry into a state must equal the rate of departure from that state. Thus,

$$\lambda_{R2,0}\pi(0) = \mu_{R2}\pi(1) \Leftrightarrow \pi(1) = \frac{\lambda_{R2,0}}{\mu_{R2}}\pi(0) \tag{14}$$

And,

$$\begin{aligned}
&\pi(1)(\lambda_{R2,1} + \mu_{R2}) = \lambda_{R2,0}\pi(0) + \mu_{R2}\pi(2) \Leftrightarrow \\
&\Leftrightarrow \frac{\lambda_{R2,0}}{\mu_{R2}}\pi(0)(\lambda_{R2,1} + \mu_{R2}) = \lambda_{R2,0}\pi(0) + \mu_{R2}\pi(2) \Leftrightarrow \\
&\Leftrightarrow \pi(2) = \frac{\lambda_{R2,0}\lambda_{R2,1}}{\mu_{R2}^{2}}\pi(0) \qquad (15)
\end{aligned}$$

We can easily conclude that:

$$\pi(n) = \frac{\lambda_{R2,0}\lambda_{R2,1}^{n-1}}{\mu_{R2}^{n}}\pi(0) \tag{16}$$

Since:

$$\sum_{n=1}^{\infty}\pi(n)=1 \Leftrightarrow \pi(0)+\pi(0)\sum_{n=1}^{\infty}\frac{\lambda_{R2,0}\lambda_{R2,1}^{n-1}}{\mu_{R2}^{n}}=1 \qquad (17)$$

So, from Eq. 17 the expression for the probability of state 0 is given by:

$$\pi(0)=P(Q_{R2}=0)=\frac{\mu_{R2}-\lambda_{R2,1}}{\mu_{R2}-\lambda_{R2,1}+\lambda_{R2,0}} \qquad (18)$$

If $\lambda_{R2,1} < \mu_{R2}$

From Eq. 12, 13, 18 and 11 we have:

$$\begin{aligned}\lambda_{R2} &= P(Q_{R2}=0)\lambda_{R2,0}+(1-P(Q_{R2}=0))\lambda_{R2,1} = \\ &= \frac{\mu_{R2}-\lambda_{R2,1}}{\mu_{R2}-\lambda_{R2,1}+\lambda_{R2,0}}\lambda_{R2,0}+\left(1-\frac{\mu_{R2}-\lambda_{R2,1}}{\mu_{R2}-\lambda_{R2,1}+\lambda_{R2,0}}\right)\lambda_{R2,1} = \\ &= \frac{\mu_{R2}\lambda_{R2,0}}{\mu_{R2}-\lambda_{R2,1}+\lambda_{R2,0}} \qquad (19)\end{aligned}$$

Combining Eq. 11, 12, 13 and 19 we obtain the expression of the arrival rate λ_{R2} :

$$\begin{aligned}\lambda_{R2} &= \frac{\mu_{R2}\lambda_{R2,0}}{\mu_{R2}-\lambda_{R2,1}+\lambda_{R2,0}} = \frac{\mu_{R2}\lambda_{R2,0}}{\mu_{R2}-(1-q_{R2})\lambda_{R2,0}+\lambda_{R2,0}} = \frac{\mu_{R2}\lambda_{R2,0}}{\mu_{R2}+q_{R2}\lambda_{R2,0}} = \\ &= \frac{q_{R2}p_{R2d}(1-q_{R1})\prod_{i=1}^{N}(1-q_i)[\sum_{i=1}^{N}q_i p_{iR2}(1-p_{id})(1-q_{R1})\prod_{j=1,j\neq i}^{N}(1-q_j)[(1-p_{iR1})+\frac{1}{2}p_{iR1}]]}{q_{R2}p_{R2d}(1-q_{R1})\prod_{i=1}^{N}(1-q_i)+q_{R2}\sum_{i=1}^{N}q_i(1-p_{id})p_{iR2}(1-q_{R1})\prod_{j=1,j\neq i}^{N}(1-q_j)[(1-p_{iR1})+\frac{1}{2}p_{iR1}]} = \\ &= \frac{p_{R2d}\prod_{i=1}^{N}(1-q_i)[\sum_{i=1}^{N}q_i p_{iR2}(1-p_{id})(1-q_{R1})\prod_{j=1,j\neq i}^{N}(1-q_j)[(1-p_{iR1})+\frac{1}{2}p_{iR1}]]}{p_{R2d}\prod_{i=1}^{N}(1-q_i)+\sum_{i=1}^{N}q_i p_{iR2}(1-p_{id})\prod_{j=1,j\neq i}^{N}(1-q_j)[(1-p_{iR1})+\frac{1}{2}p_{iR1}]} \qquad (20)\end{aligned}$$

An interesting result that is derived by Eq. 20 is that the arrival rate λ_{R2} does not depend on q_{R2}, the probability of transmission of $R2$.

Dominant System S2: Relay R2 transmits "dummy packets"

By following exactly the same procedure as for the dominant system S1, we obtain the following expressions for μ_{R1}, λ_{R1}, μ_{R2} and λ_{R2}:

$$\mu_{R1} = q_{R1} p_{R1d} (1 - q_{R2}) \prod_{i=1}^{N} (1 - q_i) \tag{21}$$

$$\lambda_{R1} = \frac{p_{R1d} \prod_{i=1}^{N} (1 - q_i) [\sum_{i=1}^{N} q_i p_{iR1} (1 - p_{id})(1 - q_{R2}) \prod_{j=1, j \neq i}^{N} (1 - q_j) [(1 - p_{iR2}) + \frac{1}{2} p_{iR2}]]}{p_{R1d} \prod_{i=1}^{N} (1 - q_i) + \sum_{i=1}^{N} q_i p_{iR1} (1 - p_{id}) \prod_{j=1, j \neq i}^{N} (1 - q_j) [(1 - p_{iR2}) + \frac{1}{2} p_{iR2}]} \tag{22}$$

$$\mu_{R2} = q_{R2} p_{R2d} (1 - q_{R1} \frac{\lambda_{R1}}{\mu_{R1}}) \prod_{i=1}^{N} (1 - q_i) \tag{23}$$

$$\lambda_{R2} = \sum_{i=1}^{N} q_i p_{iR2} (1 - p_{id})(1 - q_{R1} \frac{\lambda_{R1}}{\mu_{R1}})(1 - q_{R2}) \prod_{j=1, j \neq i}^{N} (1 - q_j) [(1 - p_{iR1}) + \frac{1}{2} p_{iR1}] \tag{24}$$

It is interesting to note that in [72], the stability conditions obtained by the dominant systems are not merely sufficient, but sufficient and necessary for the stability of the original system. The proof relies on the *indistinguishability* argument which also applies in our case. By considering the properties of the dominant system S1, we can see that the queue sizes of the two relays cannot be smaller than those in the original system, provided the queues start with identical initial conditions in both systems. By Loynes' Theorem [75], the stability condition of a queue is given by $\lambda < \mu$. Therefore, given that $\lambda_{R2} < \mu_{R2}$, if for some λ_{R1} the queue $R1$ in the dominant system S1 is stable, then the queue is also stable in the original system. Conversely, if for some λ_{R1} in the dominant system S1 the queue $R1$ is unstable (exploding), then it will never transmit any "dummy packets" and since the queue does not empty, the dominant and the original systems behave identically and as a consequence, the queue is unstable in the original system as well. A more detailed analysis of the stochastic dominance approach and its proof is provided in Appendix A.

2.3.2 Conditions for the stability of the queues

In this sub-section we use the equations derived in the previous sub-section in order to obtain the q_{R1} and q_{R2} for which the queues of the two relays are stable. We do that by utilizing Loyne's criterion [75], which states that if the arrival and service processes of a queue are strictly jointly stationary and the average arrival rate is less than the average service rate, then the queue is stable. If not, the queue is unstable and the length of the queue approaches infinity almost surely.

1) For system S1: By invoking the Loyne's criterion the queue of the relay $R1$ is stable if and only if:

$$\lambda_{R1} < \mu_{R1} \Leftrightarrow q_{R1} > q_{R1,\min} \Leftrightarrow$$
$$\Leftrightarrow q_{R1} > \frac{\sum_{i=1}^{N} q_i p_{iR1}(1-p_{id}) \prod_{j=1, j\neq i}^{N} (1-q_j)[(1-p_{iR2}) + \frac{1}{2} p_{iR2}]}{\sum_{i=1}^{N} q_i p_{iR1}(1-p_{id}) \prod_{j=1, j\neq i}^{N} (1-q_j)[(1-p_{iR2}) + \frac{1}{2} p_{iR2}] + p_{R1d} \prod_{i=1}^{N} (1-q_i)} \quad (25)$$

So, the $q_{R1,\min}$ for which the queue is stable is given by:

$$q_{R1,\min} = \frac{\sum_{i=1}^{N} q_i p_{iR1}(1-p_{id}) \prod_{j=1, j\neq i}^{N} (1-q_j)[(1-p_{iR2}) + \frac{1}{2} p_{iR2}]}{\sum_{i=1}^{N} q_i p_{iR1}(1-p_{id}) \prod_{j=1, j\neq i}^{N} (1-q_j)[(1-p_{iR2}) + \frac{1}{2} p_{iR2}] + p_{R1d} \prod_{i=1}^{N} (1-q_i)} \quad (26)$$

From Eq. 26 we observe that q_{R1} does not depend on q_{R2}. The queue of the relay $R1$ is stable if q_{R1} satisfies the inequality:

$$q_{R1,\min} < q_{R1} < 1 \quad (27)$$

2) For system S2: Following exactly the same procedure as for system S1, we obtain expressions and bounds for q_{R2} and $q_{R2,\min}$ similar to Eq. 25 and 26 respectively with $R1$ and $R2$ interchanged. That is:

$$\lambda_{R2} < \mu_{R2} \Leftrightarrow q_{R2} > q_{R2,\min} \Leftrightarrow$$

$$q_{R2} > \frac{\sum_{i=1}^{N} q_i p_{iR2}(1-p_{id}) \prod_{j=1,j\neq i}^{N} (1-q_j)[(1-p_{iR1})+\frac{1}{2}p_{iR1}]}{\sum_{i=1}^{N} q_i p_{iR2}(1-p_{id}) \prod_{j=1,j\neq i}^{N} (1-q_j)[(1-p_{iR1})+\frac{1}{2}p_{iR1}]+p_{R2d}\prod_{i=1}^{N}(1-q_i)} \tag{28}$$

And,

$$q_{R2,\min} = \frac{\sum_{i=1}^{N} q_i p_{iR2}(1-p_{id}) \prod_{j=1,j\neq i}^{N} (1-q_j)[(1-p_{iR1})+\frac{1}{2}p_{iR1}]}{\sum_{i=1}^{N} q_i p_{iR2}(1-p_{id}) \prod_{j=1,j\neq i}^{N} (1-q_j)[(1-p_{iR1})+\frac{1}{2}p_{iR1}]+p_{R2d}\prod_{i=1}^{N}(1-q_i)} \tag{29}$$

Similarly to system S1, we observe that q_{R2} does not depend on q_{R1}. The queue of the relay $R2$ is stable if q_{R2} satisfies the inequality:

$$q_{R2,\min} < q_{R2} < 1 \tag{30}$$

The “indistinguishability” argument holds here as well.

2.3.3 Stability region ($\lambda_{R1},\lambda_{R2}$)

Generally, the stability region of the system is defined as the set of arrival rate vectors $\lambda = (\lambda_{R1},\lambda_{R2})$ for which the queues in the system are stable. Thus, the stability region of the two queues of the two relays is defined by the following equations derived from the dominant systems S1 and S2.

From system S1 we have:

$$\lambda_{R1} < \mu_{R1} \Leftrightarrow \lambda_{R1} < q_{R1} p_{R1d} (1 - q_{R2} \frac{\lambda_{R2}}{\mu_{R2}}) \prod_{i=1}^{N} (1 - q_i) \quad (31)$$

$$\lambda_{R2} < \mu_{R2} \Leftrightarrow \lambda_{R2} < q_{R2} p_{R2d} (1 - q_{R1}) \prod_{i=1}^{N} (1 - q_i) \quad (32)$$

From system S2 we have:

$$\lambda_{R1} < \mu_{R1} \Leftrightarrow \lambda_{R1} < q_{R1} p_{R1d} (1 - q_{R2}) \prod_{i=1}^{N} (1 - q_i) \quad (33)$$

$$\lambda_{R2} < \mu_{R2} \Leftrightarrow \lambda_{R2} < q_{R2} p_{R2d} (1 - q_{R1} \frac{\lambda_{R1}}{\mu_{R1}}) \prod_{i=1}^{N} (1 - q_i) \quad (34)$$

Thus, the stability region of the system is shown in Figure 7:

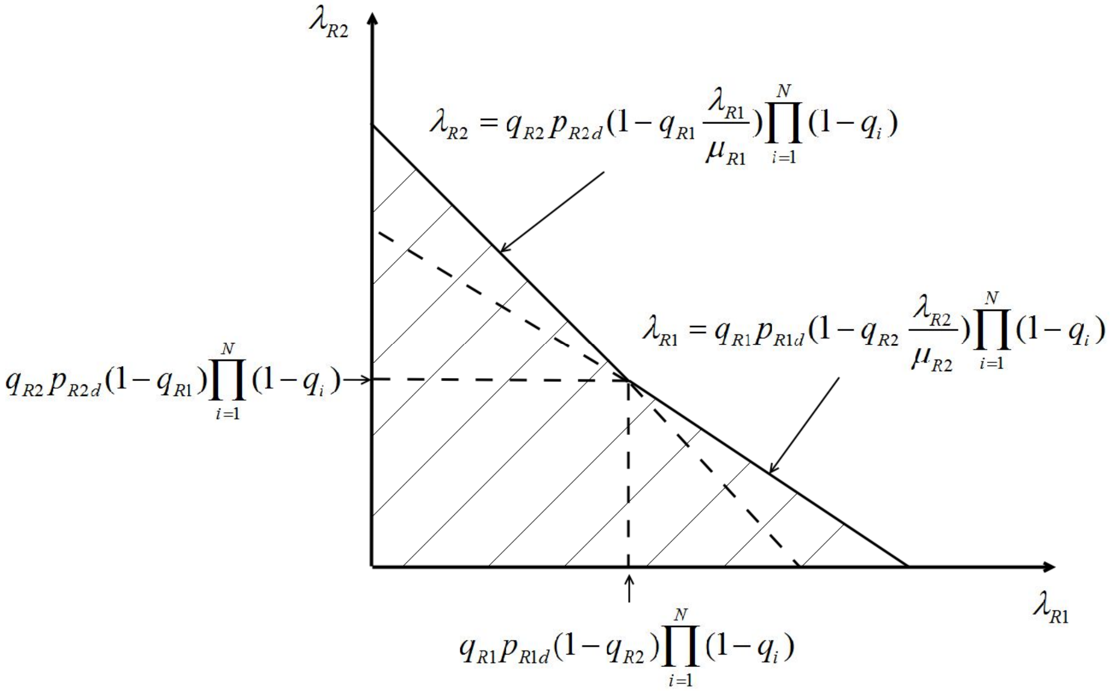

Figure 7: Stability region of the system

2.3.4 Throughput per user

There is a departure of a packet from a node if it transmits whereas the two relays and all the other users are silent, and its transmission is either successfully received by the destination or if unsuccessful, it is successfully received by $R1$ or $R2$. Thus, the throughput rate μ_i for the user i is given by:

$$\begin{aligned}\mu_i &= q_i(1-q_{R1}P(Q_{R1}>0))(1-q_{R2}P(Q_{R2}>0))\prod_{i=1}^{N}(1-q_i) \\ &\quad [p_{id}+(1-p_{id})p_{iR1}(1-p_{iR2})+(1-p_{id})(1-p_{iR1})p_{iR2}+(1-p_{id})p_{iR1}p_{iR2}]= \\ &= q_i(1-q_{R1}P(Q_{R1}>0))(1-q_{R2}P(Q_{R2}>0))\prod_{j=1,j\neq i}^{N}(1-q_j)[p_{id}+(1-p_{id})(p_{iR1}+(1-p_{iR1})p_{iR2})] \qquad (35)\end{aligned}$$

We assume that the two queues are stable so that the arrival rate from each user to the queues of the relays is the contributed throughput from it. We observe that the throughput per user depends on whether both queues are empty or not. So, it is difficult to find an explicit expression of the throughput per user in terms of the parameters of the model. Instead, we will find an upper and a lower bound and by simulation we will study the tightness of these bounds.

In order to find an upper bound, we will consider the case when the two relays do not relay any packets they receive from the users. This provides an upper bound because if the relays remain silent, the interference in the system is less and thus we get higher throughput per user (=rate of packets departing from each user). This upper bound is given by:

$$\mu_{i,upper} = q_i\prod_{j=1,j\neq i}^{N}(1-q_j)[p_{id}+(1-p_{id})(p_{iR1}+p_{iR2}-p_{iR1}p_{iR2})] \qquad (36)$$

In order to find a lower bound, we will assume that the two relays always transmit packets, possibly “dummy packets”, and the bound is given by:

$$\begin{aligned}\mu_{i,lower} &= q_i(1-q_{R1})(1-q_{R2})\prod_{j=1,j\neq i}^{N}(1-q_j)[p_{id}+(1-p_{id})(p_{iR1}+p_{iR2}-p_{iR1}p_{iR2})]= \\ &= \mu_{i,upper}(1-q_{R1})(1-q_{R2}) \qquad (37)\end{aligned}$$

In Figure 8 we present the upper, lower and simulation throughput per user with values of q_{R1} and q_{R2} (shown in Table 2) which are slightly higher (plus about 0.01) than $q_{R1,\min}$ and $q_{R2,\min}$ (shown in Table 1), for 1 to 20 users in the system. We assume that we have symmetric users which have the same link characteristics and transmission probabilities, that is: $p_{iR1} = p_{iR2} = 0.9$, $p_{R1d} = p_{R2d} = 0.9$, $p_{id} = 0.25$, $q_{R1} = q_{R2} = 0.85$, $q_i = 0.25, i = 1,\ldots,N$.

Table 1 presents the $q_{R1,\min}$ and $q_{R2,\min}$ for 1 to 20 users calculated by Eq. 26 and 29. We observe that the values are the same because we assume symmetric users.

Number of Users	$q_{R1,\min} = q_{R2,\min}$
1	0.120879120879121
2	0.215686274509804
3	0.292035398230089
4	0.354838709677419
5	0.407407407407407
6	0.452054794520548
7	0.490445859872612
8	0.523809523809524
9	0.553072625698324
10	0.578947368421053
11	0.601990049751244
12	0.622641509433962
13	0.641255605381166
14	0.658119658119658
15	0.673469387755102

16	0.6875
17	0.700374531835206
18	0.712230215827338
19	0.72318339100346
20	0.733333333333333

Table 1: Values of $q_{R1,\min}$ and $q_{R2,\min}$ obtained from Eq. 26 and 29 for 1 to 20 users

So, in order for the queues of the two relays to be stable, we must have $q_{R1} > q_{R1,\min}$ and $q_{R2} > q_{R2,\min}$. Table 2 presents the values of q_{R1} and q_{R2} that were used in order to calculate the lower bound of the throughput per user from Eq. 37 and also in the simulation. We use slightly greater $q_{R1} > q_{R1,\min}$ and $q_{R2} > q_{R2,\min}$ as of the values presented in Table1.

Number of Users	$q_{R1} = q_{R2}$
1	**0.13 >** 0.120879120879121
2	**0.22 >** 0.215686274509804
3	**0.3 >** 0.292035398230089
4	**0.355 >** 0.354838709677419
5	**0.41 >** 0.407407407407407
6	**0.46 >** 0.452054794520548
7	**0.5 >** 0.490445859872612

8	**0.53 >** 0.523809523809524
9	**0.56 >** 0.553072625698324
10	**0.58 >** 0.578947368421053
11	**0.61 >** 0.601990049751244
12	**0.63 >** 0.622641509433962
13	**0.65 >** 0.641255605381166
14	**0.66 >** 0.658119658119658
15	**0.68** > 0.673469387755102
16	**0.69 >** 0.6875
17	**0.71** > 0.700374531835206
18	**0.72** > 0.712230215827338
19	**0.73** > 0.72318339100346
20	**0.74** > 0.733333333333333

Table 2: Values of q_{R1} and q_{R2} used to calculate lower bound by Eq. 37 and in simulation

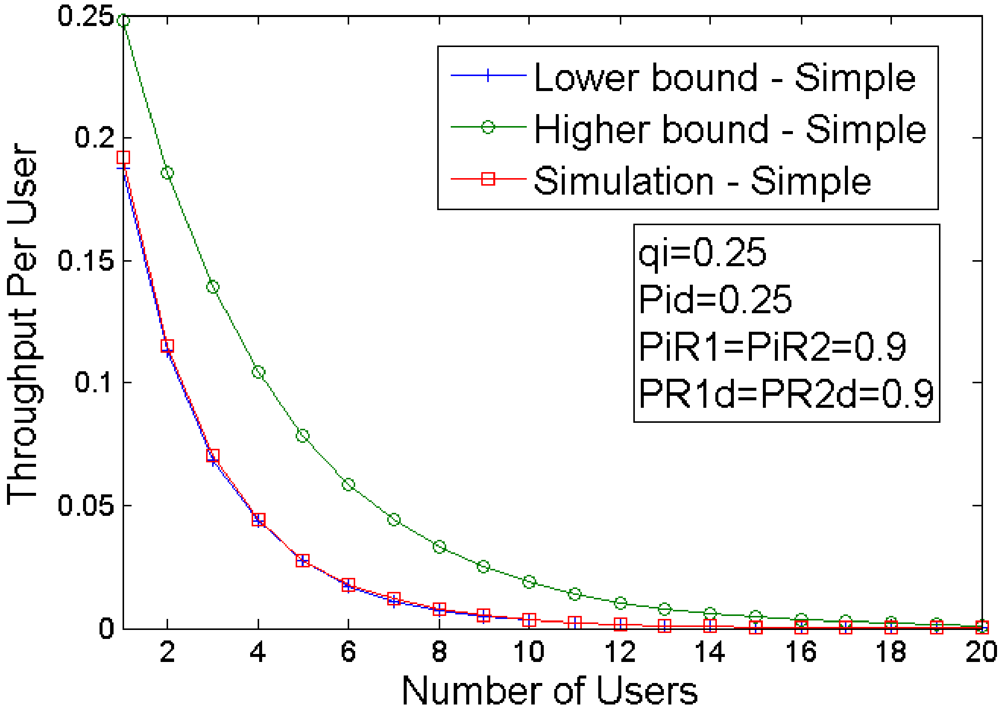

Figure 8: Lower, upper and simulation throughput per user vs number of users, for the minimum q_{R1} and q_{R2}

From Figure 8 we observe that the simulation gave almost the same (slightly higher) throughput per user as compared to the lower bound given by Eq. 37. This means that the two relays have packets to transmit in their queues in almost every timeslot. Thus, we encounter a very large number of collisions in the system leading in degraded performance. In order to improve the performance of the system we present a topology of the system described in the next section 2.4, in which the users are divided into two clusters.

2.4 Improving Throughput per User by Dividing Users into Clusters

In order to improve the throughput per user of the system, we divide the users into two clusters served by relays $R1$ and $R2$. A possible topology of the system is depicted in Figure 9. We assume that due to the distance between clusters the users of the one cluster do not interfere with the users of the other cluster at their relay. If two users transmit simultaneously we will have a collision at the destination. We also assume that when a relay transmits simultaneously with the users, the users' transmissions do not affect the relay's transmission to the destination whereas their transmissions to the destination fail. That is because of the shorter distance between the relay and the destination and also the higher transmit power of the relay compared to that of the users'. Furthermore, when both relays transmit simultaneously we have a collision at the destination. We divide the users equally to both clusters and we assume that each cluster has N_k users with k=1, 2 where $N_1 = N_2 = N/2$.

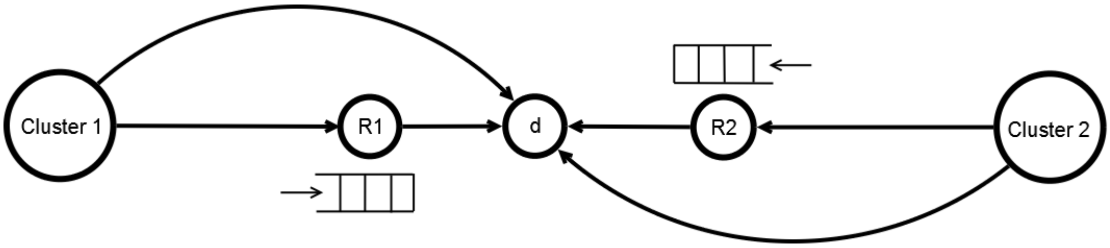

Figure 9: Network with two relay nodes and two clusters of users

The throughput per user of the system described depends again on whether both queues are empty or not. Thus, we find an upper and a lower bound and we will show that the results of the simulation of that system lie between those two bounds.

The upper bound of the throughput per user i of cluster k is given by:

$$\mu_{i,k,upper} = q_i p_{id} \prod_{j=1, j\neq i}^{N} (1-q_j) + q_i (1-p_{id}) p_{iRk} \prod_{j=1}^{N_k} (1-q_j) \tag{38}$$

And the lower bound is given by:

$$\begin{aligned}\mu_{i,k,lower} &= q_i (1-q_{R1})(1-q_{R2}) p_{id} \prod_{j=1, j\neq i}^{N} (1-q_j) + q_i (1-q_{R1})(1-q_{R2})(1-p_{id}) p_{iRk} \prod_{j=1}^{N_k} (1-q_j) = \\ &= \mu_{i,k,upper} (1-q_{R1})(1-q_{R2})\end{aligned} \tag{39}$$

2.5 Arithmetic and Simulation Results

In this section, we present arithmetic results for the per user and aggregate throughput of the systems with two stable relays described in sections 2.3 and 2.4. We first verify that the throughput per user for the cases of two relays lies between the upper and lower bounds given by Eq. 36, 37 and 38, 39. Then, we compare these two cases with the system without relay and the system with one relay.

To simplify the presentation we consider the case where all the users and relays of the system described in section 2.3 have the same link characteristics and transmission probabilities, that is: $p_{iR1} = p_{iR2} = 0.9$, $p_{R1d} = p_{R2d} = 0.9$, $p_{id} = 0.25$, $q_{R1} = q_{R2} = 0.85$, $q_i = 0.25, i = 1,...,N$. Also, for the system described in section 2.4 the relays and the users of the two clusters have the same link characteristics and transmission probabilities: $p_{iR1} = 0.9,\ i = 1,...,N1$ and $p_{jR2} = 0.9,\ j = 1,...,N2$, $p_{R1d} = p_{R2d} = 0.9$, $q_{R1} = q_{R2} = 0.85$, $q_i = 0.25, i = 1,...,N$. The results presented below have been verified with extensive simulations in Matlab which confirmed the accuracy of the analysis in the previous sections. Brief notes about the code in Matlab are provided in Appendix B.

2.5.1 Throughput per User for Systems with 2 Relays

Figures 10 and 11, present the throughput per user versus the number of users of the simple system described in section 2.3 and the clustered system described in section 2.4.

As expected the simulations lie between the lower and the upper bounds defined in previous sections. In Figure 10, as the number of the users in the system increases, we see that the throughput per user tends to the lower bound, while in Figure 11, the throughput per user tends to the upper bound. Thus, we have better utilization of the system with clustering.

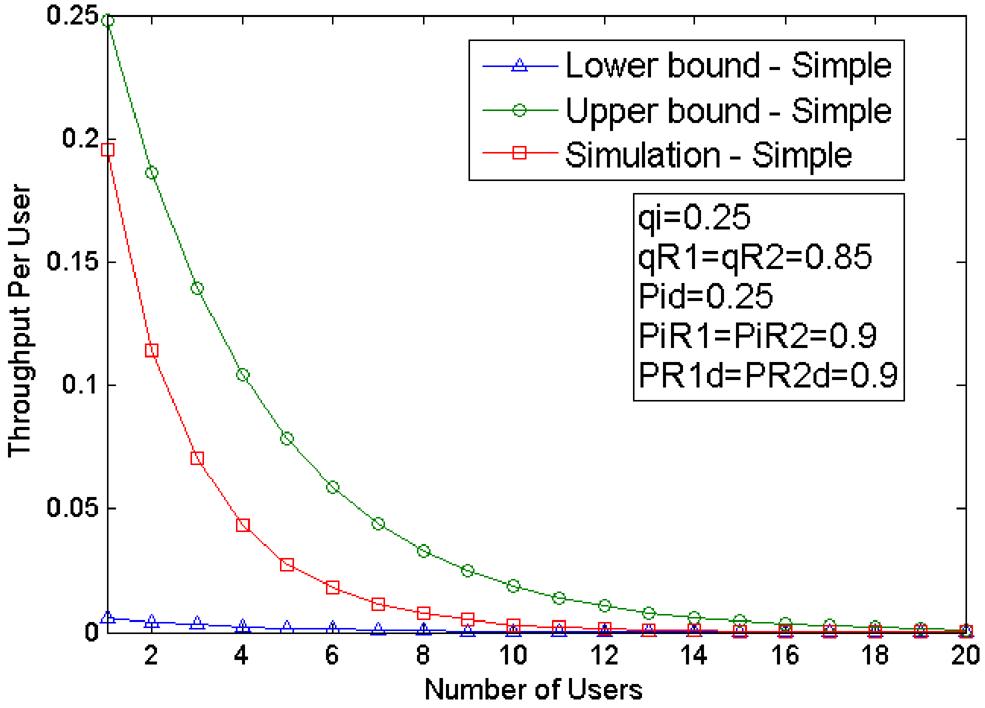

Figure 10: Lower, upper and simulation throughput per user vs number of users for simple network

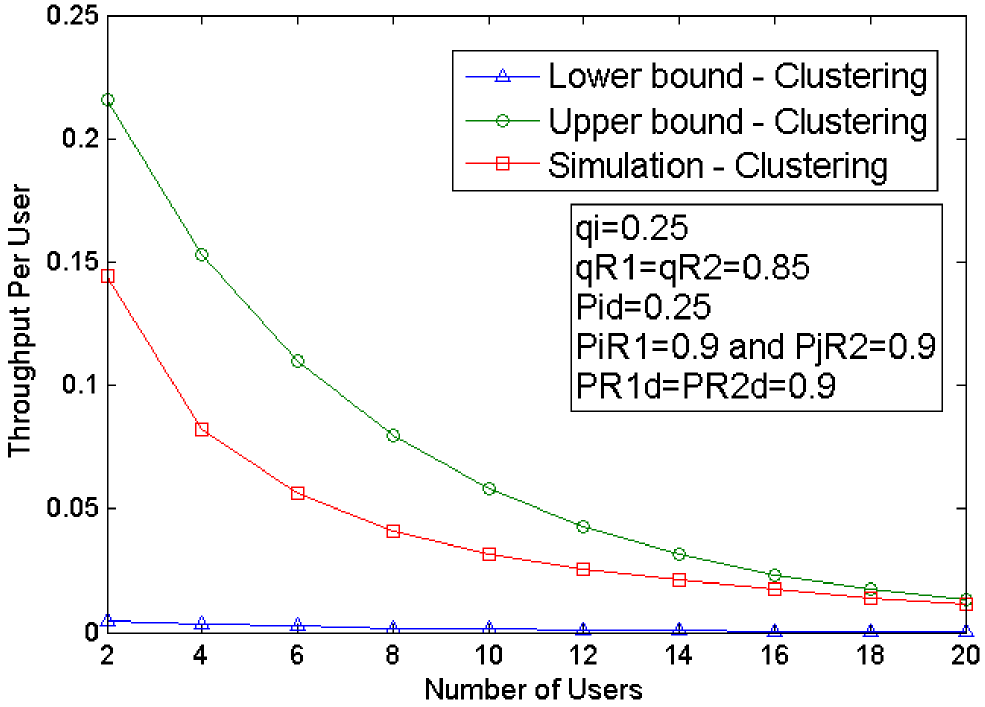

Figure 11: Lower, upper and simulation throughput per user vs number of users for network with clustering

2.5.2 Impact of Insertion of a Second Relay in the System

Figures 12 and 13, present the aggregate and per user throughput versus the number of users for the cases of no relay, one relay and two relays (with and without clustering), obtained by simulations.

We observe that the simple system with two relays does not offer any advantage over the system with one relay. This is expected because the insertion of a second relay with high probability to attempt transmission when its queue is not empty generates more interference in the system. However, the system with two relays and clustering offers significant advantage over the system with one relay (more than 300% higher aggregate throughput in our specific setup).

It is interesting to note that given the link characteristics and the transmission probabilities there is an optimum number N_{max} of users that maximizes the aggregate throughput of the clustered system. This number could be used to allocate the users among the relays.

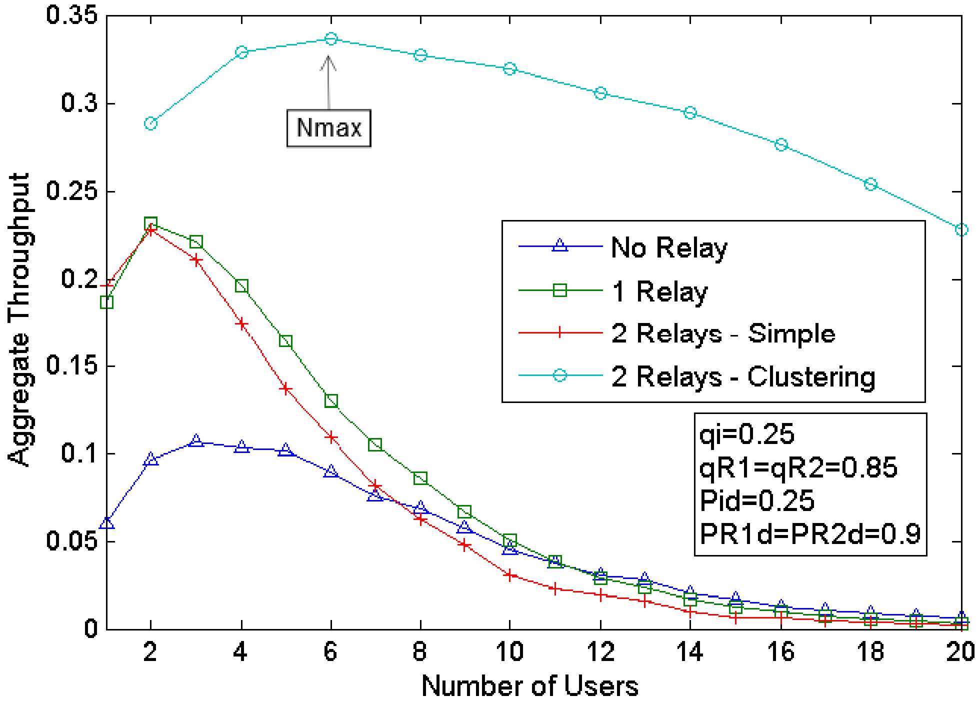

Figure 12: Aggregate throughput vs number of users

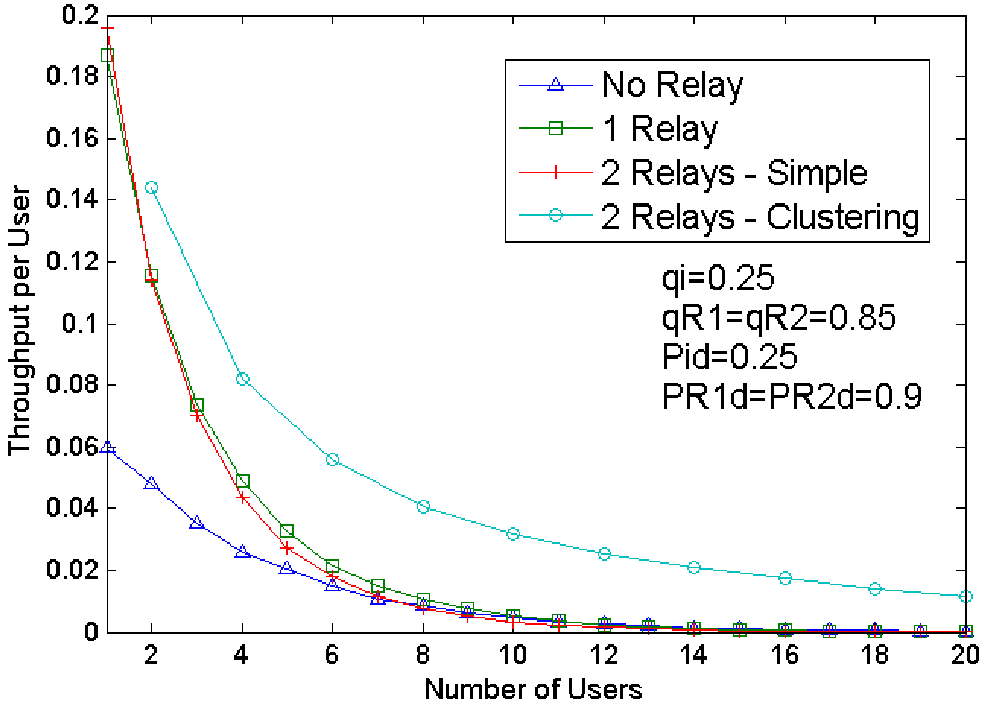

Figure 13: Throughput per user vs number of users

2.6 Conclusions

In this chapter, we examine the operation of two nodes assisting the communication of a number of users to a common destination by relaying (when necessary) their packets. We obtain analytical expressions for the arrival and service rates of the queues of the two relays and also the stability conditions. We present a topology of the system in which the users are divided into two clusters and study the impact of clustering on the per user and aggregate throughput.

We show that the two relays are free to choose their transmission probabilities independently from each other, provided that these are greater from some minimum values which guarantee the stability of their queues. It is interesting to note that the insertion of a second relay in a system generally does not offer higher throughput per user in comparison to a system with one relay, but the system in which the users are divided into two clusters separated by some distance offers significant advantage. Moreover, there is an optimum number N_{max} of users that maximizes the aggregate throughput of the clustered system.

These results could be used to allocate the users among the relays for example in cellular and sensor networks. Future extensions of this work will include users with non-saturated queues and relays with their own packets and priorities for the users. An extension of this model in which the relays and the destination have multi-packet reception (MPR) capabilities is presented in Chapter 3.

Chapter 3

Performance Issues of Multiple-Relay Cooperation with Multi-Packet Reception (MPR) Capabilities

3.1 Introduction

As we mentioned in previous chapters, recent works [67-70] suggest that network-layer cooperation can achieve similar gains to cooperation at the physical layer.

In [71], the impact of a single relay node on per user and aggregate throughput is investigated in a system in which a relay node relays packets from a number of users to a destination node. In that work a random access scheme with collision channel model with erasures is considered. In Chapter 2 we presented an extension of [71] in which the impact of the insertion of a second relay node in a network where the relay nodes relay packets from a number of users to a destination node is investigated.

Recently, random access with Multi-Packet Reception (MPR) capabilities has attracted attention [76-79]. In [76], the notion of MPR was introduced and two important theorems for the slotted ALOHA network with MPR are provided. The seminal paper [77] was the first to examine MPR as an interaction between the physical and medium access control layers for a wireless random access network. In [78], the authors specify a general asymmetric MPR model and the medium access control capacity region. They consider the effect of MPR on stability and delay of slotted Aloha based random-access system and it is shown that the stability region undergoes a phase transition from a concave region to a convex polyhedral region as the MPR capability improves in a two-user system. Finally, an overview of MPR-related research work covering the theoretically proved impacts and advantages of using MPR from a channel perspective to network capacity and throughput, the various technologies that enable MPR from transmitter, transceiver, and receiver perspectives and previous work on protocol improvement to better exploit MPR, is provided in [79].

In [80], the impact of a relay node to a network with a finite number of users-sources and a destination node is investigated. In this network the relay and the destination nodes have MPR capabilities, and it is an extension of [71]. Analytical equations for the characteristics of the relay's queue such as average queue length, stability conditions etc. are obtained.

In this chapter, we investigate the impact of the insertion of a second relay node in a network where the relay nodes relay packets from a number of users to a destination node, and is an extension of previous works [71, 80] and our work in Chapter 2. The main difference from the model studied in Chapter 2 is that here we assume that the relays and the destination are equipped with multiuser detectors, so that they can decode packets successfully from more than one transmitter at a time (MPR capability).

We assume as before that the users have saturated queues and random access to the medium with slotted time and each transmission of a packet takes the duration of exactly one time slot. The wireless link between any two nodes of the network is modeled as a Rayleigh narrowband flat-fading channel with additive Gaussian noise. A node's transmission is successful if the received Signal to Interference plus Noise Ratio (SNIR) is above a threshold γ. The two relays do not have packets of their own, but assist the users by relaying their packets when necessary.

Due to the fact that the queues of the two relays are coupled (i.e. the service process of each queue depends on whether the other queue is empty or not), the stability analysis and the derivation of analytical expressions for the characteristics of the relays' queues such as arrival and service rate, is a difficult task. Thus, in this chapter we perform extensive simulations using the Matlab tool in order to investigate the performance of the two-relay system. A brief description of the Matlab code is provided in Appendix B.

We show that the use of two relays offers significant advantage in terms of aggregate and per user throughput compared to systems with one and no relay, for values of SINR threshold $\gamma>1$. We also present a topology of the system in which the users are divided into two distant clusters and study the impact on the aggregate and per user throughput compared to the cases of no relay, one relay and two variations of two relays' operation (a packet received by both relays is either kept by both relays or by the one with the smaller queue) in the system. Furthermore, we present a way to verify if the queues of the relays are stable and compare the average queue size and the average delay per packet of all the systems presented. Finally, we present the conditions under which an interference cancellation technique in the systems with two relays provides higher aggregate throughput and what are the effects of the distance of the two clusters in terms of aggregate throughput.

In section 3.2 we describe the system model and in section 3.3 we present the simulation results for various cases. Finally, our conclusions are given in section 3.4.

3.2 System Model

3.2.1 Network Model

We consider a network with N source users, two relay nodes R1 and R2 and a common destination node d, as depicted in Figure 14 (with N = 2 users). The sources transmit packets to the destination with the cooperation of the two relays. We assume that the queues of the two users are saturated. The users have random access to the medium with no coordination among them. The channel is slotted in time and the transmission of a packet takes the duration of exactly one time slot. The acknowledgements (ACKs) of successful transmissions are instantaneous and error free.

The two relays do not have packets of their own and the queue length of the relays has infinite capacity. If a transmission of a user's packet to the destination fails, the relays store it in their queues and try to forward it to the destination at a next time slot. Each of the receivers (relays and destination) is equipped with multiuser detectors, so that they may decode packets successfully from more than one transmitter at a time. Nodes cannot transmit and receive at the same time.

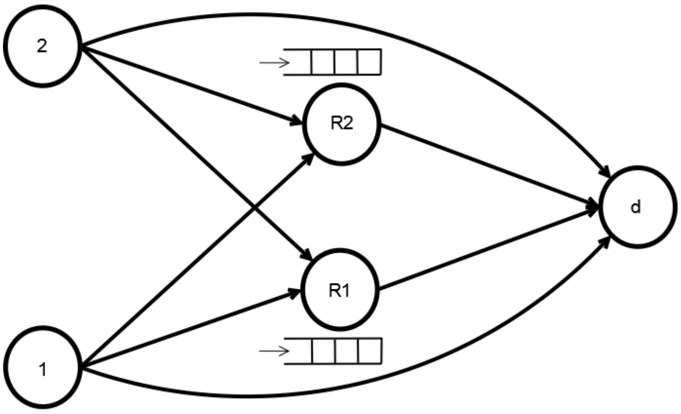

Figure 14: Two relay nodes with N=2 user nodes

3.2.2 Physical Layer Model

The MPR channel model considered in this chapter is a generalized form of the packet erasure model [80]. In the wireless environment a node's transmission is successful if the SINR is above a certain threshold. More specifically, if there exists a set of T nodes transmitting in the same time slot and $P_{rx}(i,j)$ is the signal power received from node i at node j (when i transmits), then the SINR(i,j) determined by node j is given by:

$$SINR(i,j) = \frac{P_{rx}(i,j)}{n_j + \sum_{k \in T \setminus \{i\}} P_{rx}(k,j)} \tag{1}$$

Where n_j is the receiver noise power at j.

We assume that a packet transmitted by i is successfully received by j if and only if $SINR(i,j) \geq \gamma_j$, where γ_j is a threshold characteristic of node j. Moreover, the wireless channel is subject to fading. Let $P_{tx}(i)$ be the transmitting power of node i and r(i,j) be the distance between i and j. Then, the power received by j when i transmit is:

$$P_{rx}(i,j) = A(i,j)g(i,j) \tag{2}$$

Where A(i,j) is a random variable representing channel fading and under Rayleigh fading it is exponentially distributed [73]. The receiver power factor g(i,j) is given by:

$$g(i,j) = P_{tx}(i)(r(i,j))^{-\alpha} \tag{3}$$

Where α is the path loss exponent with typical values between 2 and 4.

Thus, in the simulations presented in this chapter we calculate the SINR in every link (nodes-destination, nodes-relays and relays-destination) of the network and given a certain value of threshold γ for the SINR, we decide whether a transmission of a packet between two nodes is successful or not.

3.3 Simulations and Results

In this section, we use several techniques for the network with two relays presented in section 3.2 in order to compare it with networks with one and no relay in terms of aggregate throughput, throughput per user, average delay per packet and average queue size.

Moreover, we use an interference cancellation technique between the two relays in order to decrease the interference and increase the aggregate throughput of the network.

3.3.1 Impact of the Insertion of a Second Relay in the System

In this sub-section, we present the aggregate throughput obtained by simulations for the cases of no relay, one relay and two relays in the system and for different values of threshold γ. As mentioned in section 3.2.2 the simulations were performed by calculating the SINR in every link (nodes-destination, nodes-relays and relays-destination) of the network when a node transmits, and given a certain value of threshold γ for the SINR, we decide whether a transmission of a packet between two nodes is successful or not. To simplify the presentation we consider the case where all the users have the same link characteristics and transmission probabilities. An example topology of such a network with N users is depicted in Figure 15.

It is important to note that for the system with two relays described in this sub-section, we assume that if both relays receive successfully a packet from the same user, they both forward it to the destination.

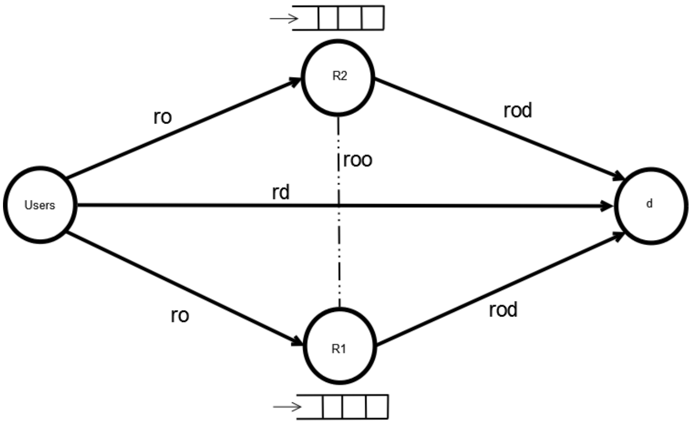

Figure 15: Two relay nodes with N users with same link characteristics and transmission probabilities

The parameters used in the simulations for each of the three cases are the following (obviously not all parameters exist in every system):

- Distance between users-destination: **rd=101m**
- Distance between users-relays: **ro= 58.738m**
- Distance between relays-destination: **rod= 58.738m**
- Distance between the two relays: **roo=60m**
- Path loss exponent between users-destination: **a_id=4**
- Path loss exponent between users-relays: **a_ir=2**
- Path loss exponent between relays-destination: **a_rd=2**
- Path loss exponent between the two relays: **a_rr=4**
- Transmit power of i-th user: **Ptx(i)=1mW**
- Transmit power of both relays: **Ptx(0)=5mW**
- Probability that a user attempts to transmit in each timeslot: **q=0.25**
- Probability that the relays attempt to transmit in each timeslot, in case its queue is not empty: **qo=0.85**

We should also note that the path loss exponent between users-destination as well as between the two relays is 4 while between users-relays and relays-destination is 2. That is because the relay nodes must be more accessible than the destination node for the users, meaning that the user-relay channel has to be more reliable than the user-destination one and at the same time the relay-destination channel must be more reliable than the user-destination channel. Otherwise, the presence of the relays degrades the performance of the whole network [80]. Also, we assume that the transmit power of the relays is 5 times higher than that of the users'.

We should also note that with small values of γ it is more likely to have more successful simultaneous transmissions comparing to larger γ. For $\gamma<1$ the probability for two or more users to transmit successfully at the same time is higher, than the same probability when $\gamma>1$, which tends to zero [80].

Figures 16, 17 and 18 show the aggregate throughput versus the number of users, for $\gamma=0.2$, $\gamma=1.2$ and $\gamma=2.5$ and for the cases of no relay, 1 relay and 2 relays.

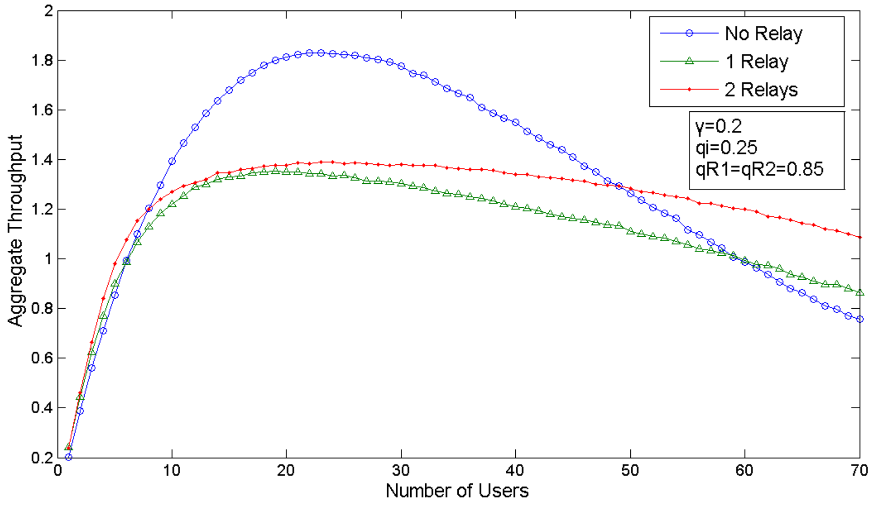

Figure 16: Aggregate throughput vs number of users for γ=0.2 and 1-70 users

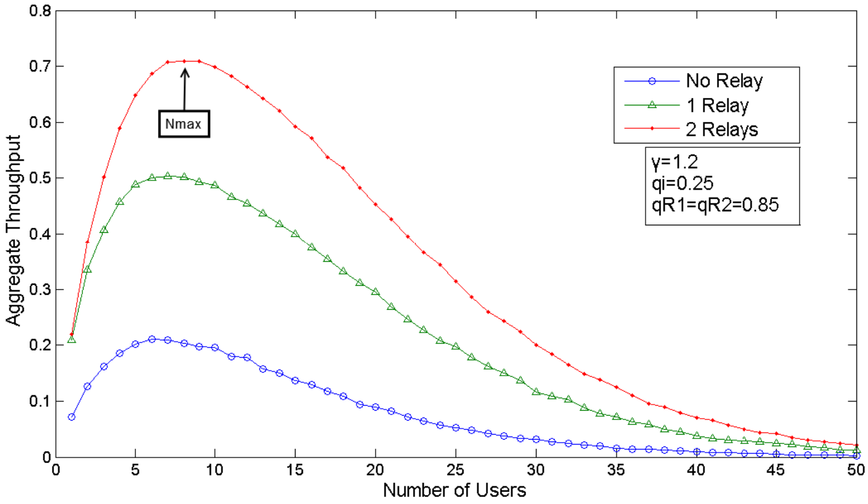

Figure 17: Aggregate throughput vs number of users for γ=1.2 and 1-50 users

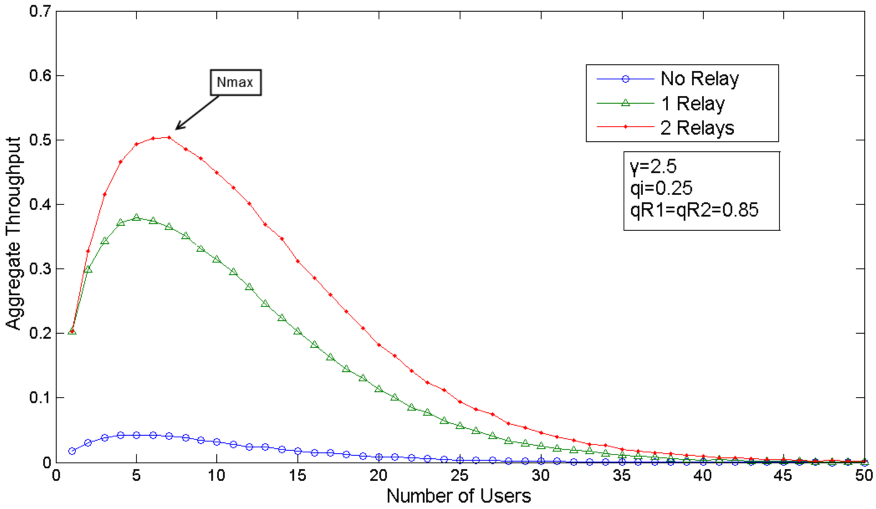

Figure 18: Aggregate throughput vs number of users for γ=2.5 and 1-50 users

From Figure 16 we observe that for low γ=0.2 the aggregate throughput obtained from the system with 2 relays is higher compared to that of the system with 1 relay and increases as more users are inserted in the system. However, it is interesting to note that while the aggregate throughput obtained from the system with two relays is slightly higher for 1 to about 8 users compared to that of the system with no relay, from 8 users and up to about 50 users the aggregate throughput of the system with no relay is much higher. For more than about 50 users the aggregate throughput provided by the system with two relays is higher compared to the system with no relay and increases as more users are inserted in the system, but networks with so many users may not be realistic and also the throughput per user for so many users tends to zero (as we will see in Figure 25 in section 3.3.3).

So, there is no need to use one or two relays in a system with low threshold γ, because as we explained earlier, with values of γ<1 it is more likely to have more successful simultaneous transmissions. This is expected because the insertion of one or even two relays, which transmit with higher power levels, increases the interference of the system and results in the degraded performance observed in Figure 16.

Unlike what we observed in Figure 16, in Figures 17 and 18 we observe that the system with two relays offers significant advantage compared to the networks with no relay and one relay with higher values of γ=1.2 and γ=2.5. This is expected because for higher values of γ the relays receive a larger percentage of packets in their queues in order to forward them to the destination. It is also interesting to note that given the link characteristics and the transmission probabilities, there is an optimum number of users Nmax that maximizes the aggregate throughput of the system with two relays. This number could be used as a criterion for finding the optimum size of a subset of users that the two relays can serve.

3.3.2 Relay with Smaller Queue Size Stores the Packet

In previous sub-section 3.3.1, we assumed that in case that both relays receive the same packet from a user, they both store it in their queues and try to forward it in a next timeslot to the destination. In this sub-section we assume that in such a case, the packet is stored by the relay which has the smaller queue size. If the queue size of the two relays is equal, then the two relays choose randomly and with equal probability which one will store the packet in its queue. We assume that the two relays communicate to exchange information in a separate channel and thus these transmissions do not interfere with the transmissions of the nodes of the system.

Figures 19, 20 and 21 show the aggregate throughput versus the number of users for the simple system described in sub-section 3.3.1 and the system in which the relay with the smaller queue size stores the packet for γ=0.2, γ=1,2 and γ=2.5.

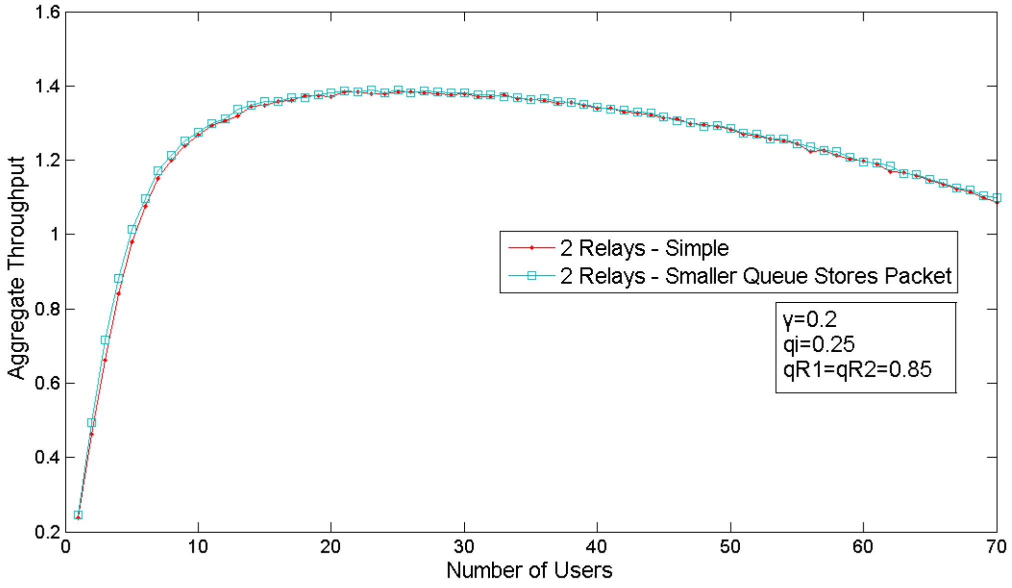

Figure 19: Aggregate throughput vs number of users for γ=0.2 and 1-70 users (Simple Network vs Smaller Queue Stores Packet)

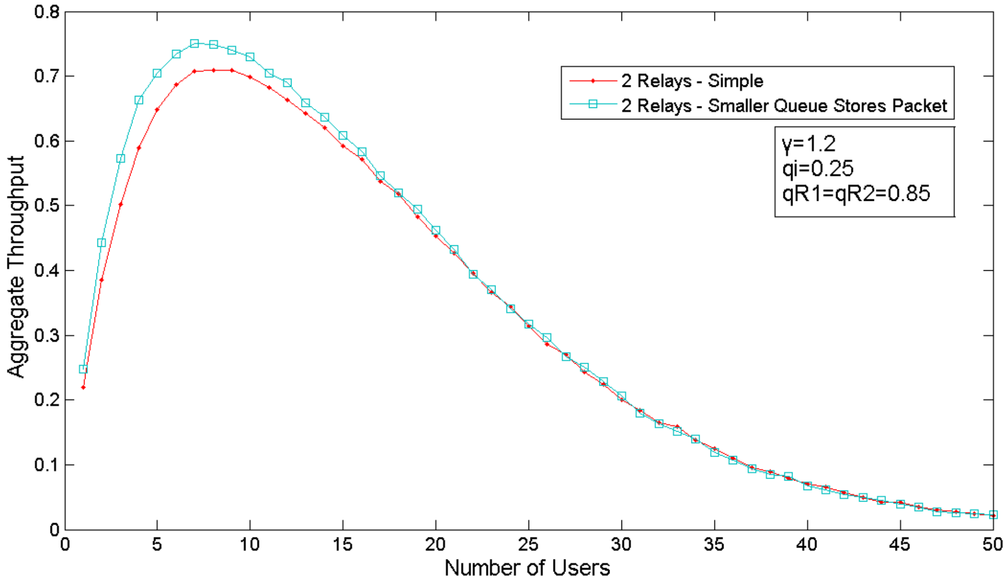

Figure 20: Aggregate throughput vs number of users for γ=1.2 and 1-50 users (Simple Network vs Smaller Queue Stores Packet)

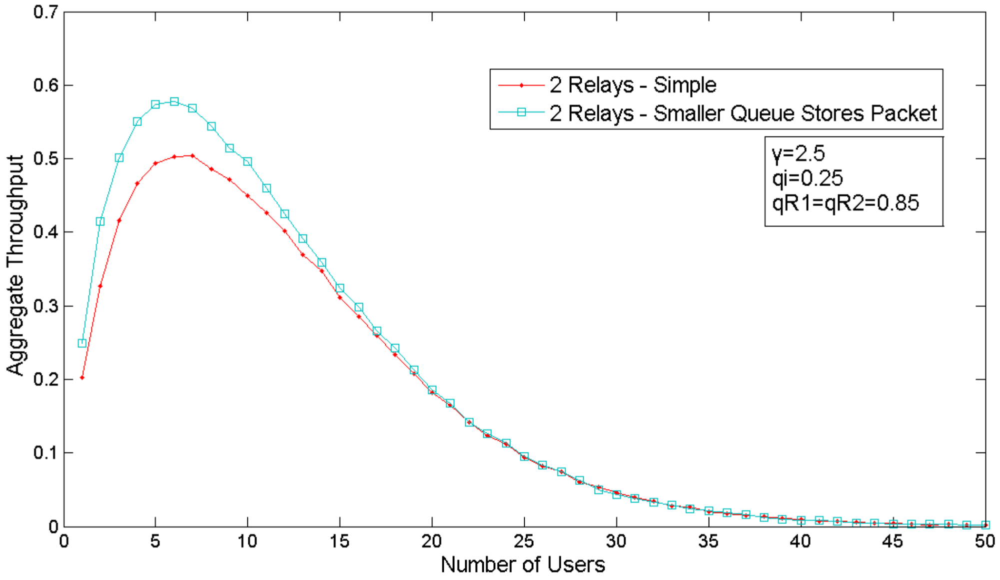

Figure 21: Aggregate throughput vs number of users for γ=2.5 and 1-50 users (Simple Network vs Smaller Queue Stores Packet)

From Figure 19 we observe that the aggregate throughput obtained by the two systems is almost equal for γ=0.2. However, from Figures 20 and 21 we obtain higher aggregate throughput for 1 to about 15 users in the network and we observe that when the threshold γ increases the gain as a percentage increases. The insertion of more users makes the aggregate throughput of the two systems almost equal. Thus, this technique can provide an enhancement in terms of aggregate throughput in a system with two relays for values of γ>1.

3.3.3 Impact of Dividing the Users Into Two Clusters

In this sub-section, we study the impact, in terms of aggregate and per user throughput, of dividing the users into two clusters served by relays R1 and R2, as we did in section 2.4 for the collision channel model. We divide the users equally to both clusters and we assume that each cluster has N_k users with k=1,2 where $N_1 = N_2 = N/2$. Again, to simplify the presentation we consider the case where all the users have the same link characteristics and transmission probabilities. We assume that relay R1 cannot receive packets from users of cluster 2 due to the long distance, and relay R2 cannot receive packets from users of cluster 1 respectively. The distance between cluster 1 and relay R2 is 1.5 times the distance between cluster 1 and relay R1, and vice-versa.

The parameters used in the simulations for this case are the following:

- Distance between users-destination: **rd=101m**
- Distance between cluster1-relay1 and cluster2-relay2: **r_cl12_r12 = 58.738m**
- Distance between cluster1-relay2 and cluster2-relay1: **r_cl12_r21= 88.107m**
- Distance between relays-destination: **rod= 58.738m**
- Distance between the two relays: **roo=60m**
- Path loss between users-destination: **a_id=4**
- Path loss between cluster1-2 and relay1-2: **a_i12r12=2**
- Path loss between cluster1-relay2 and cluster2-relay1: **a_i1r2_ i2r1 = 4**
- Path loss between relay-destination: **a_rd=2**
- Path loss between the two relays: **a_rr=4**
- Transmit power of i-th user: **Ptx(i)=1mW**
- Transmit power of both the relays: **Ptx(0)=5mW**
- Probability that a user attempts to transmit in each timeslot: **q=0.25**
- Probability that the relay attempt to transmit in each timeslot, in case its queue is not empty: **qo=0.85**

Figures 22, 23 and 24 show the aggregate throughput versus the number of users for the cases of 1) no relay, 2) 1 relay, 3) 2 relays simple, 4) 2 relays (smaller queue stores the packet), and 5) 2 relays with clustering, for γ=0.2, γ=1.2 and γ=2.5. Figures 25, 26 and 27 show the throughput per user for the same cases.

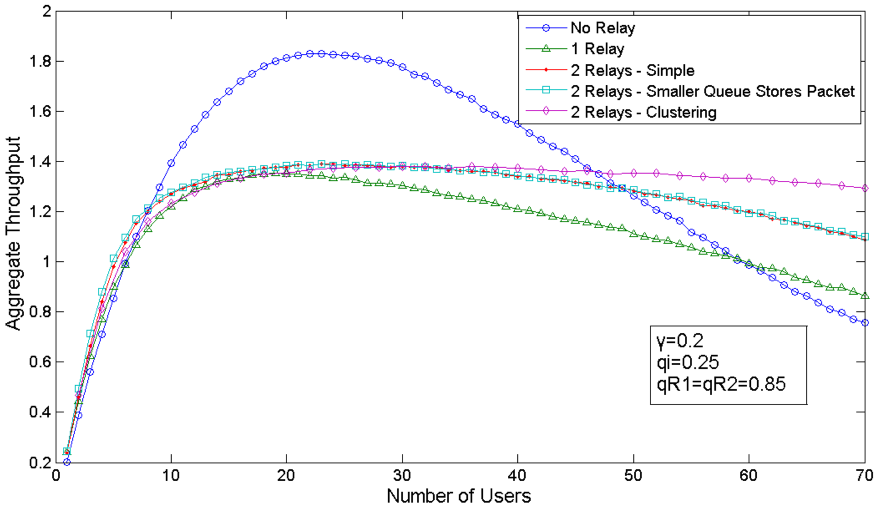

Figure 22: Aggregate throughput vs number of users for γ=0.2 and 1-70 users for the 5 cases

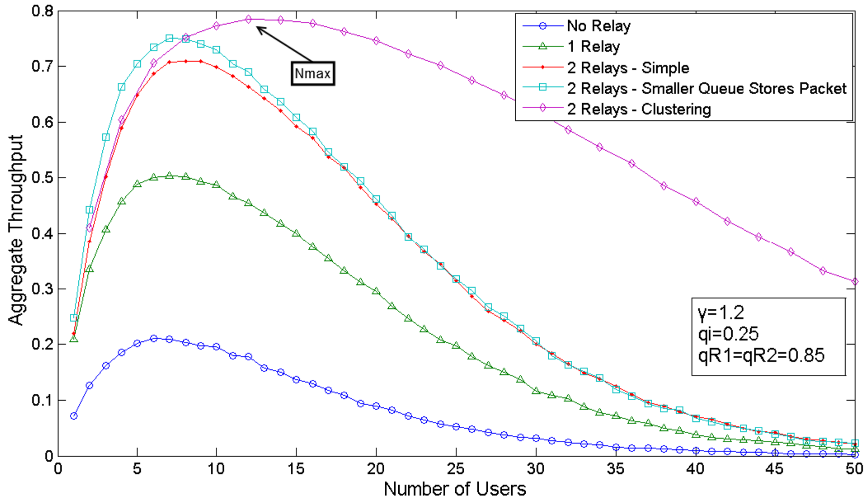

Figure 23: Aggregate throughput vs number of users for γ=1.2 and 1-50 users for the 5 cases

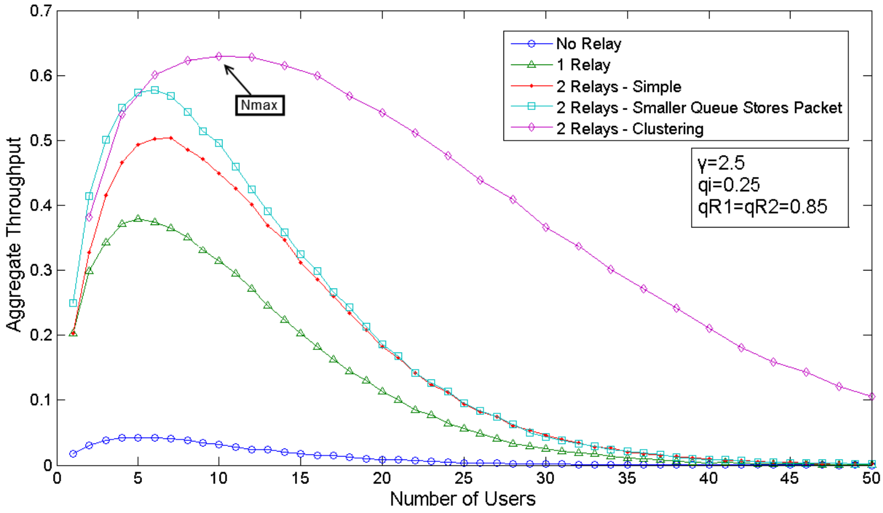

Figure 24: Aggregate throughput vs number of users for γ=2.5 and 1-50 users for the 5 cases

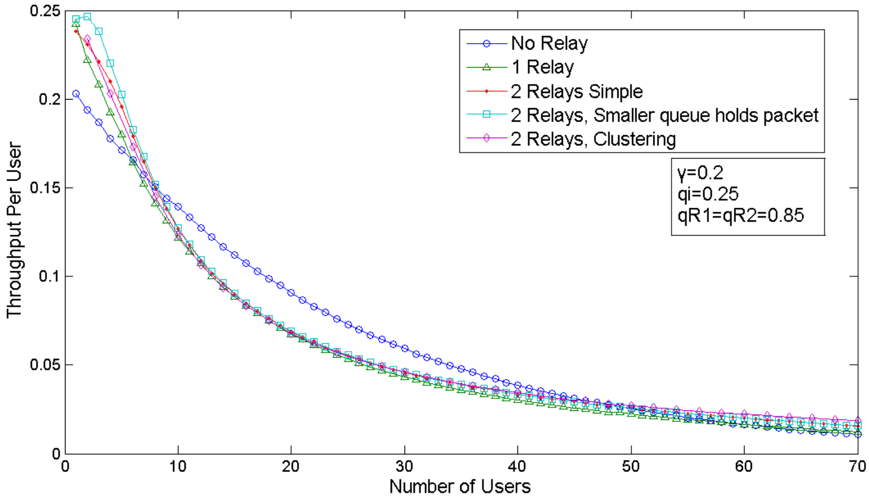

Figure 25: Throughput per user vs number of users for γ=0.2 and 1-70 users for the 5 cases

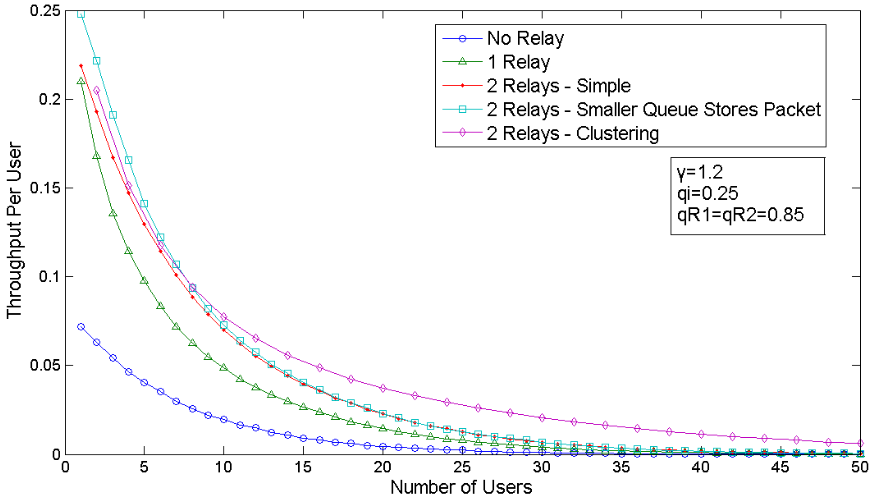

Figure 26: Throughput per user vs number of users for γ=1.2 and 1-50 users for the 5 cases

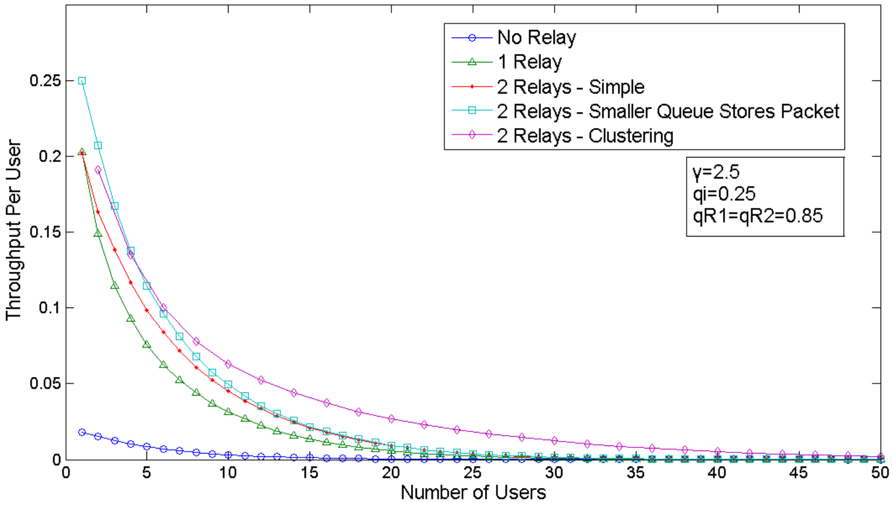

Figure 27: Throughput per user vs number of users for γ=2.5 and 1-50 users for the 5 cases

From Figures 22 and 25 we observe that for γ=0.2, the system with two relays and clustering does not provide any advantage compared to the system with no relay up until about 45 users. The clustered system offers higher aggregate throughput compared to the other four cases, for more than 45 users in the system but as we can see from Figure 25 the throughput per user achieved for more than 45 users is rather low. This result can be explained using the same arguments of section 3.3.1 for the simple system with two relays.

However, Figures 23, 24, 26 and 27 show that the system with two relays and clustering with higher values of threshold γ, offers significant advantage over the other four systems, for more than about 10 users in the system. This is expected because in each cluster the users interfere with half the users of the system in order to successfully reach the corresponding relay (the interference caused in each cluster's relay, by the users of the other cluster is almost negligible due to the long distance). Furthermore, there is an optimum number of users Nmax that maximizes the aggregate throughput of the system with two relays and clustering. This number could be used as a criterion for finding the optimum size of users in each cluster that each relay can serve in order to provide the maximum aggregate throughput.

3.3.4 Stability Check of Relays' Queues

Since we cannot verify from analytical equations that the probabilities we use for the queues of the two relays to transmit, lead in stable queues, we can verify that by means of simulation as follows: It is known that if the average arrival rate of a queue is greater than the average service rate, then the queue is unstable and the size of the queue approaches infinity almost surely. Thus, we can verify that a queue is stable if the queue size throughout the simulation does not increase excessively and retains an acceptable number of packets.

Figures 28 and 29 show the evolution of the queue size of the two relays in every timeslot of the simulation. This example is from the clustered system with 40 users and presents the queue evolution for the queues of relay R1 and R2 for a simulation of 20.000 timeslots.

We can see that the maximum number of packets that each queue reaches is 4 and there is no trend of an increase of both queue sizes. Thus, we can conclude that both queues are stable, for the transmission probabilities and the link characteristics that we used in the simulations. Working in exactly the same way for all the simulations presented in this chapter we verify that the transmission probabilities of all the nodes in every system that we use, lead in stable queues.

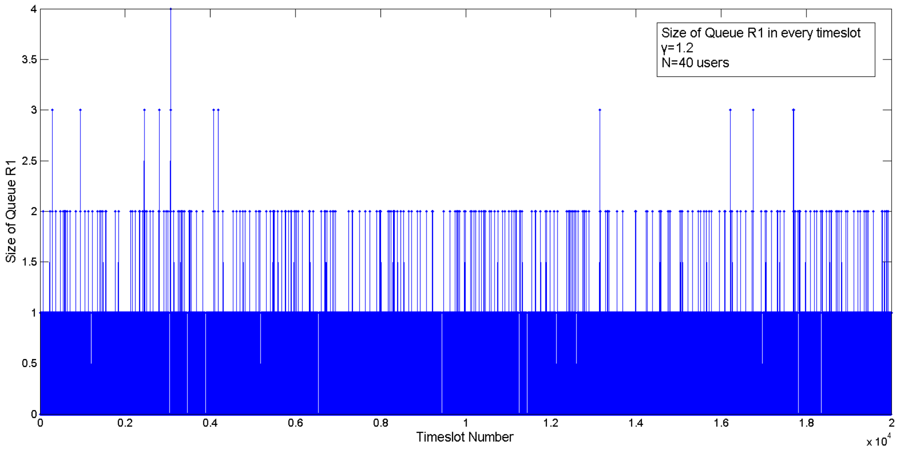

Figure 28: Size of queue R1 in every timeslot for the clustered system for N=40 users and γ=1.2

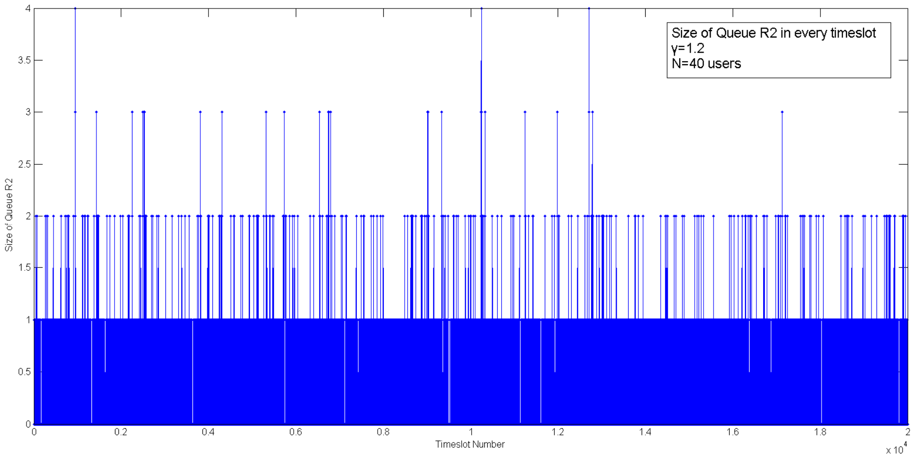

Figure 29: Size of queue R2 in every timeslot for the clustered system for N=40 users and γ=1.2

3.3.5 Average Queue Size

In such cooperative systems with relays, an important parameter that has to be taken into account is the queue size of the relays. It is important not only to keep the queues of the relays stable but also to hold the queue size as low as possible to decrease delay.

Figures 30 and 31 present the average queue size (in packets) versus the number of users for the systems with one and two relays studied in previous sections for γ=1.2 and γ=2.5. For the systems with two relays only the average queue size of the one relay is presented (the average queue size of the second is almost equal because we assume symmetric users in the systems).

The figures show that the average queue size of the clustered system is higher compared to the other systems. This is expected because as each relay serves half the users of the system, the interference between them in the corresponding relay is less and more simultaneous transmissions at a time at each relay may be successful. In that way, the two relays receive more packets resulting in higher queue sizes. It is interesting though to note that the maximum average queue size of the clustered system is less than one packet (about 0.65 packets for γ=1.2 and 0.6 for γ=2.5). Moreover, the average queue size of the other three systems tends to become equal after about 25 users.

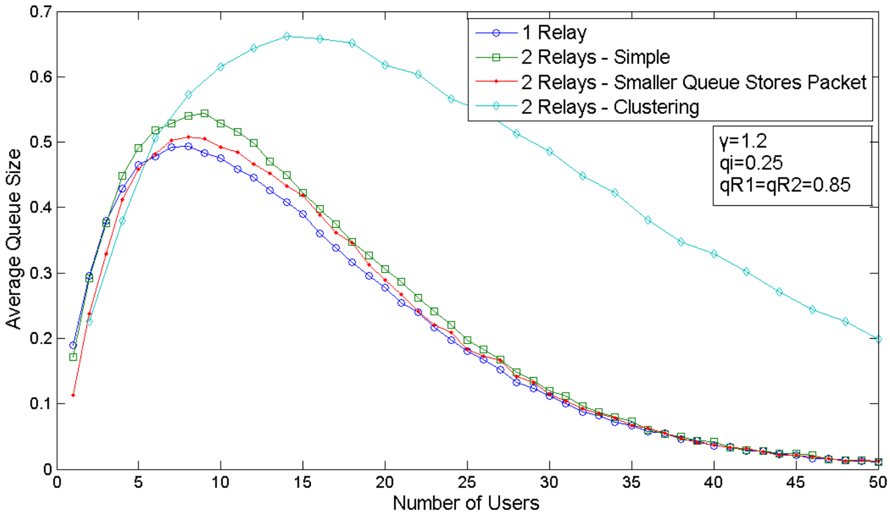

Figure 30: Average Queue Size versus number of users for γ=1.2 and 1-50 users for the systems with one and two relays

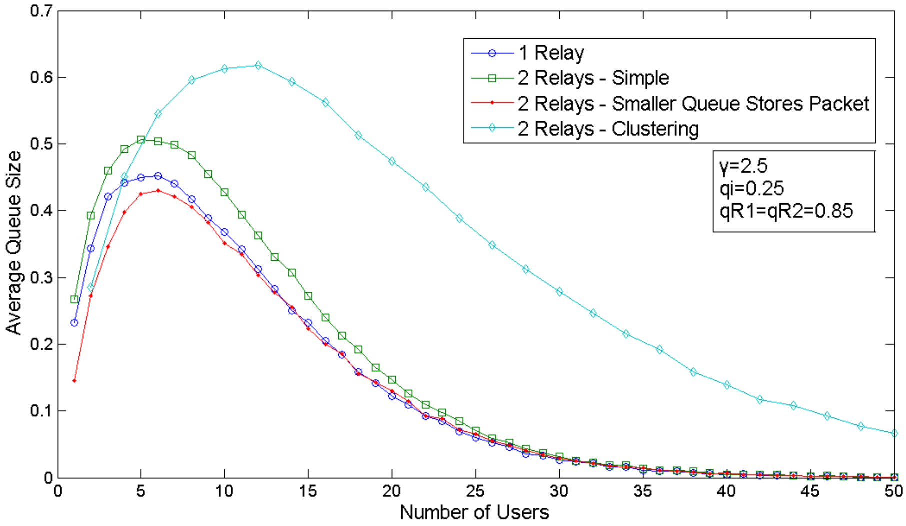

Figure 31: Average Queue Size versus number of users for γ=2.5 and 1-50 users for the systems with one and two relays

3.3.6 Average Delay per Packet

Another very important parameter in cooperative systems is the average delay per packet. By the term delay we refer at the time needed to deliver a packet to the destination from the moment it has been transmitted. This parameter is important especially in delay sensitive networks that require real time services. Thus, we have to investigate the average delay per packet of systems with two relays and compare it with the systems with one and no relay.

Figures 32 and 33 present the average delay per packet (counted in timeslots) versus the number of users, for γ=1.2 (1-30 users) and γ=2.5 (1-25 users) for the 5 cases presented in previous sub-sections. As expected, as more users insert packets into the system the average delay per packet increases due to the increased interference resulting in an increase of the number of collisions. The two figures show that the systems with two relays provide less average delay compared to the systems with one and no relay when the number of users is larger than 10. More specifically, for 30 users and γ=1.2 in Figure 32, the clustered system offers the lowest average delay per packet and it is interesting to note that whereas its value increases as the number of users also increases, it does not exceed 50 timeslots, while for the two other cases with two relays its value is about 150 timeslots and for the one relay 240 timeslots and for no relay 900 timeslots. We can make similar observations from Figure 33.

Furthermore, for more than 30 users when γ=1.2 and 25 users when γ=2.5, the average delay per packet for all the cases except the clustered one, increases excessively. Also, due to the fact that the aggregate throughput is fairly low and tends to zero as the number of users tend to 50 (see Figures 17, 18), there are not enough samples in order to make an accurate calculation of the average delay per packet. However, the simulation showed that the average delay per packet obtained from the clustered system for 50 users and γ=1.2 is no more than 160 timeslots and for 50 users and γ=2.5 it is no more than 460 timeslots.

So we can conclude that the systems with two relays offer significant advantages compared to the systems with no and one relay and also the clustered system is the only one that can sustain higher aggregate throughput compared to the other systems together with very low average delay.

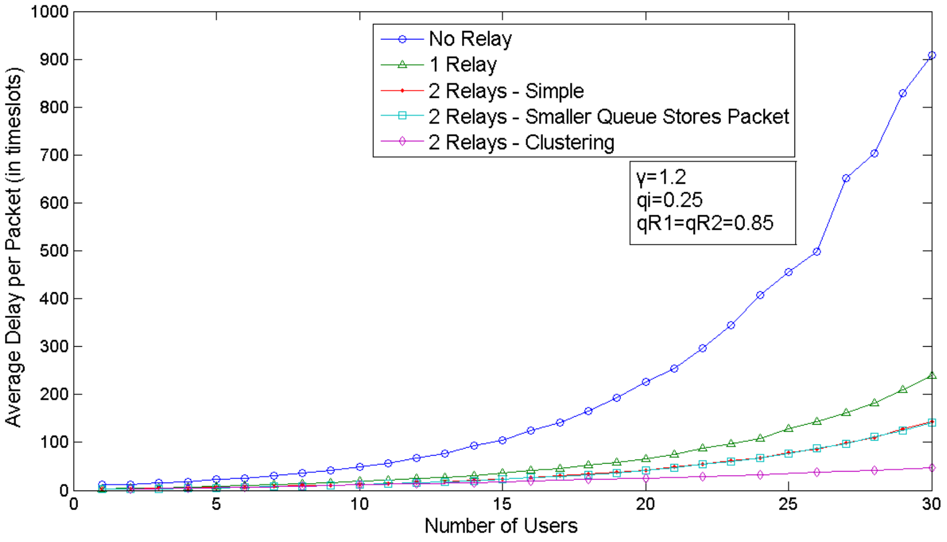

Figure 32: Average Delay per Packet (in timeslots) versus number of users for γ=1.2 and 1-30 users for 5 cases

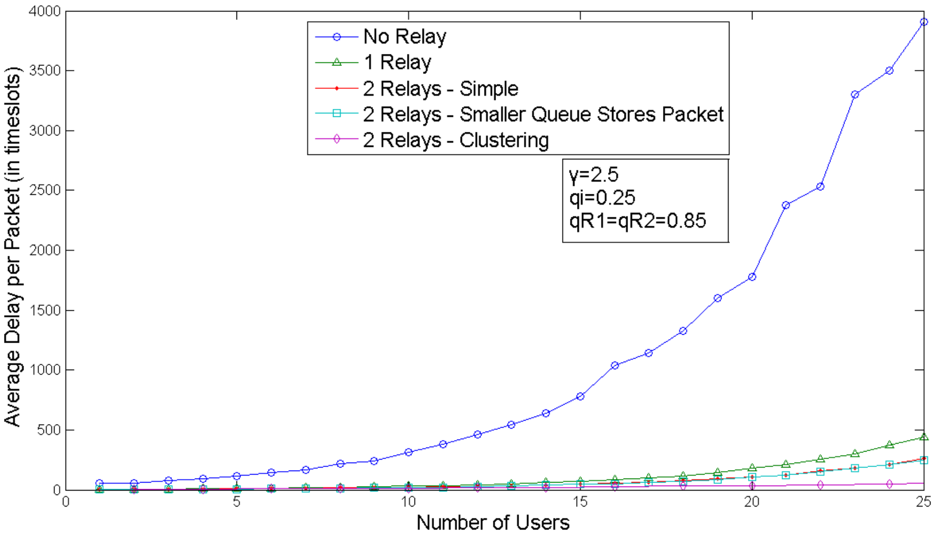

Figure 33: Average Delay per Packet (in timeslots) versus number of users for γ=2.5 and 1-25 users for 5 cases

3.3.7 Impact of Interference Cancellation Factor

In this sub-section, we try to further increase the aggregate throughput of the systems with two relays. Since we assume that the two relays are fixed and in known positions in the network, we can use interference cancellation techniques in order to decrease the interference between them as follows: When one of the two relays transmit a packet to the destination, its transmission interferes with the transmissions of the users at the other relay which does not transmit and it could receive packets in its queue. Thus, by utilizing a proper interference cancellation technique we can reduce the interference from the transmitting relay at the relay that does not transmit and allow for more packets to be successfully received in its queue.

A technique to achieve interference cancellation is to use properly designed and placed antennas at the relays, which have nulls at their radiation patterns in the direction of the other relay. In that way the interference of a transmission can be reduced by a certain factor depending on the environment (distance, obstacles etc) between the two relays. In our simulations for the clustered system below, we assume that we can achieve interference cancellation by a constant factor of 10^(-3).

Figures 34 and 35 present the aggregate throughput versus the number of users obtained by the clustered system for γ=1.2 and γ=2.5 for the same parameters used in previous sub-sections and for path loss exponent a=4 between the two relays.

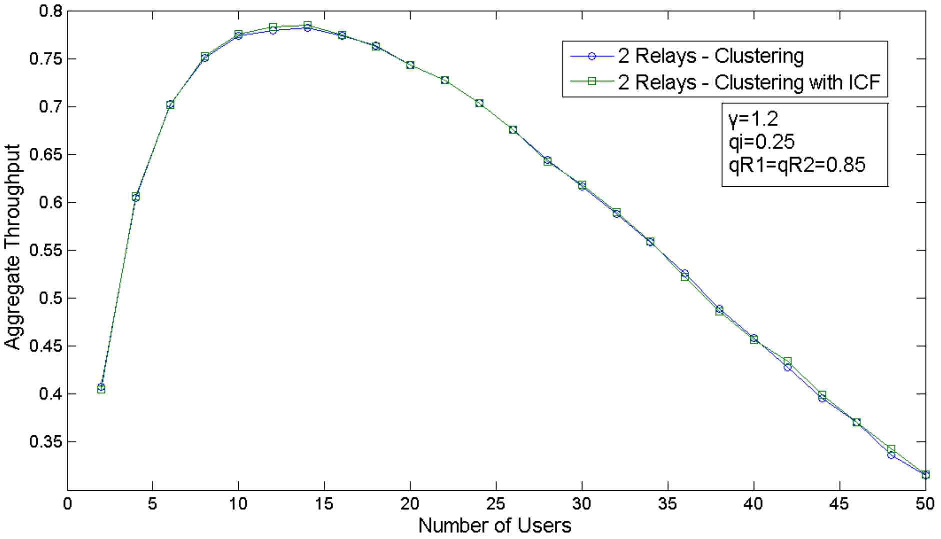

Figure 34: Aggregate throughput vs number of users for clustered network for γ=1.2, 1-50 users, path loss exponent between relays a=4 and Interference Cancellation Factor=10^(-3)

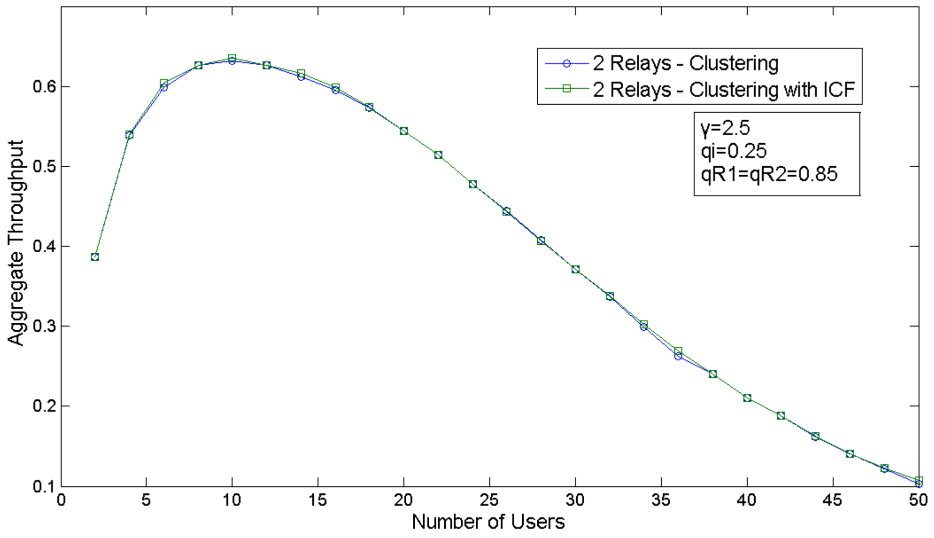

Figure 35: Aggregate throughput vs number of users for clustered network for γ=2.5, 1-50 users, path loss exponent between relays a=4 and Interference Cancellation Factor=10^(-3)

From Figures 34 and 35, we observe that the use of interference cancellation factor in our simulations does not provide any advantage in terms of aggregate throughput which remains exactly the same compared to the system without interference cancellation factor. This is expected because we assumed in our model from the beginning that we experience a relatively lossy environment between the two relays. That is, we assume that the path loss exponent is 4 and thus, the interference of the relays’ transmissions is not very high in order for the interference cancellation technique to provide an advantage.

However, if we consider the case that the two relays have line-of-sight (LOS) with path loss exponent a=2, then we obtain the following Figures 36 and 37. These figures show that the use of an interference cancellation technique offers a significant advantage for the case of LOS between the two relays. This is also expected because the better the channel conditions between the two relays, the higher the received signal power that causes interference with the other transmissions from the users at the relay that does not transmit.

To conclude, the location of the two relays and the wireless environment between them has to be taken into account by the system designer in order to use an interference cancellation technique or not.

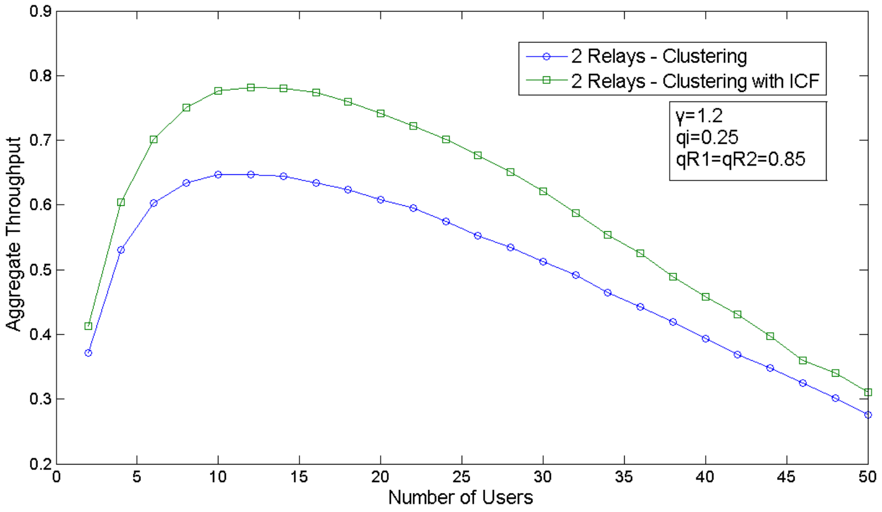

Figure 36: Aggregate throughput vs number of users for clustered network for γ=1.2, 1-50 users, path loss exponent between relays a=2 and Interference Cancellation Factor=10^(-3)

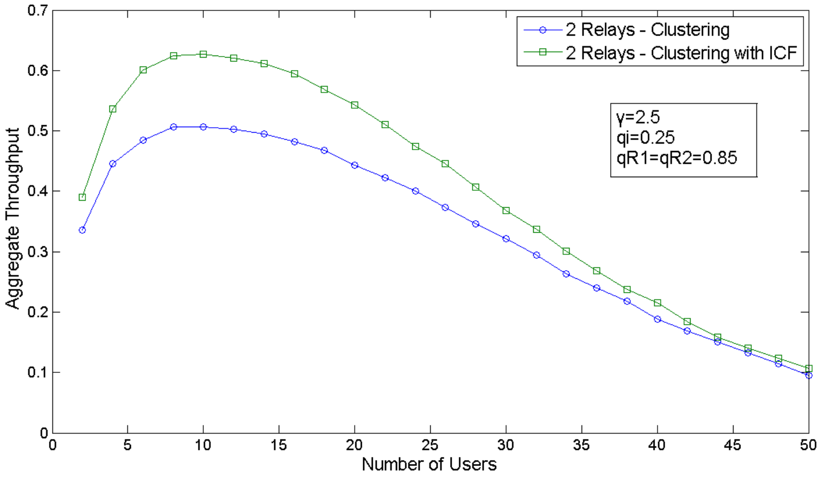

Figure 37: Aggregate throughput vs number of users for clustered network for γ=2.5, 1-50 users, path loss exponent between relays a=2 and Interference Cancellation Factor=10^(-3)

3.3.8 Impact of Higher Distance Separation of the Clusters

In this sub-section we investigate the effect of the distance between the two clusters. We consider the case where the distance between cluster 1 – relay 2 and cluster 2 – relay 1 is r_cl12_r21= 88.107m as in the above systems and the case where this distance becomes r_cl12_r21=120m. We also assume the case that the path loss exponent between the two above links is a=2 (all the other parameters of the system are the same as in previous sub-sections).

Figures 38 and 39 present the aggregate throughput versus the number of users for the two cases and for γ=0.2 and γ=1.2.

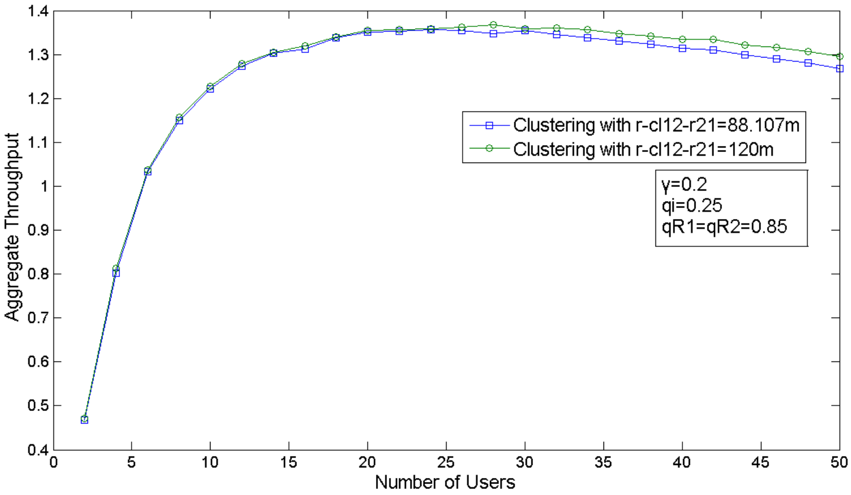

Figure 38: Aggregate throughput vs number of users for distance between cluster 1-relay 2 and cluster 2-relay 1, 88.107m and 120m for γ=0.2

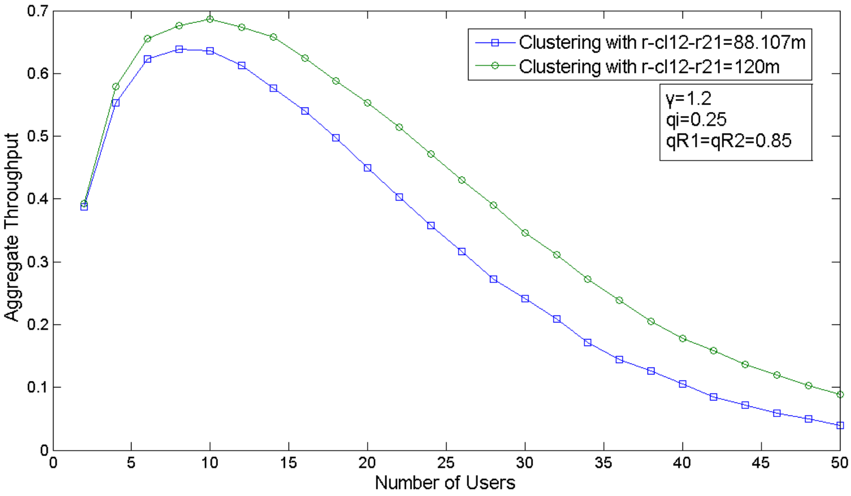

Figure 39: Aggregate throughput vs number of users for distance between cluster 1-relay 2 and cluster 2-relay 1, 88.107m and 120m for γ=1.2

In Figure 38 we observe that the advantage in terms of aggregate throughput for γ=0.2, when the distance between cluster 1 – relay 2 and cluster 2 – relay 1 increases, is not significant and appears for a large number of users. That is because as mentioned before, for low values of threshold γ the probability for two or more users to transmit successfully at the same time is high. However, as the number of users in the system increases, the interference to the destination and the two relays also increases and results in higher number of collisions. So, the separation in higher distance of the two clusters decreases the interference of the users of each cluster at the relay of the other cluster and allows more packets to reach each relay.

In Figure 39 we observe a significant advantage in terms of aggregate throughput for $\gamma=1.2$. That is because the interference between the users of the one cluster at the relay of the other cluster is decreased due to the increased distance between them.

3.4 Conclusions

In this chapter, we examine (by simulations in Matlab) the operation of two relay nodes that relay packets (when necessary) from a number of users to a destination node in random access systems with MPR capabilities. We present two variations of a system with two relays, the first in which if both relays receive the same packet from a user they both store it and forward it to the destination, and the second in which the relay with the smaller queue size stores the packet in its queue and is responsible for forwarding it to the destination. We also present a topology of the system in which the users are divided into two clusters and the users of each cluster are served only by the corresponding relay.

We show by extensive simulations that all the systems with two relays offer significant advantage in terms of aggregate and per user throughput, compared to the systems with one and no relay when the SINR threshold is $\gamma>1$. For values of $\gamma<1$ the use of one or two relays results in degradation of the system performance. The second variation in which the relay with the smaller queue size stores the packet offers higher aggregate and per user throughput compared to the first variation, and the system in which the users are divided into clusters offers the higher aggregate and per user throughput of all systems. Moreover, there is an optimum number of users that maximizes the aggregate throughput of the systems with two relays. We also show that although the average queue size of the clustered system is higher, the average delay per packet is much lower and in combination with the higher aggregate and per user throughput that it can provide, the clustered system is the most appropriate solution. Finally, we examine under what conditions an interference cancellation technique can provide significant advantages in terms of aggregate throughput and what are the effects of the distance of the two clusters in terms of aggregate throughput.

These results could be used to allocate the users among the relays for example in cellular and sensor networks. Future extensions of this work will include users with non-saturated queues (i.e. users-sources with external random arrivals) and relays with their own packets and priorities for the users. Other interesting extensions consist of relays which are capable of transmitting and receiving at the same time and the investigation of energy consumption in the total network and in particular at the relay nodes.

Chapter 4

Conclusions

4.1 Summary

This thesis focuses on cooperative communications and in particular on wireless network – level cooperation with two relays.

We first provided a basic introduction to cooperative communication systems and the relay channel. We presented some basic architectures, relaying protocols and multiple access methods. Furthermore, we discussed advantages and disadvantages of cooperation and some fundamental system tradeoffs that arise. Then, we referred to certain application scenarios and standardization of cooperative communications and provided a brief history. Finally, we have given the motivation behind our study of network – level cooperation in systems with multiple relays.

In Chapter 2, we examined the operation of two relay nodes assisting the communication of a number of users to a common destination by relaying (when necessary) their packets. We assumed a collision channel random access scheme in which simultaneous transmission attempts by two or more nodes result in a collision. We obtained analytical expressions for the arrival and service rates of the queues of the two relays and also the stability conditions. We presented a topology of the system in which the users are divided into two clusters and studied the impact of clustering on the per user and aggregate throughput. We showed that the two relays are free to choose their transmission probabilities independently from each other, provided that these are greater from some minimum values which guarantee the stability of their queues. It is interesting to note that the insertion of a second relay in a system generally does not offer higher throughput per user in comparison to a system with one relay, but the system in which the users are divided into two clusters separated by some distance offers significant advantage. Moreover, there is an optimum number $N_{\max}$ of users that maximizes the aggregate throughput of the clustered system. These results could be used to allocate the users among the relays for example in cellular and sensor networks.

In Chapter 3, we examined (by simulations in Matlab) the operation of two relay nodes that relay packets (when necessary) from a number of users to a destination node in time slotted random access systems with MPR capabilities. We presented two variations of a system with two relays, the first in which if both relays receive the same packet from a user they both store it and forward it to the destination, and the second in which the relay with the smaller queue size stores the packet in its queue and is responsible for forwarding it to the destination. We also presented a topology of the system in which the users are divided into two clusters and the users of each cluster are served only by the corresponding relay. In the wireless environment a node's transmission is successful if the SINR is above a certain threshold γ. We showed by extensive simulations that all the systems with two relays offer significant advantage with respect to aggregate and per user throughput, compared to the systems with one and no relay when the threshold $\gamma>1$. For values of $\gamma<1$ the use of one or two relays results in degradation of the system performance. The second variation in which the relay with the smaller queue size stores the packet offers higher aggregate and per user throughput compared to the first variation, and the system in which the users are divided into clusters offers the highest aggregate and per user throughput of all systems. Moreover, there is an optimum number of users that maximizes the aggregate throughput of the systems with two relays. We also showed that although the average queue size of the clustered system is higher, the average delay per packet is much lower and in combination with the higher aggregate and per user throughput that it can provide, the clustered system is the most appropriate solution. Finally, we examined under what conditions an interference cancellation technique can provide significant advantages in terms of aggregate throughput and what are the effects of the distance of the two clusters in terms of aggregate throughput. These results could be used to allocate the users among the relays for example in cellular and sensor networks.

4.2 Future Work

In Chapter 2, we assumed users with saturated queues and an extension could be to assume users with non-saturated queues (i.e. external random arrivals). However, this extension would make the analysis of the system rather difficult. Further extensions could be to consider relays having their own packets and different priorities for the users.

In Chapter 3, we also assumed users with saturated queues and we could expand the model with users with non-saturated queues. Again, we could consider relays with their own packets and priorities for the users. Another extension could be relays which are capable of transmitting and receiving at the same time and the investigation of energy consumption in the total network and in particular at the relay nodes.

Appendix A

Stochastic Dominance Approach

In this Appendix we present the proof of the stochastic dominance approach that was utilized in [72] to determine the region of values of the arrival rates λ_i, i=1,…,M for which a system of M queues is stable. With this approach, that was first introduced by Tsybakov and Mikhailov [81], the stability region for M=2 queues, can be determined in a simple way. We use this approach in Chapter 2 for M=2 queues of the two relays and in this appendix we will provide more details using a simple example.

Network Model

In [72], the network model considered (which has many similarities with the model we considered in Chapter 2) is the following: Discrete-time slotted ALOHA with M users, each of which has a buffer of infinite capacity to store incoming packets. Time is considered slotted and the transmission of a packet takes the duration of exactly one timeslot. Each user receives (generates) packets according to a Bernoulli process and the rate of arrivals is denoted by λ_i for the *i*th user. Also, the arrivals of different queues are independent. In each timeslot user i attempts to transmit the head-of-line packet with probability q_i provided that the buffer is not empty. Based on instantaneous ternary feedback (collision, idle, success) each user determines the outcome of the attempted transmission. Simultaneous transmission attempts by two or more users result in collision.

Analysis for M=2 queues

We denote by S the original system with M=2 queues that is the object of our study as described above. Also, let Q_i denote the queue size of the *i*th queue.

The probability of success (=departure of a packet, or service of a client) of the original system S seen by queue 1 clearly depends on whether queue 2 is empty or not. If $Q_2 = 0$ the probability of success seen by queue 1 is q_1 and if $Q_2 \neq 0$ the probability of success is $q_1(1-q_2)$. Thus, the average probability of success seen by queue 1 is:

$$q_1 + q_1(1-q_2) \tag{1}$$

Similarly, the average probability of success seen by queue 2 is:

$$q_2 + q_2(1-q_1) \tag{2}$$

Since, the average probability of success of each queue depends on the queue size of the other queue, they cannot be computed directly. If the probabilities of each queue to transmit were identical regardless of whether $Q_1 = 0$ and $Q_2 = 0$, then the system of the two queues would be decompose nicely and each queue would be separately analyzable. This observation motivates the introduction of auxiliary hypothetical systems that have precisely this property.

The stochastic dominance approach implies the construction of two hypothetical dominant systems. We consider the first system, say S1, consisting of two copies of the two queues of the original system S, with the following properties:

1) Arrivals at queue i in the new system occur at exactly the same instants as in the original system S, with i=1,2
2) The "coin tosses" that determine transmission attempts at queue i, with i=1,2, have exactly the same outcomes in both systems
3) Whenever $Q_1 = 0$, the queue 1 continues to transmit "dummy packets" with the same probability q_1, thus continuing its interference with queue 2 whether it is empty or not.

Similarly, in the second system $S2$ the properties 1 and 2 of the system S1 apply as well, but now it is the queue 2 that continues to transmit "dummy packets" with the same probability q_2 whenever $Q_2 = 0$, thus continuing its interference with queue 1 whether it is empty or not.

Dominant System S1: Queue 1 transmits "dummy packets"

The queue sizes of both queues in the new system S1 will never be smaller than their counterparts in the original system, provided that the queues start with identical initial conditions in both systems. This is true because the queue 1 that always transmits with the same probability regardless of having or not a packet to transmit, causes more collisions when queue 2 transmits a packet.

Although the stability region of the dominant system S1 is expected to inner-bound that of the original system S it turns out that the stability region obtained using stochastic dominance approach coincides with that of the original system as we present below and the stability regions for both the original and the dominant systems are the same.

In dominant system S1 queue 2 always sees a worst case service rate (because queue 1 always transmits packets with the same probability even when its queue is empty) which is given by:

$$\mu_2 = q_2(1-q_1) \tag{3}$$

So, we can see that system S1 dominates the original system S since either queue will have a successful departure in S whenever it has one in S1, but not necessarily vice-versa. It is also clear that in S1 the stability of queue 2 is easily determined by the fact that it operates as a discrete-time M/M/1 system. Thus, by Loyne's theorem queue 2 will be stable if and only if the arrival rate is less than its average service rate:

$$\lambda_2 < \mu_2 \Leftrightarrow \lambda_2 < q_2(1-q_1) \tag{4}$$

If we assume that Eq. 4 is satisfied the criterion for the stability of queue 1 is determined as follows:

- The probability of success rate of queue 1 is given by q_1, if $Q_2 = 0$ which happens with probability:

$$P(Q_2 = 0) = (1 - P(Q_2 \neq 0)) = (1 - \frac{\lambda_2}{\mu_2}) = (1 - \frac{\lambda_2}{q_2(1-q_1)}) \tag{5}$$

- The probability of success rate of queue 1 is given by $q_1(1-q_2)$, if $Q_2 \neq 0$, which happens with probability:

$$P(Q_2 \neq 0) = \frac{\lambda_2}{\mu_2} = \frac{\lambda_2}{q_2(1-q_1)} \tag{6}$$

Thus, by Loyne's theorem queue 1 will be stable if and only if the arrival rate is less than its average probability of success:

$$\lambda_1 < \mu_1 \Leftrightarrow \lambda_1 < q_1(1 - \frac{\lambda_2}{q_2(1-q_1)}) + q_1(1-q_2)\frac{\lambda_2}{q_2(1-q_1)} \Leftrightarrow$$

$$\Leftrightarrow \lambda_1 < q_1(1 - \frac{\lambda_2}{1-q_1}) \tag{7}$$

The stability region of the dominant system S1 is shown in Figure 38:

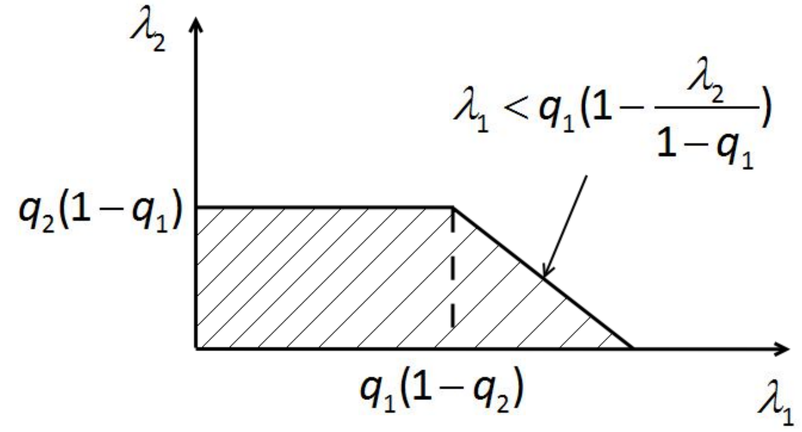

Figure 40: Stability region of dominant system S1

It is important to observe that the stability conditions obtained by Eq. 4 and 7 by using the stochastic dominance technique are not merely sufficient conditions for the stability of the original system S but are sufficient and necessary conditions. The proof relies on the observation that as long as the queues do not empty, systems S and S1 are *indistinguishable*.

That is, given that $\lambda_2 < q_2(1-q_1)$, if for some λ_1 the queue 1 is stable in system S1, then queue 1 is also stable in system S. This is true because if queue 2 is stable although queue 1 always transmits with the same probability (whether it has a packet or not), then the assumption that the queues at the dominant and original system start with identical initial conditions implies that queue 1 must also be stable since as mentioned earlier, “either queue will have a successful departure in S whenever it has one in S1”.

Conversely, if for some λ_1 queue 1 is unstable in dominant system S1 the queue size will grow to infinity without emptying with finite probability, and thus it will not transmit any “dummy packets” but source packets of the queue. So, as long as queue 1 does not empty, systems S1 and S behave identically if started from the same initial conditions. Thus, we can conclude that the original system S and the dominant system S1 are *indistinguishable* at the boundary points, because the “dummy packet” transmissions are increasingly rare as we approach the stability boundary.

Dominant System S2: Queue 2 transmits “dummy packets”

We now assume that queue 2 transmits “dummy packets” when it empties. Thus, by reversing the roles of the two queues in system S1 we obtain the stability region for system S2 that is given by:

$$\lambda_1 < q_1(1-q_2) \tag{8}$$

$$\lambda_2 < q_2\left(1-\frac{\lambda_1}{1-q_2}\right) \tag{9}$$

We can show that the previous two boundaries are part of the stability region of the original system S in exactly the same way as we did for system S1. The indistinguishability argument holds here as well.

Eventually, the union of the boundaries 4, 7, 8 and 9 defines the stability region of the original system S and it is shown in Figure 39:

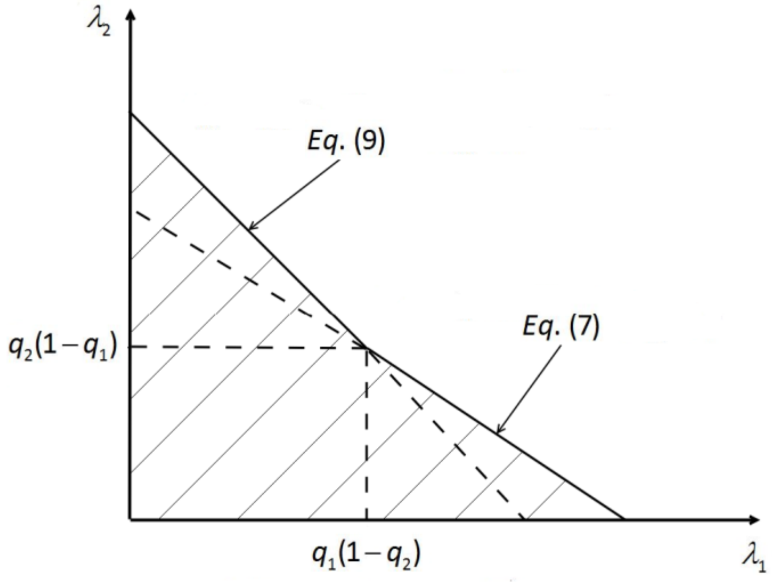

Figure 41: Stability region of original system S

The stability region depicted in Figure 39 is proved to be identical to the region obtained in [81].

Appendix B

Matlab Simulation Notes

In this appendix we present some basic functions in Matlab and algorithm steps we used in our simulations for this thesis. The simulations are divided in two parts, the collision channel (chapter 2) and the MPR (chapter 3) simulations.

Collision Channel Simulations

The basic steps that we follow in every timeslot for our simulations are the following:

1) In the beginning of each timeslot we find which users and which relay/s attempt to transmit.
2) If there is only one user that attempts to transmit, we calculate whether the transmission to the destination is successful. If it is, we increase the counter of correct transmissions by +1.
3) If transmission to the destination is not successful, we calculate whether the relay/s receive the packet. Depending on the case (one relay or two relays with clustering or not) we proceed as we described in chapter 2 for each case and increase the queue size of the relay that receives the packet by +1 and also the counter of correct transmissions (see section 2.3.4).
4) If only one relay attempts to transmit, we calculate whether the transmission to the destination is successful and if it is, we decrease the queue size of the relay by -1.

We perform the above steps in every system with the desired number of users and desired number of timeslots as well as link characteristics and transmission probabilities.

In order to find if a user attempts to transmit we use the **"rand"** function. For example, if q is the probability of a node to attempt transmission in a timeslot then, variable A gets the value 1 if the pseudorandom value obtained by rand is less than the value of q:

A = (rand(1,1) < q);

Thus, A gets the value of 1 if the node attempts to transmit and the value 0, otherwise. We use the same function in order to find if a relay attempts to transmit but first we check if the queue of the relay is empty or not.

In order to find if a transmission is successful or not we again use the **"rand"** function. For example, if p_id is the probability of a successful transmission of a user to the destination (when there are no collisions) then variable receive_qD gets the value 1 if the pseudorandom value obtained by rand is less that the value of p_id:

receive_qD = (rand(1,1) < p_id);

Thus, receive_qD gets the value of 1 if the transmission of the user to the destination is successful and the value 0, otherwise.

Depending on the values (0 or 1) we obtain from the use of "rand" as we showed above for every user, every relay and every transmission in the system we proceed based on the system model described in chapter 2.

MPR Simulations

The basic steps that we follow in every timeslot for our simulations are the following:

1) In the beginning of each timeslot we find which users and which relay/s attempt to transmit.
2) If at least one user attempts to transmit, we calculate the SINR of each user at the destination (as we described in section 3.2.2). If the SINR is above the threshold γ the transmission is successful and we increase the counter of correct transmissions by +1.
3) If the destination does not receive the packet from a user we calculate the SINR at the relay/s that do not transmit any packets and thus, they can receive packets in their queues.
4) If one relay receives the packet we insert the packet in its queue and if both relays receive the same packet we proceed depending on the case (as described in chapter 3).
5) If one relay attempts to transmit we calculate the SINR at the destination and if it is above the threshold γ we have a successful transmission and delete the first packet of the relays queue.

We perform the above steps (with the obvious changes for the different cases) in every timeslot in all the systems with MPR capabilities. Next, we describe how we calculate the SINR to decide if a transmission is successful or not, how we calculate the average delay per packet and the average queue size of the relays and we provide a brief description of two functions that we use.

SINR Calculation

As described in section 3.2.2 a transmission between nodes i and j is successful if the SINR(i,j) is above a certain threshold γ. For example, if we want to calculate the SINR of user i at destination j when a number of users and both relays transmit simultaneously, a sample code is the following where:

- *number_i*: is the number of users that attempt simultaneous transmission in the current timeslot
- *Prx_id_relay:* is the total signal power received by the other users at the destination j
- *Fading_id(node(k),t)*: is the random variable representing channel fading for node i for the transmission to the destination in current timeslot t and under Rayleigh fading it is exponentially distributed (we show later how this is calculated)
- *Ptx_nodes*: is the transmit power of the i-th user
- *rd*: Distance between users and destination j
- *a_id*: is the path loss between users and destination j
- *number_of_relays_trying_to_transmit*: is 0 if no relay attempts transmission and 1 or 2 if one or two relay attempt to transmit
- *relays_trying_to_transmit*: matrix that has the value 1 if relay 1 attempts to transmit or 2 if relay 2 attempts to transmit or 1 in position (1,1) and 2 in position (1,2) if both relays attempt to transmit simultaneously
- *Prx_r1d_relay*: is the power received by relay 1 at the destination j
- *Prx_r2d_relay*: is the power received by relay 2 at the destination j
- *Fading_r1d(t)*: is the random variable representing channel fading for relay 1 for the transmission to the destination in current timeslot t and under Rayleigh fading it is exponentially distributed
- *Fading_r2d(t)*: is the random variable representing channel fading for relay 1 for the transmission to the destination in current timeslot t and under Rayleigh fading it is exponentially distributed
- *Ptx_relay*: is the transmit power of the relays
- *rod*: is the distance between relays and destination
- *a_rd*: is the path loss between relays and destination
- *SINR_id_relay*: is the SINR of user i at destination j based on Eq. 1 of section 3.2.2.

```
Prx_id_relay = 0;
for k = 1:number_i
  if k~=i
    Prx_id_relay=Prx_id_relay+Fading_id(node(k),t)*(Ptx_nodes)*((rd)^(-a_id));
  end
end
Prx_r1d_relay = 0;
Prx_r2d_relay = 0;
for k = 1:number_of_relays_trying_to_transmit
  if (relays_trying_to_transmit(k) == 1)
    Prx_r1d_relay=Prx_r1d_relay+Fading_r1d(t)*(Ptx_relay)*((rod)^(-a_rd));
  else
    Prx_r2d_relay=Prx_r2d_relay+Fading_r2d(t)*(Ptx_relay)*((rod)^(-a_rd));
  end
end
Prx_rd_relay_total=Prx_r1d_relay+Prx_r2d_relay;        %Total power received in
%destination by the two relays.
SINR_id_relay(i)=(Fading_id(node(i),t)*(Ptx_nodes)*((rd)^(-a_id)))/ (ni + Prx_id_relay
+ Prx_rd_relay_total);   %SINR of user i at destination.
```

If “*SINR_id_relay(i)”* calculated is above the threshold γ then the transmission of user i at the destination is considered successful. If not we calculate the SINR on both relays to see which receives the packet successfully (depending on the case).

Finally, the random variable representing channel fading which is exponentially distributed, for every link between two nodes of the system and for every timeslot is calculated using the “**exprnd**” function. In the following example we pre-calculate the fading of the link between all nodes i and the destination j in every timeslot throughout the simulation:

```
for i = 1:N
        for j = 1:total_timeslots
                Fading_id(i,j) = exprnd(1,1,1);
        end
end
```

We do exactly the same for every possible link in the system (users-relays, relays-destination, and relay-relay).

Average Delay per Packet Calculation

The basic idea is to calculate the delay of every packet that reaches the destination either directly by users or through the relays, and keep this delay time in a matrix (we call it “delay” matrix). When the simulation is over we calculate the average delay using “**mean**” like: avg_delay = mean(delay);

For every user we keep in the matrix “last_delay” the number of a timeslot that he first attempted a transmission. If it is the first attempt of a user to transmit a packet at the destination and it is successful then the next position of the matrix “delay” gets the value 1. Otherwise, we deduct the value of matrix “last_delay” of the value of the current timeslot:

```
if (last_delay(node(i)) == 0)
        delay_next = delay_next + 1;   %Pointer to the next position of matrix "delay".
        delay(delay_next) = 1;
else
        delay_next = delay_next + 1;
        delay(delay_next) = t - last_delay(node(i)) + 1;
        last_delay(node(i)) = 0;
end
```

If the transmission at the destination is not successful but one or both relays receive the packet, we use two other matrixes “relay_1_last_delay” and “relay_2_last_delay” in which we keep the value of the matrix “last_delay” in order to know when the packet we store in the queue of the relay was first attempted to be sent by the user. If it was the first transmission attempt by the user then the corresponding position of each matrix of the relay that receives the packet, takes the number of the current timeslot, otherwise the value of the matrix “last_delay” for that user. Finally, when a relay transmits a packet, we calculate the “delay” of that packet by deducting the value of the corresponding position of the matrixes “relay_1_last_delay” or “relay_2_last_delay” (depending on which relay transmits) of the value of the current timeslot, and keep it at the next position of the matrix “delay”.

Average Queue Size

In every timeslot we store in two matrixes the current size of the queues of the relays and when the simulation is over we calculate the mean of those matrixes using “**mean**”.

Functions

For our simulations we implemented two very simple functions the “Packet_In_Queue” and the “Erase_Same_Packets”.

The first finds the next position of the queue that we should store a packet that is received by the relays from the users.

The second is used for the simple systems with two relays, when at least one relay transmits successfully a packet at the destination. In that case a packet that is received by both relays may be sent by one of the two relays successfully to the destination. In that case, we should find the packet in the queue of the other relay and delete it. This function does exactly that.

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